Figure 1 is a block diagram of a conventional data-parallel firewall;

Figure 2 is a block diagram illustrating an exemplary function-parallel firewall architecture according to an embodiment of the subject matter described herein;

Figure 3A is graph comparing simulation results for average packet delay for different firewall architectures;

Figure 3B is a graph comparing simulation results for maximum packet delay for different firewall architectures;

Figure 4A is a graph illustrating average packet delay for different packet types for a data-parallel firewall;

Figure 4B is a graph illustrating simulation results for packet delay for different packet types for a function-parallel hierarchical firewall according to an embodiment of the subject matter described herein;

Figure 5 is a data structure diagram illustrating a full trie representation of the security policy illustrated in Table 1;

Figure 6 is a data structure diagram illustrating a pruned trie representation of the security policy given in Table 1 where each packet is processed within four field comparisons;

Figure 7A is a data structure diagram illustrating a trie representing two security rules assuming that the default action per node is deny;

Figure 7B is a data structure diagram illustrating a reordered version of the trie data structure illustrated in Figure 7A;

Figure 8A is a diagram illustrating a Jackson model for a function-parallel hierarchical firewall according to an embodiment of the subject matter described herein;

Figure 8B is a diagram illustrating a Jackson model for a data-parallel firewall;

Figure 9 is a graph illustrating simulation results for average delay for different firewall architectures;

Figure 10 is a block diagram illustrating a stateful hierarchical firewall according to an embodiment of the subject matter described herein;

Figure 11A is a block diagram illustrating physical connections of a firewall grid according to an embodiment of the subject matter described herein;

Figure 11B is a block diagram illustrating logical connections of the firewall grid illustrated in Figure 11A according to an embodiment of the subject matter described herein;

Figure 12 is a policy directed acyclical graph (DAG) representation of the firewall rules given in Table 2;

Figure 13A is a block diagram illustrating rule distribution among a data-parallel firewall;

Figure 13B is a block diagram illustrating a function-parallel firewall and rule distribution among nodes in the function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 14A is a block diagram illustrating one exemplary rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 14B illustrates another distribution of rules among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 14C illustrates an illegal rule distribution among nodes in a function-parallel firewall;

Figure 15A is a block diagram illustrating non-redundant rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 15B is a block diagram illustrating redundant rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 16A illustrates a policy DAG where deny rules are indicated by a square node;

Figure 16B is a block diagram illustrating initial gateless rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 16C is a block diagram illustrating final gateless rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 17A is a graph illustrating simulation results for average packet delay as packet arrival rate increases for different firewall designs;

Figure 17B is a graph illustrating simulation results for packet delay as the arrival rate and number of rules increase for different firewall designs;

Figure 18A is a graph illustrating simulation results for average packet delay for different firewall architectures;

Figure 18B is a graph illustrating simulation results for maximum packet delay for different firewall architectures; and

Figure 19 is a flow chart illustrating exemplary steps for filtering packets using a rule set distributed among nodes in a function-parallel manner according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION OF THE INVENTION

According to one aspect of the subject matter described herein may include multiple firewall machines configured in a hierarchy, as shown in Figure 2. In the example illustrated in Figure 2, a plurality of firewall nodes **200**, **202**, **204**, and **206** collectively implement a firewall policy. Each firewall node or set of nodes implements a different level of the firewall policy in a hierarchy. For example, firewall node **200** may implement a first level of a firewall policy that includes rules that are not present in subsequent levels. If a packet passes the first level of screening, the packet may be forwarded immediately to the internal network without impacting other firewall nodes. If the packet is identified as requiring further scrutiny, the packet may be forwarded to the next level where it is screened by firewall node **202** or **204** using rules that were not applied by firewall node **200**. If the packet passes level 2 screening, the packet may be forwarded directly to the internal network. If the packet is indicated as requiring further screening, the packet will be passed to level 3 where level 3 screening is applied by firewall node **206**.

At each level in the firewall hierarchy illustrated in Figure 2, firewall nodes may implement different portions of a packet filtering rule set. An architecture in which different firewall nodes implement different portions of a firewall rule set is referred to herein as a function-parallel architecture. A function-parallel firewall architecture in which packet filtering rules are distributed among firewall nodes such that if a packet passes or fails at a

certain level, the packet may bypass later levels is referred to herein as a hierarchical firewall architecture.

In the architecture illustrated in Figure 2, at each level, machines may be configured to perform a specific security task quickly and efficiently. In one implementation, the firewall rules may be distributed across the different hierarchy levels such that increased scrutiny is placed at lower levels. Since the rules are distributed among the levels, no machine in the hierarchy is required to implement the entire rule set. In contrast, a data-parallel firewall architecture requires all machines to implement the complete rule set.

As described above, in the exemplary architecture illustrated in Figure 2, packets start at the highest level and progress downward through the hierarchy. At each level, a packet can be forwarded to the internal network if deemed safe, forwarded to the next lower level for more processing, or dropped. The benefit of this divide-and-conquer approach is that traffic will incur delays consistent with its perceived security threat; therefore, traffic that is deemed safe will not be delayed by traffic that requires more processing. As a result, the hierarchical firewall can provide differentiated service and support QoS guarantees, unlike current designs. Furthermore, traffic that is forwarded to the internal network can be shaped at the particular firewall level, constraining the amount of traffic entering the network and lessening the effect of DoS attacks.

For example, in the hierarchical firewall depicted in Figure 2, packets are forwarded from the external network to the first level, where initial security checks are performed, such as a quick validity check and comparisons of IP addresses. Packets with trusted IP addresses are immediately forwarded to the internal network, while the remaining packets are sent to the next level. At the second level, packets are separated based on transport protocols and/or port numbers. Again, if a packet is deemed safe it is immediately forwarded to the secure network; otherwise, they are sent to the next level for auditing. Log files may be used at one or more of the firewall nodes indicate which connections are open and have been requested. Each level may also drop packets based on perceived threat.

The preceding example illustrates a simple hierarchical firewall; however, the size and complexity can vary. In general, the hierarchy attempts to quickly divide traffic and provide differentiated service. More levels can be used for

stronger security policies and to distribute traffic more efficiently. Determining the appropriate number of levels, the number of machines per level, and how to distribute the rule set are implementation details that may be used to optimize a function-parallel firewall according to an embodiment of the subject matter described herein.

Preliminary Experimental Results

In this section, simulation is used to compare a hierarchical firewall with a traditional single-machine firewall and a data-parallel firewall [4, 22]. Each architecture implemented the same 325-rule security policy, where each rule required 1 unit of time to complete. The single firewall architecture consisted of one machine that processed each packet received from the external network. The data-parallel architecture consisted of four machines, as shown in Figure 1, each implementing the same 325-rule set. The hierarchical firewall consisted of four machines configured in three levels, as shown in Figure 2. Rules were distributed across the levels such that the first level implemented 25 rules; the second level implemented 50 rules each; and the third level implemented 75 rules. The group of rules performed at a certain machine will be referred to as a security task. The hierarchical firewall incurred an additional delay of one time unit when a packet was transmitted from machine to machine. Packets randomly arrived to the system using a Poisson distribution with a mean of 30 units and would randomly match one of the 325 rules based on a uniform distribution. For classification purposes, each packet was associated with the security task it matched (which group of rules). In this experiment, the performance parameters analyzed are the overall average packet delay, the maximum packet delay, and the average delay experienced by each packet type.

Experimental results for the different architectures are shown in Figures 3 and 4. More particularly, Figure 3A illustrates average packet delay for a single firewall design, for the data-parallel firewall design illustrated in Figure 1, and for the hierarchical firewall design illustrated in Figure 2. Figure 3B illustrates maximum packet delay for the single, data-parallel, and hierarchical firewall designs. Figure 4A illustrates average packet delay for the data-parallel firewall design for different packet types. Figure 4B illustrates average packet

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delay for the hierarchical firewall design for different packet types. Packet types refer to packets of a classified based on which security task was satisfied. Unlike the data-parallel firewall, the hierarchical design consistently yields different delays for each packet type.

For both delay measurements, the hierarchical architecture performed better than the single firewall and the data-parallel firewall. The single firewall had an average delay 31 times greater than the hierarchical architecture, which demonstrates how a single firewall machine can quickly become a bottleneck. Although the data-parallel firewall performed better than the single firewall, it had an average and maximum delay 6 times longer than the hierarchical architecture. In the parallel configuration, traffic that needed little processing often queued behind traffic that required more processing, which resulted in longer delays. In contrast, the hierarchical system consistently yielded better results, since traffic was distributed among the levels based on processing requirements.

The average delay experienced by each packet type is also important and is illustrated in Figures 4A and 4B. Delays in the hierarchical firewall were proportional to the amount of processing required; for example, security task 1 traffic had the shortest delay, security task 2 traffic had the second shortest delay, security task 3 traffic had the third shortest delay; and security task 4 traffic had the highest delay. Even though security tasks 2 and 3 were on the same level, security task 3 traffic had a delay slightly higher that security task 2 traffic, since it was queued with security task 4 traffic. Therefore, the hierarchical firewall is capable of providing differentiated service to multiple packet types/classes. In contrast, the delays varied for each packet type in the data-parallel firewall. Packets were constantly delayed by lower type/class traffic (e.g., security task 1 packets delayed by security task 4 packets); thus, no differentiation was achieved. Although these results are preliminary, they indicate the hierarchical architecture has merit, offering significantly better performance than current firewall systems.

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Refinements

The previous section described an initial hierarchical firewall architecture for employing a security policy. Although preliminary results indicate the architecture has merit, refinements can be made so that the design can achieve its full potential. One refinement relates to the hierarchical architecture. Important questions include determining the appropriate number of levels and how to effectively distribute the security policy rules. Another refinement may include providing stateful packet inspection (maintaining connection tables) and increasing redundancy. Finally, another refinement may include examining other high-speed firewall architectures, such as a dynamic firewall grid. Analytical models and simulation will be used for design and analysis; in addition, a prototype will be implemented along with analysis tools and software.

Architecture Design and Rule Set Distribution

Important questions about the firewall architecture include the number of levels, the number of machines per level, and the number of security tasks per machine. The security policy is central for addressing these questions and, for this reason, will be formally defined and modeled. The model will be optimized to reduce the physical size, minimize the traversal time, and provide differentiated service. Afterward, the optimized policy model will be used to implement the actual hierarchical firewall.

One method for designing the hierarchy is to represent the security policy graphically as a tree data structure. This representation will aid the translation to the actual firewall, since it has a hierarchical form. Although a variety of tree data structures exist, a trie will be initially investigated [1]. A trie is a special type of data structure that has the advantages of fast retrievals and quick unsuccessful search determination, which are important for enforcing a security policy. In a security policy trie, each path from the root node to a leaf corresponds to one rule. The nodes of the trie correspond to the rule fields, while branches are possible values. Figure 5 is a trie data structure for the rules in Table 1. For example, in Figure 5, the root node is the protocol field. The next level represents the source IP address, while the leaf nodes represent

the rule action. Rules that have the same field value at a node will share a branch for that value.

The trie in Figure 5 referred to as full trie, since every noncycle path from the root to a leaf has the same length, and every leaf lies at the same depth [6]. Unlike other policy models, the rule order must be preserved if the trie is to be successfully translated to a hierarchical firewall. The action to apply to a packet is determined by a preorder traversal. Starting at the root node, branches are compared to the fields of the packet. Since multiple branches may match a packet, they are traversed in order from left to right. If a packet field does not match any possible branches, it moves back to the previous node (parent), where the next branch is tested. Once the policy trie is developed, it can be translated into a hierarchical firewall. The nodes of the trie represent the machines in the hierarchy, while the branches represent the links between nodes. The value associated with each branch indicates the packet field value required to traverse it. Although a full trie representation of a security policy can be created, it is not necessarily optimal. Further trie manipulation is required create an effective hierarchical firewall, such as preventing routing to parents and limiting trie traversal time.

Pruning yields a trie that never requires routing to parent nodes, which provides faster packet processing [1, 15]. Assuming a full trie consists of n nodes and k levels (where k <= n), the worst case packet processing would be O(n*k) tuple-compares. In contrast, a pruned trie requires only O(k + n) tuple-compares in the worst case which is a processing reduction of 1/k.. Pruning is accomplished by replacing general rules with descendants. Rule r_1 is a descendant of rule r_2, if $r_2[i]$ is a prefix of $r_1[i]$ for $i = 1, \ldots, k$. Therefore, pruning occurs by pushing a rule down to all its descendents, then deleting the rule. An example of a pruned version of the trie illustrated in Figure 5 is given in Figure 6, where [*, *, *, deny] is a general rule that can be pushed down to every other rule. Although the original branch has been removed and added to the other branches, the order is preserved, if branches are tested from left to right. Current pruning algorithms do not consider rule order, since tries were primarily developed for storing data [6]. New pruning techniques that preserve order may be developed and used to distribute rules among nodes in a functional-parallel firewall according to an embodiment of the subject matter described

herein. Pruning may also cause the number of nodes in the hierarchy to increase, since a general rule is duplicated at different levels. For this reason, other techniques are needed to reduce the trie size.

Reducing the trie size is important, since delay increases each time a packet is forwarded from one node to another. The trie can be reduced by compressing nodes, which is achieved by removing single branching paths or consolidating sub-ties into one node [2, 6, 15]. As a result, a node may compare multiple rule fields or perform multiple security tasks per packet. For example, in Figure 5, the rule [UDP, 150.*, *, 3030, accept] is considered a leaf chain [6] and can be compressed into one node (a single machine). Two other methods commonly used to reduce the size of a trie are Directed Acyclic Graphs (DAG) and level reordering [1, 6, 15]. If the same sub-trie appears in multiple places, then the trie structure can be changed to a DAG. The possible use of DAG is seen in Figure 6, where nodes labeled $Port^a$ and $Port^b$ are equivalent sub-tries. Parent nodes of both sub-tries could point to just one, eliminating the need for the other.

Another method for reducing the trie size is level reordering. As seen in Figures 7A and 7B, the order of the levels can significantly affect the number of nodes in the trie. More particularly, in Figure 7A, an original trie representing the security rule [TCP, 120.*, 210.*, 90, accept] and [TCP, 130.*, 210.*, 90, accept] is illustrated. Both Figures 7A and 7B assume that the default action per node is deny. Since some of the rules in the original trie in Figure 7A include common elements, the rules can be reordered so that the number of branches in the subtrie are reduced. For example, in Figure 7A, the destination IP address and port for each branch of the subtrie are the same. Accordingly, if these common portions of the rule are implemented at higher levels, the duplicate nodes in the trie can be reduced, as illustrated by Figure 7B. More particularly, in Figure 7B, the nodes for destination IP and port are placed before the node for source IP address. As can be seen from Figure 7B, reordering the levels produces a smaller trie. Using a DAG can also reduce the number of nodes.

The problem of finding an ordering that guarantees a minimum size trie has been shown to be NP-complete; however, several heuristics have been developed [2, 6]. It should be noted that DAGs and reordering only reduce the

number of nodes in the hierarchy and do not reduce the depth of the trie, which influences the traversal time.

Regardless of the applicability of these different trie modifications, they must be performed in concert to achieve an optimal hierarchical design. For example, the architecture utilizes multiple nodes to distribute traffic load and provide differentiated service; however, the trie path length (depth) impacts the packet traversal time. Therefore, compression and ordering must be performed together to provide differentiated service and optimize packet delay.

To achieve these goals, information not explicitly given in the security policy (e.g., QoS, level of trust, and processing time) may be used. For example, it is advantageous to place security tasks that require the most time at the lowest levels. This prevents packets from queueing behind traffic that requires more processing time; thus, lowering delay. A weight w_i can be assigned to each security task s_i (a single rule or multiple rules) based on the amount of time it requires. For example, an auditing security task requires more time (updating system files) than those that only perform field comparisons. Using these weights, the trie can be ordered to minimize the average traversal time. For example assuming i and j are hierarchy levels, where $i < j$, the trie can be ordered such that the average weight per level increases from the highest to the lowest level $\overline{w}_i < \overline{w}_j, \forall i \neq j$. In addition, the trie can be designed to separate traffic based on QoS or level of trust. Traffic would traverse different sub-tries, based on the type of service required, providing class isolation and different delays. The algorithms described in this section can then be applied to these sub-tries independently to reduce size and traversal time. These ideas were used to design the hierarchical firewall simulated in the preceding section, which showed excellent results. New algorithms for trie compression based on traversal time with constraints on QoS will be developed for optimizing function-parallel firewall design.

Packet traversal time remains a key performance metric for firewall systems. For this reason, queueing models will be used to analyze the delay of different firewall designs. The node delay encountered by a packet consists of the processing time, queueing delay, and transmission time. The processing delay is the time required to perform the security task. Assume node i must

process R_i rules per packet and can perform xi rules per unit time, then the service rate is x_i/R_i packets per unit time. Queueing is the delay associated with waiting for processing and depends on the system state. The transmission delay is the time required to transmit the packet, which depends on the packet's length and the line speed. The maximum delay experienced by a packet traversing the firewall is the sum of the node delays along the path from the root to a leaf.

If it is assumed the packet arrival and processing (transmission and security task) rates are exponentially distributed, the node can be modeled as an M/M/1 queue [5, 17]. The firewall can then be considered an open network of M/M/1 queues, where probabilities are assigned to each link to indicate the likelihood of moving to the next node. This is a Jackson network model, which has a product-form solution for the average delay [5, 17]. The average end-to-end delay for N cascading nodes (traversal path) can be computed as

$$E(T) = \sum_{i=1}^{N} \frac{1}{\mu_i - \lambda_i} \tag{1}$$

where $1/\mu_i$ is the service time (processing and transmission) and λ_i is the arrival rate to node i. Figures 8A and 8B respectively illustrate Jackson models for hierarchical and data-parallel firewalls. In Figures 8A and 8B, it is assumed that the total arrival rate to each system is λ packets per unit time, each system implements the same R rule security policy, and each node can perform x rules per unit time. For the hierarchical firewall, shown in Figure 8A, the policy rules are evenly distributed to each node; therefore, the service rate is $3x/R$ per node. The traffic arrival rate to node A is λ packets per unit time, half of the packets are forwarded to node B, while the other half is forwarded to node C. Although not considered in this example, some traffic may be forwarded into the secure network or dropped by node A; therefore in this case, the sum of the rates to nodes B and C would be less than λ. Using these values, the average end-to-end delay for either path in the hierarchical firewall is

$$E_h(T) = \frac{1}{\frac{3\chi}{R} - \lambda} + \frac{1}{\frac{3\chi}{R} - \frac{\lambda}{2}} \tag{2}$$

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For the data-parallel configuration, illustrated in Figure 8B, traffic arrives at the packet distributor, which evenly distributes the traffic to each node. Each node implements the complete rule set *R*; therefore, the service rate is *x/R*. The end-to-end delay across any node in the data-parallel firewall is

$$E_p(T) = \frac{1}{\frac{\chi}{R} - \frac{\lambda}{3}} \quad (3)$$

Using these models, the effect of increasing traffic load λ on the average end-to-end delay, for the two architectures is shown in Figure 9. For this example, the arrival rate λ ranged from 1 to 50 packets per unit time. The rule set *R* consisted of 240 rules, while *x* equaled 5000 rules per unit time. Each of the hierarchical nodes incurred an additional delay of five time units to compensate for inter-node transmission. As expected, the average delay increases as the network load increases for both architectures; however, the average delay is consistently lower for the hierarchical firewall. This is due to the decreased rule set per node and the reduced arrival rates for nodes B and C. The average is an upper bound for the hierarchical firewall. Allowing node A to forward packets to the secure network or to drop packets would reduce the load on the second level and decrease delays. The arrival rate is less per node in the data-parallel firewall; however, the system has a higher end-to-end delay because each node must implement the complete rule set. The theoretical results are consistent with the experimental results described above. These models provide an important tool for analyzing the effect of load and rule distribution on end-to-end delay. In addition to analytical results, simulation will be used to measure the performance of the hierarchical designs under various conditions.

Stateful Firewalls

Another aspect of the subject matter described herein includes a stateful hierarchical firewall. The preceding design is considered stateless, or static, since the security action taken is based solely on the packet currently inspected. A stateful firewall provides better security by tracking and controlling network flows (packets belonging to a particular network connection or

exchange) [16, 21, 22]. In one exemplary implementation, a stateful firewall can be achieved by storing state information concerning each flow in a table, and then according it with the security policy. For example, each time a TCP connection is established from the internal network to the external network, it is logged in a table. The table may contain the source and destination addresses, port numbers, sequencing information, and connection flags. Afterwards, packets arriving from the external network claiming to be part of an existing TCP connection can be checked against the table. If a packet belongs to an existing connection or exchange, it can be accepted. Otherwise, it is dropped. Table entries expire, if packets belonging to an exchange are not observed by the firewall over a period of time [21].

Therefore, a stateful firewall is dynamic and limits the hackers' opportunity to exploit certain services. The increased security does require additional memory and time for table manipulation, which is problematic for high-speed networks. Furthermore, the firewall must process all traffic arriving and departing the secure network to adequately maintain the connection tables 21]. To solve these problems, the proposed firewall system will be divided into two hierarchies, one for arriving traffic and another for departing traffic, as illustrated in Figure 10. In Figure 10, a stateful firewall system includes first and second hierarchical firewall subsystems **1000** and **1002** and a control node **1004**. First and second hierarchical firewall subsystems **1000** and **1002** may be function-parallel firewall systems including a plurality of firewall nodes with different rules distributed among different nodes as described above. In one exemplary implementation, hierarchical firewall subsystem **1000** may include at least two firewall nodes that implement different portions of a first firewall rule set. Similarly, hierarchical firewall subsystem **1002** may include at least two firewall nodes that implement different portions of a second firewall rule set. Firewall subsystem **1000** may filter packets entering the network. Firewall subsystem **1002** may filter packets departing from the network. Firewall subsystems **1000** and **1002** may share state information regarding connections established through the nodes within each system. Control node **1004** may store the state information and may be accessible by the nodes in hierarchical firewall subsystems **1000** and **1002**. Rules can be distributed to the

hierarchies and the designs can be optimized using the methods described in preceding section.

However, a new problem with the stateful model is the need to distribute state information across nodes. For example, nodes that scrutinize arriving traffic must be aware of any new connections permitted by nodes that inspect departing traffic. Furthermore, nodes must be informed of table entries that expire over time. To communicate state information, a central database machine, such as control node **1004**, may collect and distribute the information (table entries) to the appropriate nodes. In one exemplary implementation, control node **1004** may not perform table queries on behalf of nodes. Individual nodes will only query their local tables, which prevents the central machine from becoming a bottleneck. In addition, the central machine will only send information (table entries) to nodes that might require it. As a result of this policy, the table searched by an individual node is reduced (contains only relevant information) as well as the search time. In an alternate implementation, control node **1004** may store the connection table and may perform queries for packets received by firewall subsystems **1000** and **1002**.

Survivability and Firewall Grids

Another aspect of the subject matter described herein focuses on increasing the survivability of the hierarchical design. Although the proposed design has the benefit of increased packet throughput and minimal delay, the reliability of the system is decreased, since more machines (nodes) are deployed. For example, if the highest level node fails (is unable to inspect more traffic or goes off-line), then the entire hierarchy is unable to process packets. For this reason, the hierarchy is considered an n of n system, where all *n* machines must be functioning for the system to operate correctly [4, 12].

Survivability of the system can be improved with the use of redundant (parallel) nodes at different levels. For example, the first level may include multiple machines in parallel, where each machine implements the same security task (e.g., an IP check). An arriving packet would be sent to only one of the parallel machines, where it would be accepted, dropped, or forwarded to the next level for further processing. If one of the parallel nodes fails, then the

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remaining nodes can process the traffic. An additional benefit of parallel processing is the equal distribution of traffic among nodes, which can result in higher throughput and lower delays. Details such as where to locate parallel nodes and the number of machines required for each parallel configuration may depend on the desired degree of reliability versus cost of deploying redundant machines.

Yet another aspect of the subject matter described herein includes a grid of configurable firewalls (nodes) that can be used to efficiently process traffic, while being highly available. In one exemplary implementation, the grid may include a network of highly interconnected nodes (possibly via a high-speed switch or router) that can be logically deployed in various configurations (e.g., parallel, hierarchical, or hybrid). The advantage of the firewall grid is its ability to quickly adapt to new demands. When security needs change (e.g., due to policy changes, increased traffic volume, or node failure), these machines can be deployed or configured to maintain throughput and QoS requirements. For example, in a logical hierarchy, if a higher level encounters an increased traffic load, less frequently used redundant machines at lower levels can be reconfigured to process packets at the higher level. Unlike the hierarchical model, physical changes are not required, since all the machines are interconnected. Only the logical connection between nodes must be updated, which can be performed quickly. Like the stateful hierarchical firewall, the initial grid model will use a central machine to coordinate node configuration and communication. This central machine will play an important role in the system (balancing processing demand per node) and may constrain the efficiency of the firewall grid. Future versions of the firewall grid will attempt to place more intelligence in the nodes and allow them to interact independently and adapt dynamically under the guidance of a general security policy.

Figures 11A and 11B illustrate an example of a firewall grid according to an embodiment of the subject matter described herein. Referring to Figure 11A, a plurality of firewall nodes **1100-1114** are connected via a control node **1116**. Each firewall node **1100-1114** may be configured to implement different portions of a firewall rule set, as controlled by control node **1116**. Each of the firewall nodes is physically connected to the other firewall nodes via physical

connections **1118**. Physical connections **1118** may be local area network connections, such as Ethernet connections. As such, control node **1116** may be an Ethernet switch.

In Figure 11B, firewall nodes **1100-1114** are connected via logical connections **1120**. Logical connections **1120** may be implemented by control node **1116** without changing physical connections **1118**. For example, control node **1116** may configure the output port to which firewall **1106** is connected to receive frames from firewalls **1100**, **1102**, and **1104**. Similar internal configurations can be implemented for the remaining firewalls illustrated in Figure 11B. In Figure 11B, logical connections **1120** between the firewalls implement a hierarchical, function-parallel firewall design, such as that illustrated in Figure 1. In addition, the design illustrated in Figure 11B is also data-parallel at each level. For example, each firewall node at each level may implement a common rule or rule set. For example, the rule set implemented by the firewall nodes in level 1 is illustrated in Figure 11B as R1. The firewall nodes in level 2 implement a rule set represented by R2, and the firewall nodes in level 3 implement a rule set represented by R3. If any of the firewall nodes in a given level fails, the remaining firewall nodes in that level may take over operation for the failed firewall. Alternatively, as described above, if a failure or a bottleneck occurs at one level, a less-used firewall at another level may be logically configured to operate at the level where the failure or congestion occurred. Packet distributors **1122** may be configured to distribute the firewall rules between the firewalls at each level. Thus, as illustrated by Figures 11A and 11B, logical connections between firewall nodes and a firewall grid may be dynamically altered (i.e., changed on the fly without ceasing packet filtering operation) by a controller node without changing the physical connections between the firewalls.

Firewall Implementation

In addition to the analytical models and simulations described above, an implementation of a hierarchical firewall to measure performance will now be described. One exemplary implementation may utilize Linux-based PCs and Ethernet connections. Each PC will contain multiple Ethernet cards and be

loaded with the Linux 2.4 kernel. The 2.4 kernel has support for various packet queueing disciplines, traffic control methods, and packet processing (e.g., iproute2, tc, and iptable). Collectively, these functions are required for advanced packet filtering. For example, iproute2 and iptable can route packets based on information other than the destination address, while tc can mark and shape traffic. PCs will serve as hierarchical nodes, sources and receivers of network traffic, and hierarchy controllers.

Results from an initial implementation of a three-node hierarchical firewall indicate that these open-source components are suitable for high-speed networks. The Computer Science Department at Wake Forest University has 10 PCs available for this project, where each has a 600 Mhz processor and multiple 100 Mbps Ethernet cards. These machines will serve as an initial testbed for system development; however, faster machines and high-speed network connections are required for actual system testing. For this reason, this project requests the purchase of 6 additional PCs (2.4 Ghz processors), each with multiple Gigabit Ethernet cards (3 cards per machine). These new machines will be configured as the firewall, while the current machines will serve as traffic generators and receivers. For comparison purposes, parallel and single-machine firewalls will also be implemented using this equipment. Any software required will be developed and provided by the Computer Science Department.

Firewall Rule Distribution for Function-Parallel Firewall Design

As stated above, one aspect with creating an optimal function-parallel firewall design includes distributing rules among firewalls in the firewall rule set. Firewall rules are preferably distributed among firewall nodes in a manner that preserves firewall policy integrity. The following sections describe an exemplary firewall rule set and different options for distributing the firewall rule set among firewall nodes in a function-parallel firewall design.

Firewall Policy

In this section and the following sections, a rule r is modeled as an ordered tuple of sets, $r = (r[1], r[2], ..., r[k])$. Order is necessary among the tuples since comparing rules and packets requires the comparison of

corresponding tuples. Each tuple $r[l]$ is a set that can be fully specified, specify a range, or contain wildcards '*' in standard prefix format. For the Internet, security rules are commonly represented as a 5-tuple consisting of: protocol type, IP source address, source port number, IP destination address, and destination port number [21, 22]. For example, the prefix 192.* would represent any IP address that has 192 as the first dotted-decimal number. Given this model, the ordered tuples can be supersets and subsets of each other, which forms the basis of precedence relationships. In addition to the prefixes, each filter rule has an action, which is to accept or deny. However, the action will not be considered when comparing packets and rules. Similar to a rule, a packet (IP datagram) d can be viewed as an ordered k-tuple $d = (d[1], d[2], ..., d[k])$; however, ranges and wildcards are not possible for any packet tuple.

Using the previous rule definition, a standard security policy can be modeled as an ordered set (list) of n rules, denoted as $R = \{r_1, r_2, ..., r_n\}$. A packet d is sequentially compared against each rule r_i starting with the first, until a match is found ($d \Rightarrow r_i$) then the associated action is performed. A match is found between a packet and rule when every tuple of the packet is a subset of the corresponding tuple in the rule.

Definition Packet d matches r_i if

$$d \Rightarrow r_i \text{ iff } d[l] \subseteq r_i[l],\ l = 1, ..., k$$

The rule list R is comprehensive if for every possible legal packet d a match is found using R. Furthermore, two rule lists R and R' are equivalent if for every possible legal packet d the same action is performed by the two rule lists. If R and R' are different (e.g. a reorder) and the lists are equivalent, then the policy integrity is maintained.

As described above, a rule list has an implied precedence relationship where certain rules must appear before others if the integrity of the policy is to be maintained. Table 2 shown below illustrates an exemplary rule set that will be used herein to illustrate precedence relationships and rule assignment according to an embodiment of the subject matter described herein.

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No.	Proto.	Source		Destination		Action	Prob.
		IP	Port	IP	Port		
1	UDP	1.1.*	*	*	80	deny	0.01
2	TCP	1.*	*	1.*	90	accept	0.02
3	TCP	2.*	*	2.*	20	accept	0.25
4	UDP	1.*	*	*	*	accept	0.22
5	*	*	*	*	*	deny	0.50

Table 2: Example Security Policy Consisting of Multiple Ordered Rules

In Table 2, rule r_1 must appear before rule r_4, likewise rule r_5 must be the last rule in the policy. If for example, rule r_4 was moved to the beginning of the policy, then it will shadow [23] the original rule r_1. Shadowing is an anomaly that occurs when a rule r_j matches a preceding rule r_i, where $i < j$. As a result of the relative order r_j will never be utilized. However, there is no precedence relationship between rules r_1, r_2, or r_3 given in Table 2. Therefore, the relative order of these three rules will not impact the policy integrity and can be changed to improve firewall performance.

As described in [28], the precedence relationship between rules in a policy can be modeled as a Policy Directed Acyclical Graph (DAG). Let $G = (R,E)$ be a *policy DAG* for a rule list R, where vertices are rules and edges E are the precedence relationships (constraint). A precedence relationship, or edge, exists between rules r_i and r_j, if $i < j$ and the rules intersect [28].

Definition The intersection of rule r_i and r_j, denoted as $r_i \cap r_j$ is

$$r_i \cap r_j = (r_i[l] \cap r_j[l]),\ l = 1, \ldots, k$$

Therefore, the intersection of two rules results in an ordered set of tuples that collectively describes the packets that match both rules. The rules r_i and r_j intersect if every tuple of the resulting operation is non-empty. In contrast, the rules r_i and r_j do not intersect, denoted as $r_i \not\cap r_j$, if at least one tuple is the empty set. It should be noted that the intersection operation is symmetric; therefore, if r_i intersects r_j, then r_j will intersect r_i. The same is true for rules that do not intersect.

For example, for the rules given in Table 2, the intersection of r_1 and r_4 yields (UDP, 1.1.*, *, *, 80). Again, the rule actions are not considered in the

intersection or match operation. Since these two rules intersect, a packet can match both rules for example d = (UDP, 1.1.1.1, 80, 2.2.2.2, 80). The relative order must be maintained between these two rules and an edge drawn from r_1 to r_4 must be present in the DAG, as seen in Figure 12. In Figure 12, the policy DAG represents the rules in Table 2. Vertices **1200** indicate rules while edges **1202** indicate precedence relationships. Rules r_2 and r_3 in Table 2 provide an example of rules that can be re-ordered without changing the firewall policy. These two rules do not intersect due to the fifth tuple (destination port). A packet cannot match both rules indicating the relative order can change; therefore, an edge will not exist between them.

As described above, traditional firewall implementations consist of a single, dedicated machine, similar to a router, that applies the rule set to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [15, 18, 22]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [21]. Successfully handling these traffic loads becomes more difficult as rule sets become more complex [4, 14, 22]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 7, 10, 11]. Building a faster single firewall is possible [8, 15, 18, 19, 20]; however, the benefits are temporary (traffic loads and interface speeds are increasing); it is not scalable; it is a single point of failure; and it is generally not cost-effective for all installations.

Parallelization has been demonstrated to offer a scalable approach for improving the performance of network firewalls. As seen in Figure 13A, parallel designs consist of multiple firewalls, referred to as firewall nodes, connected in an array. In Figure 13A, firewall nodes **1300** each implement a common rule set. A packet distributor **1302** load shares packets among firewall nodes **1300**. In Figure 13B, a function-parallel design is illustrated where firewall nodes **1304** implement different portions of a firewall rule set. A packet duplicator **1306** duplicates each packet to each firewall node. A gate **1308** controls packets entering the network based on control information received from firewall nodes

1304. The operation of the system illustrated in Figure 13B will be described in more detail below.

The two designs depicted in Figures 13A and 13B are different based on what is distributed: packets or rules. For example, the design developed by Benecke et al consisted of multiple identical firewall nodes connected in parallel, as shown in Figure 13A. Each firewall node implements the complete security policy *R*, and arriving packets are distributed across the firewall nodes for processing (one packet is sent to one firewall node) [4]; therefore different packets are processed in parallel. Using terminology developed for parallel computing, this design is considered data-parallel since the data (packets) is distributed across the firewall nodes [25]. How the load-balancing algorithm distributes the packets is vital to the data-parallel system and typically implemented as a specialized high-speed switch [11, 12]. Although data-parallel firewalls have been shown to achieve higher throughput than traditional firewalls and have a redundant design [4], they suffer from two major disadvantages. First, these designs have difficulty maintaining QoS across networks. For example, legitimate traffic can encounter delays if it is queued behind traffic that requires more processing. Under these circumstances, users notice poor network performance, which is a growing concern as more network applications require QoS assurances. Second, stateful inspection requires all traffic from a certain connection or exchange to traverse the same firewall node, which is difficult to perform at high speeds using the data-parallel approach [4, 14].

Rule Distribution and Function-Parallel Firewall

As described above, new scalable firewall designs are needed to cope with increasing traffic loads, network speeds, and security threats. To address these issues, one implementation of the subject matter described herein includes a firewall design that consists of multiple firewalls connected in parallel and a gate machine, as shown in Figure 13B. Again in this design, the individual firewalls will be referred to as firewall nodes. However unlike the data-parallel design that distributes the packets, the function-parallel design distributes the policy rules across the firewall nodes. The distribution is done such that policy integrity is maintained. Therefore, a single traditional firewall

and a function-parallel firewall will always give the same result for any packet. The rules distributed to a firewall node will be referred to as the local rule set or local policy. Using parallel computing terminology this design will be referred to as function-parallel, since the rules are distributed across the firewall nodes [25].

The general operation of one exemplary function-parallel system can be described as follows. When a packet arrives to the function-parallel system, the packet is forwarded to every firewall node. Each firewall node processes the packet using its local rule list. The firewall node then signals the gate indicating either no match was found or provides the rule number and action if a match was found. Therefore, no match is a valid response and is required for this basic function-parallel design. The gate keeps track of the results and determines the final action to perform on the packet. For example, a first match policy can be implemented by applying the action of the lowest numbered matching rule to the packet.

The performance of this basic design can be improved by allowing the firewall nodes to pipeline packets [25]. For example, once a firewall node has completed processing a packet, it can immediately begin processing the next packet. This allows the firewall nodes to work independently, thus increasing the overall system performance. However, pipelining requires the gate to keep track of multiple packets simultaneously. Performance can also be increased if the gate can signal the firewall nodes that further processing of a certain packet is no longer needed (similar to short-circuit evaluation). This occurs when the appropriate match has been found by a firewall node before the other firewall nodes have completed processing the same packet. Short-circuit evaluation requires the gate to know how the rules are distributed as well as the dependencies, which is discussed in detail below.

The function-parallel design has several significant advantages over traditional and data-parallel firewalls. First, the function-parallel design results in the faster processing since every firewall node is utilized to process a single packet. Reducing the processing time, instead of the arrival rate (the data-parallel paradigm), yields better performance that will be proven theoretically and demonstrated experimentally. Second, unlike the data-parallel design, function-parallel can maintain state information about existing connections.

Maintaining state can be viewed as the addition of a new rule corresponding to a requested connection. Unlike the data-parallel design, the new rule can be placed in any firewall node since a packet will be processed by every firewall node. Third, the function-parallel design has the unique ability to provide service differentiation between classes of traffic; therefore, the design can provide QoS requirements. Finally, the function-parallel system can be implemented using any current firewall system (as discussed below, the gate can be removed), without any specialized hardware. The disadvantage of the system is the limited scalability, since the system cannot have more firewall nodes than rules, unless data-redundancy is provided. However, given the size of most firewall policies range in the thousands to hundred of thousands of rules, which is expected to increase, the scalability limit is not an important concern.

The operation and performance of the function-parallel design depends on the correct distribution of policy rules. Rule distribution techniques that maintain integrity, increase processing speed, allow redundancy and robustness, and eliminate the gate are described in the following sections.

Rule Distribution and Policy Integrity

As described above, the function-parallel design distributes the security policy rules across an array of firewall nodes. Using this design, all the firewall nodes process an arriving packet in parallel using its local rule set. The rules must be distributed such that the integrity of the policy is maintained. Again, it will be assumed in the examples described herein that a first-match policy is desired. Therefore, the distribution of the rules must not introduce any anomalies into the original rule list, such as shadowing.

Let m be the number of firewall nodes in the system and j be a firewall node $j = 1...m$. Each firewall node has a local rule set that is a portion of the security policy. Denote the local rule list for firewall node j as R_j that has n_j rules. The firewall node will process an arriving packet using the local rule list in a top-down fashion to find the first match. It should be noted that a software implementation of the firewall node according to the subject matter described herein is not required to have a rule list. The function-parallel design is independent of software implementation. In this scenario integrity is maintained

under two conditions: every rule is assigned to at least one firewall node, and a policy DAG edge never traverses upward within a firewall node. The first condition assures every rule in the original policy exists in the function-parallel system, while the second condition prevents rule shadowing within a firewall node. Consider a two-firewall node system and the five-rule policy given in Table 2. Possible rule distributions are depicted in Figures 14A-14C. The distribution illustrated in Figure 14A will be referred to as vertical, while the distribution illustrated in Figure 14B will be referred to as horizontal. In both cases the five rules are present and all policy DAG edges are downward; thus integrity is maintained. In contrast, Figure 14C is an illegal distribution because rule r_4 shadows r_1 (upward policy DAG edge).

The gate can also utilize the policy DAG to determine the first match, and if a short-circuit evaluation can occur. For example consider the distribution illustrated in Figure 14A. Assume a packet matches r_3 in the second firewall node and this result is reported to the gate. Using the policy DAG, the gate can determine this is the first match, since it is impossible for a packet that matches r_3 to also match any rules that preceded it in the original policy (rules r_1 or r_2). The gate can inform the remaining firewall nodes to stop processing the packet.

Optimal Rule Distribution

The previous section described the distribution requirements for maintaining policy integrity. However it was proven in [27] that any linear arrangement of a policy DAG maintains integrity, which also holds for a local policy DAG. Furthermore as evident in the previous section, many different distributions are possible. Given the possible rule distributions for the function-parallel design, a distribution is sought that minimizes the average number of comparisons required per packet [27].

Achieving this goal will require information not present in the firewall rule list. Certain firewall rules have a higher probability of matching a packet than others. As a result, it is possible to develop a policy profile over time that indicates frequency of rule matches (similar to cache hit ratio). Let $P = \{p_1, p_2, \ldots, p_n\}$ be the policy profile, where p_i be the probability that a packet will match rule r_i (first match in the policy). Furthermore, assume a packet will always find

a match, $\sum_{i=1}^{n} p_i = 1$; therefore R is comprehensive. Using this information, the average number of rule comparisons required for the policy R using a standard single machine firewall is

$$E(R) = \sum_{i=1}^{n} i \cdot p_i \quad (4)$$

This equation also applies to firewall nodes. However, the rules of a local policy include rules of the original policy; therefore, a mapping between the local and original policy rules is needed. Let $r_{i,j}$ represent the ith rule of firewall node j, that corresponds a certain rule in the original rule list R. Consider the local rule list for the second firewall node depicted in Figure 14A. The local policy is $R_2 = \{r_4, r_5\}$, where $r_{1,2} = r_4$ and $r_{2,2} = r_5$. Similarly, let $p_{i,j}$ be the probability of matching the ith rule of firewall node j. Therefore the average number of comparisons required for firewall node j is

$$E(R_j) = \sum_{i=1}^{n_j} i \cdot p_{i,j} \quad (5)$$

Using the previous equation, the average number of comparisons required for the function-parallel system is

$$E_f(R) = \sum_{j=1}^{m} E(R_j) = \sum_{j=1}^{m} \sum_{i=1}^{n_j} i \cdot p_{i,j} \quad (6)$$

For example, the average number of comparisons required for the distribution given in Figure 14A is 2.24, while the average number of comparisons for the distribution given in Figure 14B is 2.45.

Given a policy DAG $G = (R,E)$ and policy profile P, a distribution is sought that minimizes Equation 6. In the absence of precedence relationships, the average number of comparisons is minimized if the rules are sorted in non-increasing order according to the probabilities [28], which is also referred to as Smith's algorithm [29]. The sorted rules are then distributed in a horizontal fashion, as depicted in Figure 14B. Precedence constraints cause the problem

to be more realistic; however, precedence constraints also make determining the optimal permutation more problematic. In [27] determining the optimal rule order for a single machine firewall is proven to be *NP*-complete; therefore, so is determining the optimal function-parallel rule distribution. However, [27] presents a simple sorting algorithm to improve the optimal order, that can be modified to apply to function-parallel rule distribution. This modified algorithm sorts the policy rules using the method described in [27], then distributes the rules in a horizontal fashion.

Redundancy

Similar to the traditional and data-parallel firewalls, a disadvantage of the current function-parallel design is its inability to withstand a single firewall node failure. If a single firewall node fails in the function-parallel system, then part of the policy is lost and integrity is not maintained. A simple solution commonly used for traditional firewalls is to duplicate the entire system; however, this solution is cost prohibitive, not efficient, and difficult to manage.

Redundancy can be provided in the function-parallel design by replicating rules, instead of firewall nodes. Consider the function-parallel system depicted in Figure 15A, that includes four firewall nodes and an eight-rule policy distributed in a horizontal manner. If the local rule list of the right neighbor is added to the end of every firewall node, as illustrated in Figure 15B, then any non-continuous firewall nodes can fail and integrity will be maintained. It should be noted that the criteria for maintaining integrity still apply: every rule must be implemented at a node and no upward edges in the local policy DAG. Furthermore, the redundant design requires short-circuit evaluations to prevent multiple firewall nodes from evaluating the same rule.

Gateless Design

The gate plays an important role in the function-parallel design. It accepts information from the firewall nodes to determine the correct action to apply to a packet. Unfortunately, the gate is a special device that must coordinate with the individual firewall nodes in the system, which may be problematic to implement. However, it is possible to eliminate the gate and allow the firewall nodes to operate independently without any coordination. The

significant advantage is that the gateless function-parallel design can be implemented with any firewall system (from open source to proprietary).

Eliminating the gate requires a rule distribution such that for any given packet, only one machine will ever accept and the remaining machines will always deny. As described above, rule actions are either accept or deny. This can be seen in the policy DAG by denoting deny rules with a square and accept rules with a circle. To assure only one machine will accept a packet, an accept rule in a firewall node cannot intersect with another accept rule in any other firewall node. As described above, the intersection of two rules describes the set of packets that can match both rules. If an edge spans the local rules of firewall nodes, then the set of packets would be accepted by both firewall nodes; thus, duplicate packets would be accepted. In addition, every drop rule must be present in each firewall node to assure the remaining firewall nodes will drop the packet. Given these two requirements a policy DAG edge will not span firewall nodes, as illustrated in Figures 16B and 16C.

For example, consider a two-firewall node function-parallel system that implements the five-rule policy given in Table 2. The policy DAG is given in Figure 16A, where the first and last rules are deny. An initial gateless rule distribution is given in Figure 16B which has no edges spanning the firewall nodes. Given the local policy DAG, deny rules can be removed if: no inbound edges exist for the deny rule; and all out-going edges for the deny rule connect to a superset deny rule. Using these constraints, the first rule in the second firewall node depicted in Figure 16B can be removed (it is a subset of r_5 and has no other edges). This gives the final gateless rule distribution shown in Figure 16C. As a result, the first firewall node in this distribution will only process UDP traffic, while the second machine only processes TCP. The rules can be divided with respect to other tuples, and can be done to provide QoS guarantees.

Theoretical Results

Assuming arrivals and service times are exponentially distributed, a firewall system can be considered an open network of M/M/1 queues (Jackson network) [5, 17]. Probabilities can be assigned to each link to indicate the likelihood of moving to the next node, which are given from the policy profile (hit

ratio) described above. The average end-to-end delay for q cascading machines (traversal path) can be computed as

$$E(T) = \sum_{i=1}^{q} \frac{1}{\mu_i - \lambda_i} \tag{7}$$

where $1/\mu_i$ is the service time (processing and transmission) and λi is the arrival rate to node i. As a result, we have a theoretical model for the average delay across a firewall system. Consider the data-parallel and functional-parallel firewall designs given in Figures 13A and 13B. Assume each system consists of m machines and implements the same n rule security policy. Let the total arrival rate to each system be λ packets per unit time and each node performs x rules per unit time.

For the data-parallel firewall, traffic arrives at the packet distributor, which evenly distributes the traffic. As a result the arrival rate to each machine is λ m. The service rate is x n, since each node implements the complete rule set. The end-to-end delay across any machine in the parallel firewall is

$$E_d(T) = \frac{1}{\frac{x}{n} - \frac{\lambda}{m}} \tag{8}$$

In contrast, rules are distributed across each machine, in the function-parallel firewall. Furthermore, all traffic arriving to the system is forwarded to each machine. If we assume the rules in each machine are independent (no policy DAG edges spanning machines), then the end-to-end delay across any machine in the functional-parallel firewall is

$$E_f(T) = \frac{1}{\frac{m \cdot x}{n} - \lambda} \tag{9}$$

The reduction in delay compared to a data-parallel firewall system is 1 m; therefore, the functional-parallel system has the potential to be m times faster than a (data) parallel system. However, the scalability of the functional-parallel system is dependent on the rule set.

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Figures 17A and 17B compare the performance of function-parallel, data-parallel, and single firewall designs. More particularly, Figure 17A compares the average among the different firewall designs as the arrival rate λ increases. As can be seen from Figure 17A, the function-parallel design achieves lower average delay as the arrival rate increases than the data-parallel design. Figure 17B illustrates the average delay as arrival rate and the number of rules increase. In Figure 17B, the function-parallel design again achieves better simulated performance than the data-parallel design.

Experimental Results

The previous section described models that provide insight to the average delay across different firewall designs. This information is beneficial in guiding initial design; however, we are also interested in the maximum delay encountered. For this reason, a discrete event simulator has been developed to model the different systems.

The data-parallel firewall and function-parallel firewall designs were simulated, where both systems implemented a 50-rule policy and each consisted of 5 firewall nodes. Three classes of traffic were modeled, first, second, and background. The first and second classes represent legitimate traffic that was eventually accepted by the firewall system, while background traffic was typically dropped. The two designs were simulated under normal conditions, where each traffic type had the same volume. Figures 18A and 18B shows the simulation results. As seen in Figure 18A and predicted by the theoretical models, the average delay encountered by packets in the functional-parallel design was lower than the data-parallel designs. The function-parallel design also provided lower maximum delays than the data-parallel, as seen in Figure 18B. In summary, the theoretical models and simulation results indicate function-parallel is a better design than a traditional single firewall system or a data-parallel system; yet, function-parallel requires no more computing resources than data-parallel.

Summary

Thus, as described above, the subject matter described herein includes methods, systems, and computer program products for providing a function-

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parallel firewall where different portions of a firewall rule set are distributed among different firewall nodes. Figure 19 is a flow chart illustrating exemplary steps of a process for filtering packets using a rule set distributed among firewall nodes in a function-parallel manner. Referring to Figure 19, in step **1900**, packet filtering rules of a rule set are distributed among nodes in a function-parallel manner so that different nodes implement different portions of the rule set. In step **1902**, packets to be filtered are replicated to each of the nodes. In step **1904**, the packets to be filtered are replicated to each of the nodes. In a hierarchical design, step **1904** may be implemented at each level in the hierarchy. If a packet passes or fails at one level, the packet may be forwarded into a network or dropped, depending on the distribution of the rule set. In step **1904**, the rules are applied to filter the packets.

The steps illustrated in Figure 19 and in all of the examples described herein may be applied to firewall systems that filter packets based on packet header information, intrusion detection systems that filter packets based on packet payload information, or intrusion protection systems that filter packets based on a combination of packet header and packet payload information.

The following references correspond to the citations in this document. The disclosure of each of these references is hereby incorporated herein by reference it its entirety.

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It will be understood that various details of the present subject matter may be changed without departing from the scope of the present subject matter. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

CLAIMS

What is claimed is:

1. A function-parallel firewall comprising:
   (a) a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules, the first portion including less than all of the rules in the rule set; and
   (b) at least one second firewall node for filtering packets using a second portion of the rule set, the second portion including at least one rule in the rule set that is not present in the first portion, wherein the first and second portions together include all of the rules in the rule set.
2. The function-parallel firewall of claim 1 wherein the first and second portions respectively include rules present in first and second levels of a firewall hierarchy.
3. The function-parallel firewall of claim 2 wherein the first and second firewall nodes are connected to each other such that the rules in the first level are applied to received packets before the rules in the second level.
4. The function-parallel firewall of claim 3 wherein the first firewall node is adapted to forward packets that pass one of the rules in the first portion to an internal network in a manner that bypasses the second firewall node.
5. The function-parallel firewall of claim 3 wherein the first firewall node is adapted to discard packets that fail one of the rules in the first portion.
6. The function-parallel firewall of claim 3 wherein the rules in the second portion are more processor-intensive than the rules in the first portion.
7. The function-parallel firewall of claim 1 comprising:
   (a) a packet distributor for replicating each packet to the first and second firewall nodes; and
   (b) a gate machine for collecting results of applying the first and second portions of the rule set to each packet from the first and second firewall nodes and for making a forwarding decision based on the results.

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8. The function-parallel firewall of claim 7 wherein each of the first and second firewall nodes is adapted to process the packets in a pipelined manner and wherein the gate machine is adapted to maintain state information for multiple packets simultaneously.

9. The function-parallel firewall of claim 7 wherein the gate machine is adapted to signal the second firewall node when processing of a packet is no longer needed due to matching of the packet with one of the rules used by the first firewall node.

10. The function-parallel firewall of claim 1 wherein the first and second firewall nodes implement rules of the same hierarchical level.

11. The function-parallel firewall of claim 1 wherein at least one of the rules in the first portion is present in the second portion to provide redundancy.

12. The function-parallel firewall of claim 1 wherein the first and second firewall nodes are configured to implement a gateless design wherein the rules are distributed among the first and second firewall nodes such that for any given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet.

13. The function-parallel firewall of claim 1 wherein the first and second firewall nodes are implemented on different physical machines.

14. The function-parallel firewall of claim 1 wherein the first and second firewall nodes are implemented on different processors in the same machine.

15. The function-parallel firewall of claim 1 wherein the first and second firewall nodes are adapted to simultaneously process copies of the same packets.

16. The function-parallel firewall of claim 1 wherein the rule set includes firewall rules for filtering packets based on packet headers.

17. The function-parallel firewall of claim 1 wherein the rule set includes intrusion detection rules for filtering packets based on packet payloads.

18. The function-parallel firewall of claim 1 wherein the rule set includes intrusion protection rules for filtering packets based on a combination of packet headers and packet payloads.

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19. A stateful function-parallel firewall system comprising:

(a) a first function-parallel firewall subsystem including a plurality of firewall nodes implementing a first rule set for filtering packets arriving in a network, wherein the first function-parallel firewall subsystem includes at least first and second firewall nodes respectively implementing first and second portions of the first rule set, the first portion including at least one rule that is not present in the second portion; and

(b) a second function-parallel firewall sub-system including a second set of firewall nodes implementing a second rule set for filtering packets departing from the network, wherein the second function-parallel firewall subsystem includes at least third and fourth firewall nodes, the third and fourth firewall nodes implementing first and second portions of the second rule set, the first portion of the second rule set including at least one rule that is not present in the second portion of the second rule set, wherein the first and second function-parallel firewall subsystems share state information regarding connections established through the first and second sets of firewall nodes.

20. The stateful function-parallel firewall system of claim 19 comprising a database node coupled to the first and second function-parallel firewall subsystems, wherein the database node stores the state information, wherein the first set of firewall nodes obtains state information regarding connections established through the second set of firewall nodes from the database node, and wherein the second set of firewall nodes obtains state information regarding connections established through the first set of firewall nodes from the database node.

21. The stateful function-parallel firewall system of claim 20 wherein the first and second sets of firewall nodes store copies of the state information maintained by the database node.

22. The stateful function-parallel firewall system of claim 19 wherein the first and second function-parallel firewall subsystems each include a gateless design wherein rules are distributed among individual firewall nodes

such that a received packet will be accepted by a single firewall node and will be denied by remaining firewall nodes.

23. The stateful function-parallel firewall system of claim 19 wherein the firewall nodes of the first subsystem are adapted to simultaneously process copies of the same packets arriving in the network and wherein the firewall nodes in the second subsystem are adapted to simultaneously process copies of packets departing from the network.

24. The stateful function-parallel firewall system of claim 19 wherein the first and second rule sets include firewall rules for filtering packets based on packet header information.

25. The stateful function-parallel firewall system of claim 19 wherein the first and second rule sets include intrusion detection rules for filtering packets based on payloads of the packets.

26. The stateful function-parallel firewall system of claim 19 wherein the first and second rule sets include intrusion protection rules for filtering packets based on a combination of packet header and packet payload information.

27. A firewall grid comprising:

(a) a plurality of firewall nodes being physically connected to each other via a network for filtering packets; and

(b) a controller for controlling logical connections between the firewall nodes, wherein the controller is adapted to configure the firewall nodes in a logical firewall hierarchy without changing physical connections between the firewall nodes.

28. The firewall grid of claim 27 wherein the firewall nodes are adapted to simultaneously process copies of the same packets.

29. The firewall grid of claim 27 wherein the logical firewall hierarchy comprises a function-parallel hierarchy where individual firewall nodes implement different portions of a rule set.

30. The firewall grid of claim 27 wherein the controller is adapted to detect congestion at a first level in the firewall hierarchy and is adapted to reconfigure the logical connections between the firewall nodes to add a firewall node from another level in the firewall hierarchy to the level at which congestion was detected.

31. A system for providing network access control based on a function-parallel policy, the system comprising:
    (a) a first node for filtering received packets using a first portion of a rule set including a plurality of rules, the first portion including less than all of the rules in the rule set; and
    (b) at least one second node for filtering packets using a second portion of the rule, the second portion including at least one rule in the rule set that is not present in the first portion, wherein the first and second portions together include all of the rules in the rule set.
32. The system of claim 31 wherein the rule set includes firewall rules for filtering packets based on packet header information.
33. The system of claim 31 wherein the rule set includes intrusion detection rules for filtering packets based on packet payload information.
34. The system of claim 31 wherein the rule set includes intrusion protection rules for filtering packets based on a combination of packet header and packet payload information.
35. A method for controlling access to a network based on a set of packet filtering rules distributed in a function-parallel manner, the method comprising:
    (a) distributing packet filtering rules of a rule set among a plurality of different nodes in a function-parallel manner so that at least some of the different nodes implement different portions of the rule set;
    (b) replicating packets to each of the nodes; and
    (c) applying the rules to filter the packets.
36. The method of claim 35 wherein the packet filtering rules comprise firewall rules for filtering packets based on packet header information.
37. The method of claim 35 wherein the packet filtering rules comprise intrusion detection rules for filtering packets based on packet payload information.
38. The method of claim 35 wherein the packet filtering rules comprise intrusion protection rules for filtering packets based on a combination of packet header and packet payload information.

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39. The method of claim 35 comprising, receiving a first packet at a first node, determining whether the packet matches a first rule implemented by the first node, and, in response to determining that a match occurs, notifying the other nodes of the match.

40. The method of claim 36 comprising, at the other nodes, ceasing processing of the first packet.

41. A method for distributing rules in a function-parallel firewall, the method comprising:

(a) defining a rule set for a function-parallel firewall;

(b) assigning rules in the rule set to nodes and branches in a trie data structure, wherein each node in the trie data structure corresponds to a data field and each branch represents a value for each data field to be compared to values in corresponding fields in received packets; and

(c) pruning the trie data structure in a manner that preserves ordering of the rules in the rule set.

42. The method of claim 41 wherein pruning the trie data structure includes pushing a rule to its descendants and deleting the original rule.

43. The method of claim 41 comprising reducing the depth of the trie using level reordering.

44. The method of claim 41 wherein assigning rules in the rule set to nodes and branches in the trie data structure includes assigning rules requiring longer processing time to lower levels in the trie.

45. A method for assigning rules to a plurality of firewall nodes, the method comprising:

(a) assigning packet filtering rules to nodes in a directed acyclical graph (DAG);

(b) representing relationships between rules by edges in the DAG; and

(c) distributing the rules among a plurality of firewall nodes using the DAG such that different firewall nodes implement different rules and such that relationships between the rules specified in the DAG are preserved.

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46. The method of claim 45 wherein distributing the rules among a plurality of firewall nodes using the DAG includes distributing the rules such that intersecting accept rules are not present in more than one firewall node.

47. The method of claim 45 wherein distributing the rules among a plurality of firewall nodes using the DAG includes distributing the rules such that the edges to not span multiple firewall nodes.

48. The method of claim 45 wherein distributing the rules among a plurality of firewall nodes using the DAG includes replicating deny rules in each of the firewall nodes.

49. The method of claim 48 comprising eliminating a deny rule implemented by a first firewall node in response to determining that the deny rule for the first firewall node includes no inbound edges and outbound edges from the first deny rule terminate only in a superset deny rule.

50. A computer program product comprising computer executable instructions embodied in a computer readable medium for performing steps comprising:

(a) distributing packet filtering rules of a rule set among a plurality of different nodes in a function-parallel manner so that at least some of the different nodes implement different portions of the rule set;

(b) replicating packets to each of the nodes; and

(c) applying the rules to filter the packets.

51. A computer program product comprising computer executable instructions embodied in a computer readable medium for performing steps comprising:

(a) defining a rule set for a function-parallel firewall;

(b) assigning rules in the rule set to nodes and branches in a trie data structure, wherein each node in the trie data structure corresponds to a data field and each branch represents a value for each data field to be compared to values in corresponding fields in received packets; and

(c) pruning the trie data structure in a manner that preserves ordering of the rules in the rule set.

52. A computer program product comprising computer executable instructions embodied in a computer readable medium for performing steps comprising:

(a) assigning rules to nodes in a directed acyclical graph (DAG);

(b) representing relationships between rules by edges in the DAG; and

(c) distributing the rules among a plurality of firewall nodes using the DAG such that the relationships between the rules specified in the DAG are preserved.

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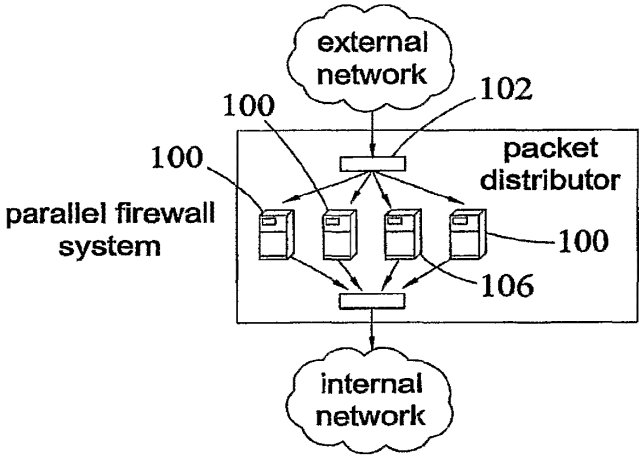

FIG. 1
(PRIOR ART)

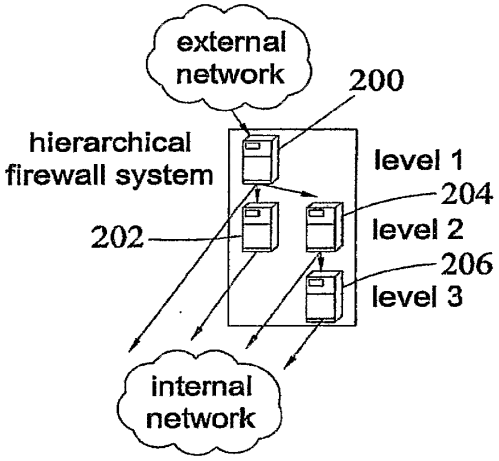
external network
200
hierarchical firewall system
level 1
204
level 2
202
206
level 3
internal network

FIG. 2

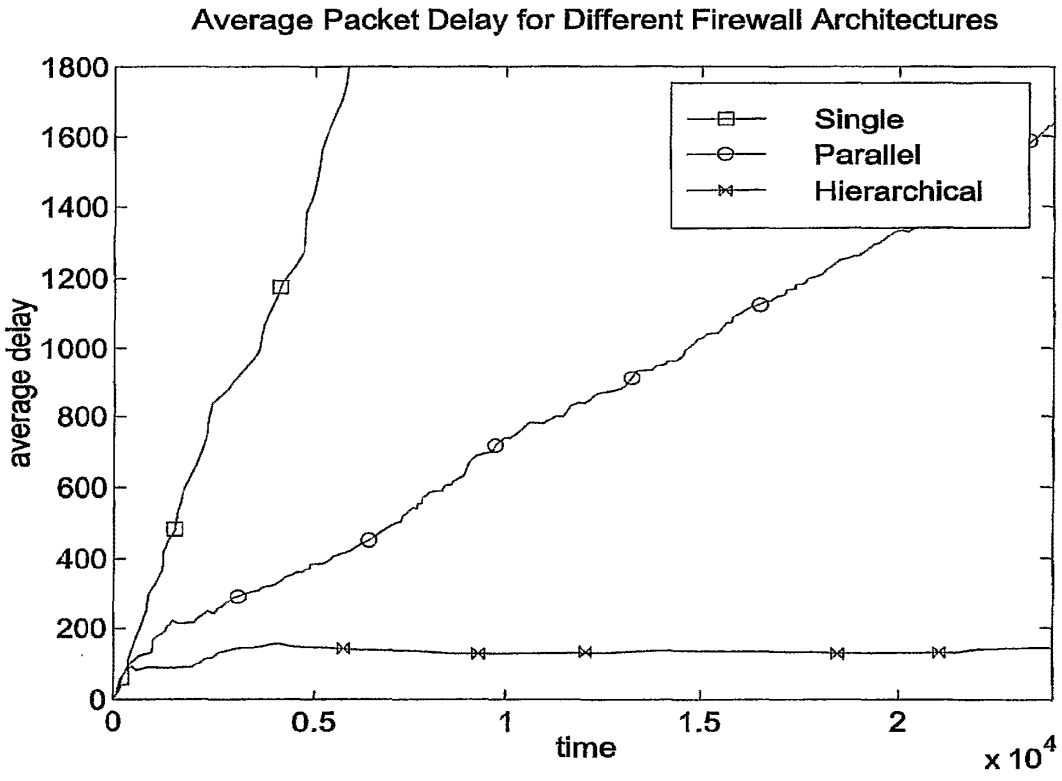
Average Packet Delay for Different Firewall Architectures
average delay
time
x 10^4
Single
Parallel
Hierarchical
0
200
400
600
800
1000
1200
1400
1600
1800
0
0.5
1
1.5
2

FIG. 3A

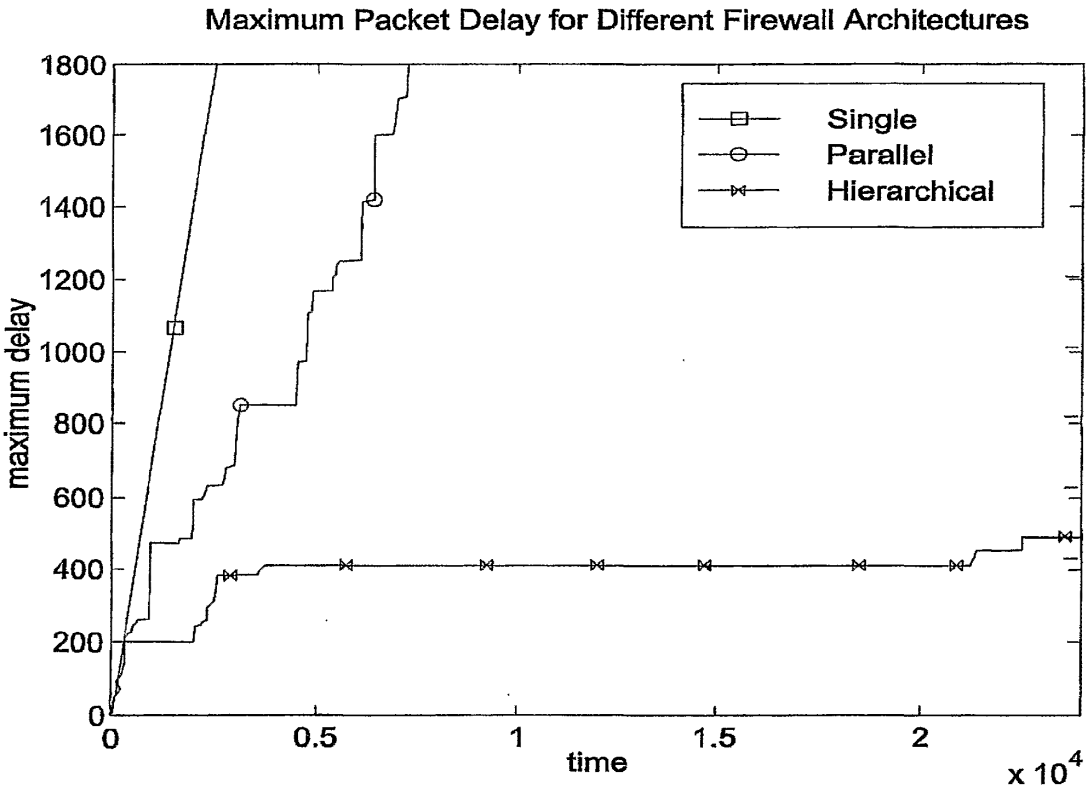
Maximum Packet Delay for Different Firewall Architectures
maximum delay
time
x 10^4
Single
Parallel
Hierarchical
0
200
400
600
800
1000
1200
1400
1600
1800
0
0.5
1
1.5
2

FIG. 3B

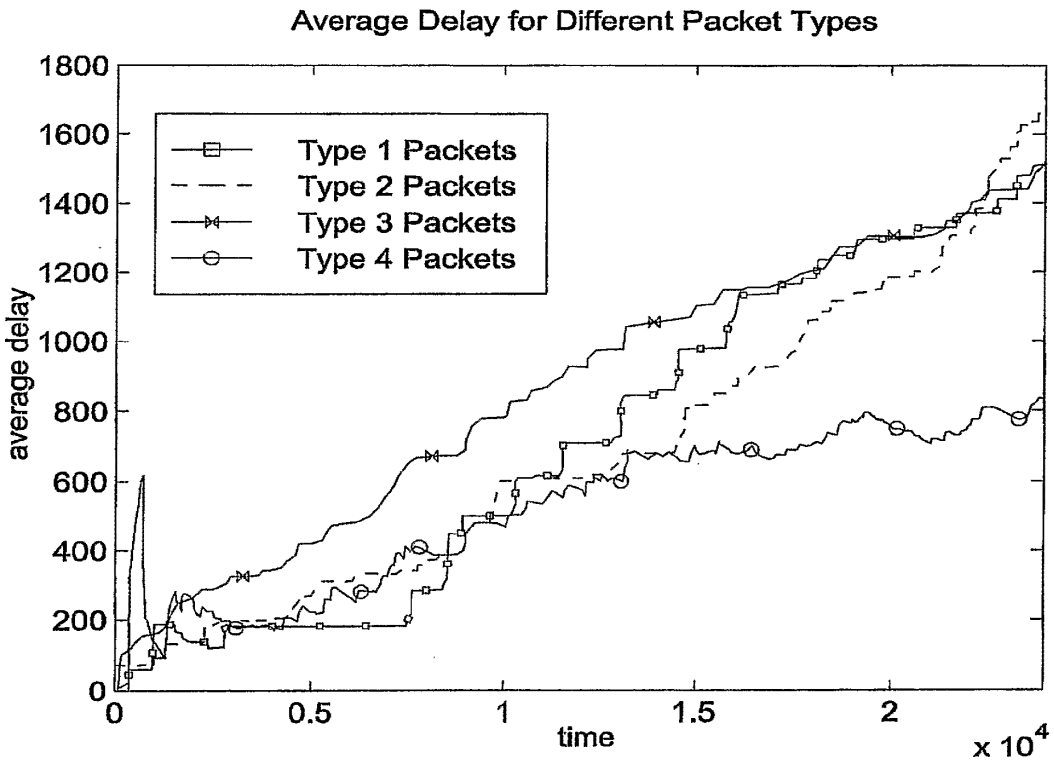
Average Delay for Different Packet Types
Type 1 Packets
Type 2 Packets
Type 3 Packets
Type 4 Packets
average delay
time
x 10^4
0
200
400
600
800
1000
1200
1400
1600
1800
0.5
1
1.5
2

FIG. 4A

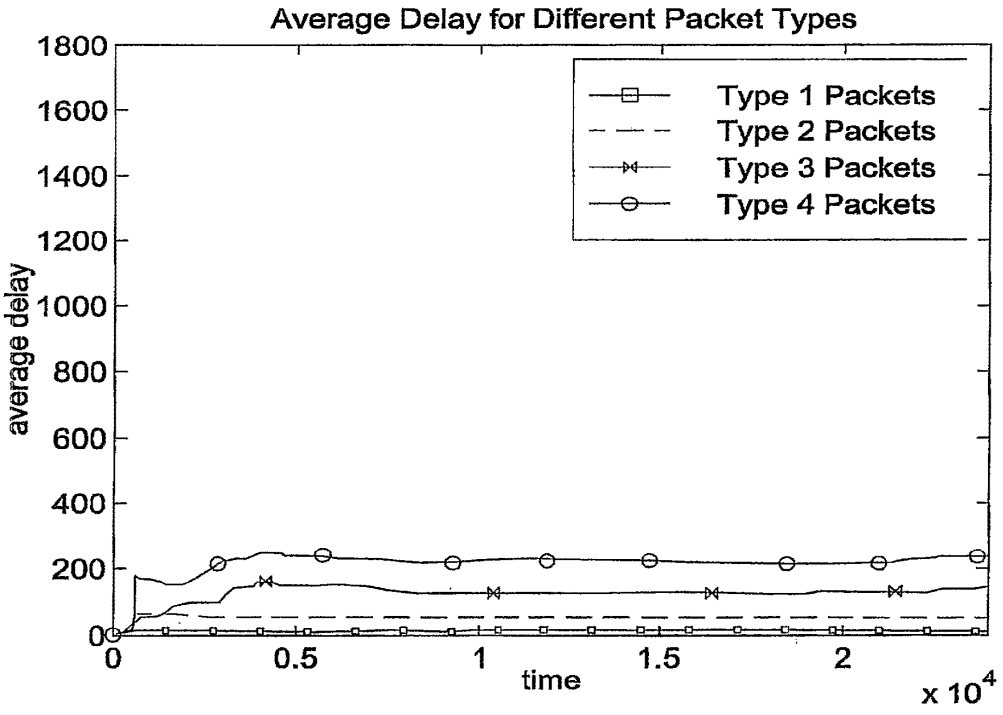
Average Delay for Different Packet Types
1800
1600
1400
1200
1000
800
600
400
200
0
average delay
0
0.5
1
1.5
2
time
x 10^4
Type 1 Packets
Type 2 Packets
Type 3 Packets
Type 4 Packets

FIG. 4B

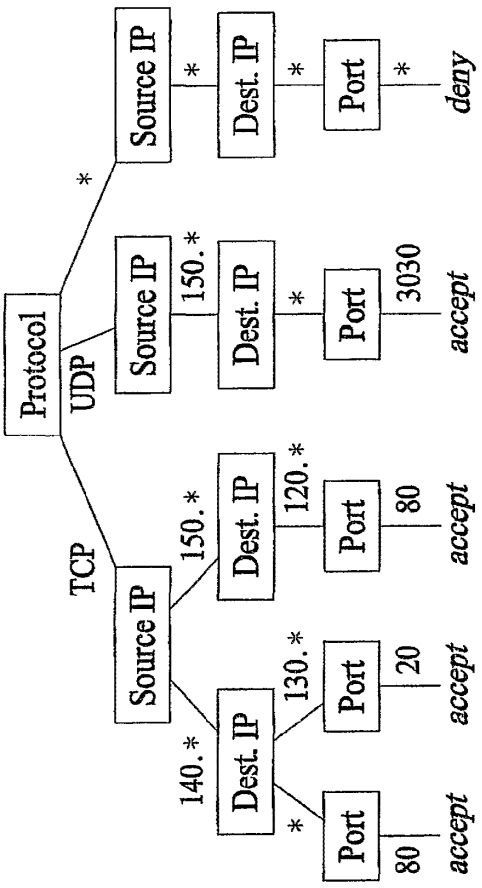
Protocol
TCP
UDP
Source IP
140.*
150.*
Dest. IP
*
130.*
120.*
Port
80
20
*
3030
accept
deny

FIG. 5

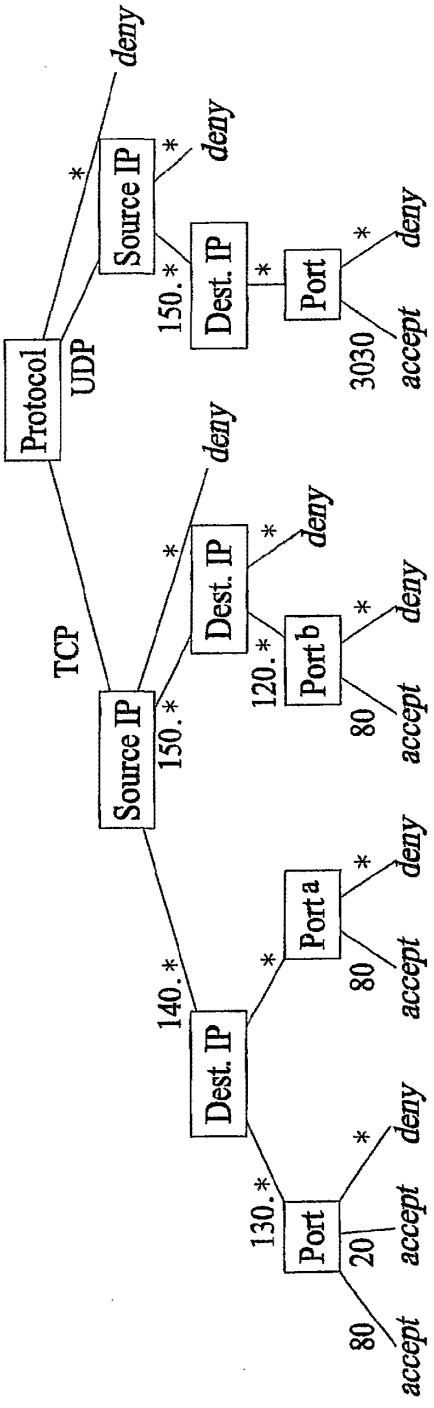
Protocol
TCP
UDP
Source IP
140.*
150.*
Dest. IP
*
130.*
120.*
Port
Port a
Port b
80
20
3030
accept
deny

FIG. 6

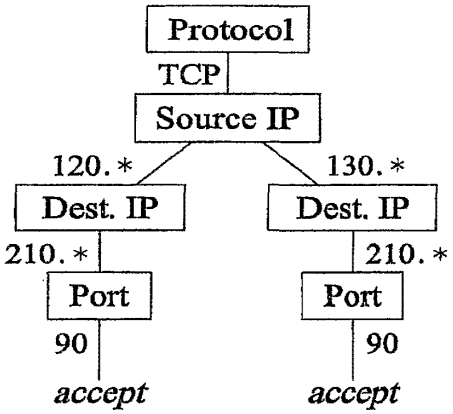
Protocol
TCP
Source IP
120.*
130.*
Dest. IP
Dest. IP
210.*
210.*
Port
Port
90
90
accept
accept

FIG. 7A

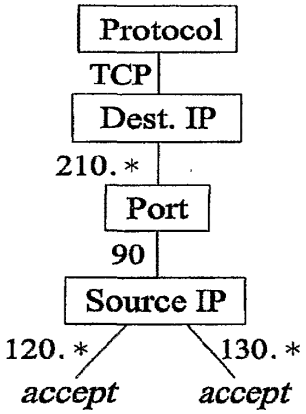
Protocol
TCP
Dest. IP
210.*
Port
90
Source IP
120.*
130.*
accept
accept

FIG. 7B

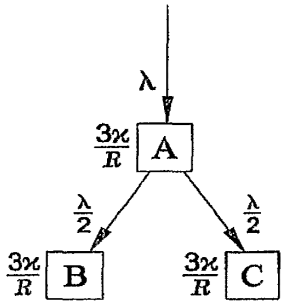
λ
3κ/R
A
λ/2
λ/2
3κ/R
B
3κ/R
C

FIG. 8A

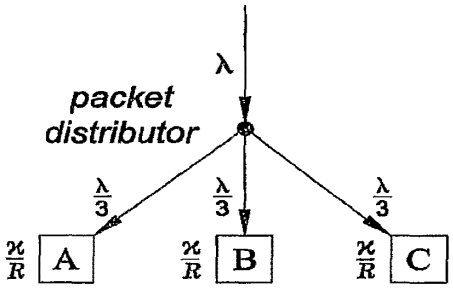
λ
packet
distributor
λ/3
λ/3
λ/3
κ/R
A
κ/R
B
κ/R
C

FIG.8B

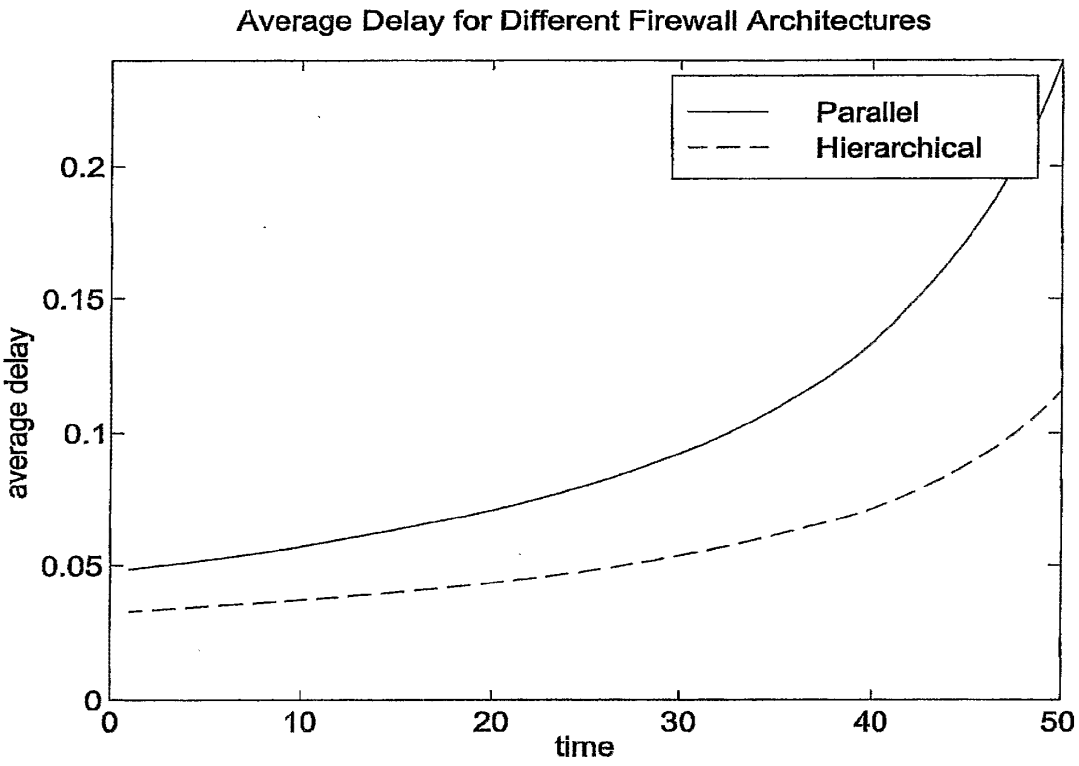
Average Delay for Different Firewall Architectures
Parallel
Hierarchical
average delay
0
0.05
0.1
0.15
0.2
0
10
20
30
40
50
time

FIG. 9

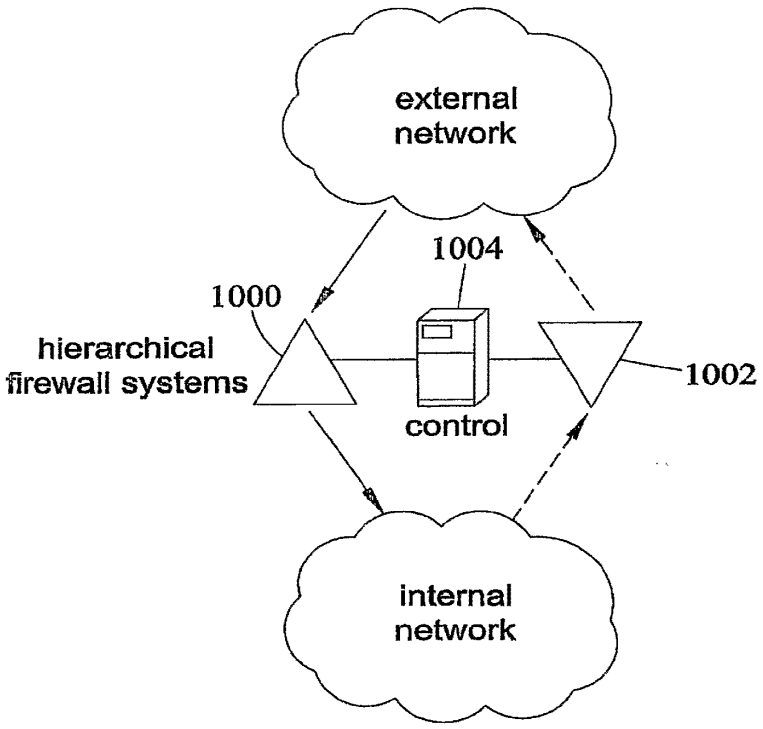
external network
1004
1000
hierarchical firewall systems
1002
control
internal network

FIG. 10

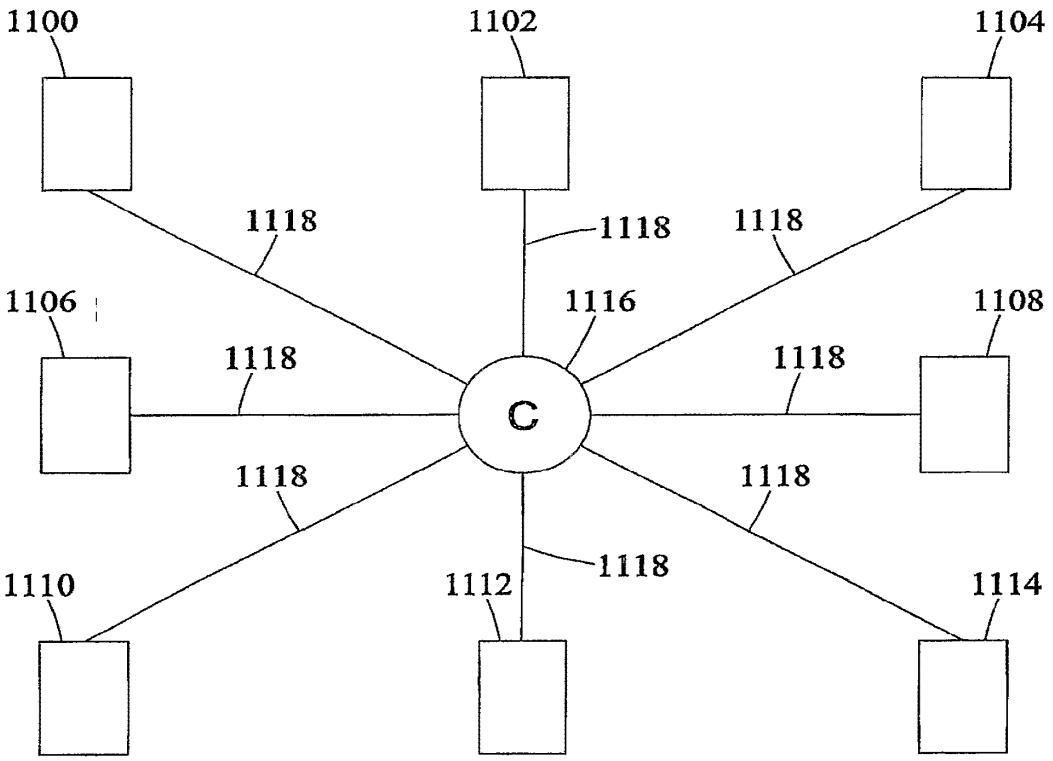
1100
1102
1104
1118
1118
1118
1106
1116
1108
1118
1118
C
1118
1118
1118
1110
1112
1114

FIG. 11A

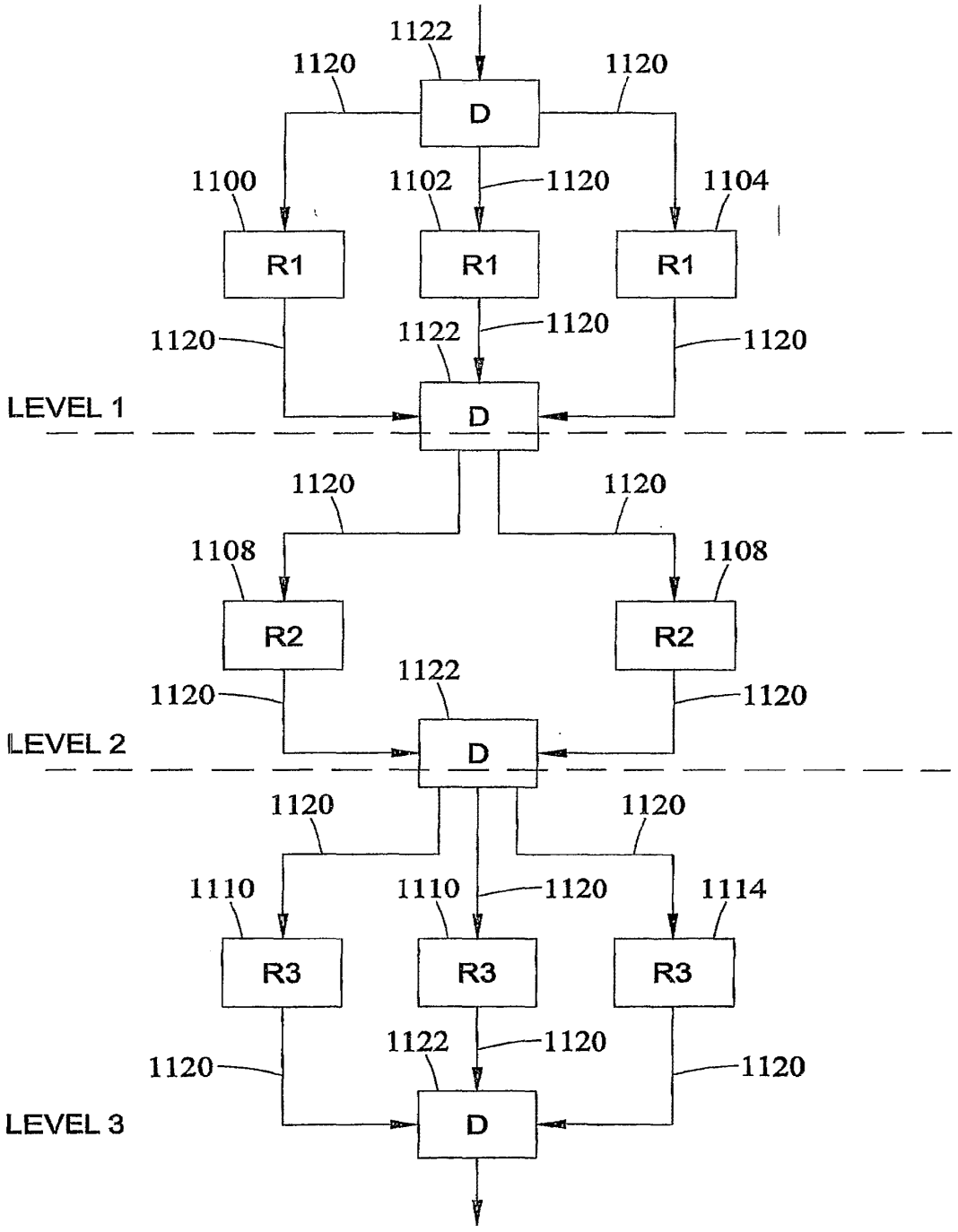
1122
1120
1120
D
1100
1102
1120
1104
R1
R1
R1
1120
1122
1120
1120
LEVEL 1
D
1120
1120
1108
1108
R2
R2
1122
1120
1120
LEVEL 2
D
1120
1120
1110
1110
1120
1114
R3
R3
R3
1122
1120
1120
1120
LEVEL 3
D

FIG. 11B

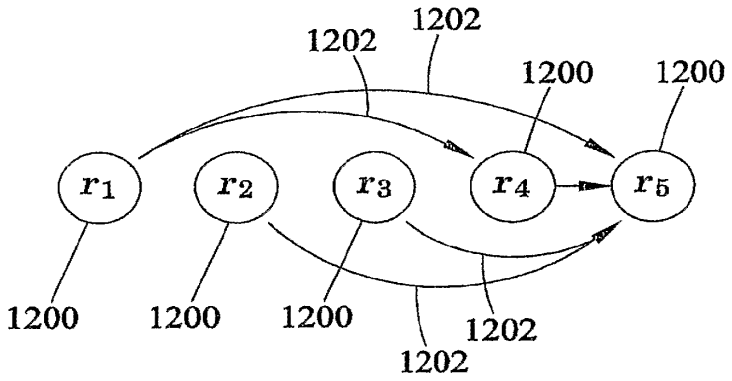

FIG. 12

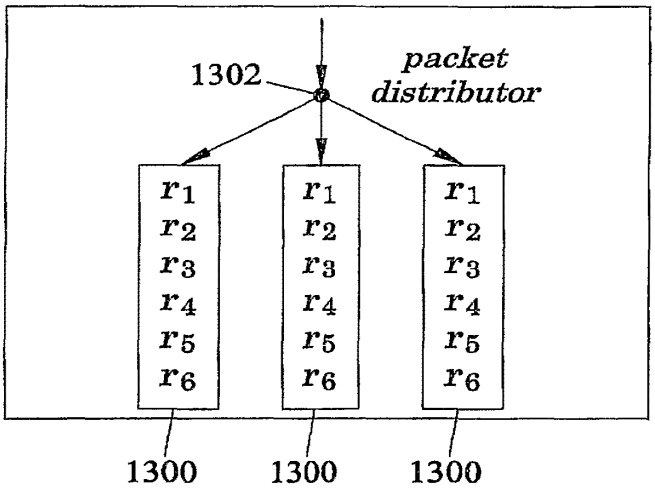

FIG. 13A

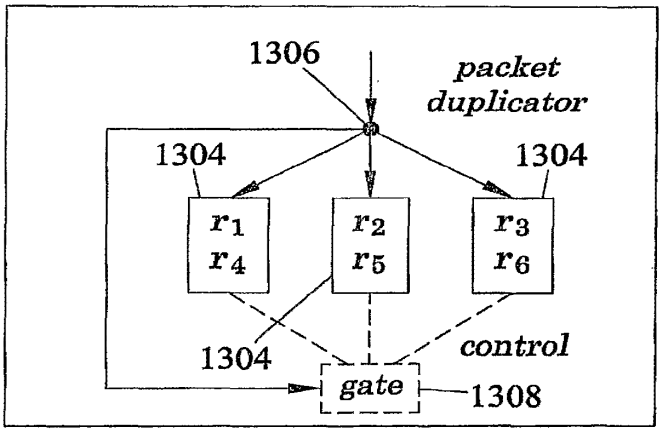

FIG. 13B

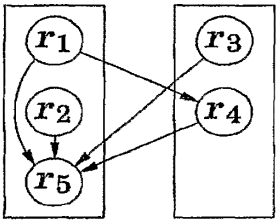

FIG. 14A

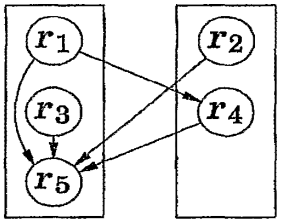

FIG. 14B

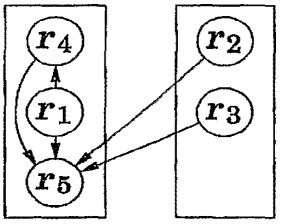

FIG. 14C

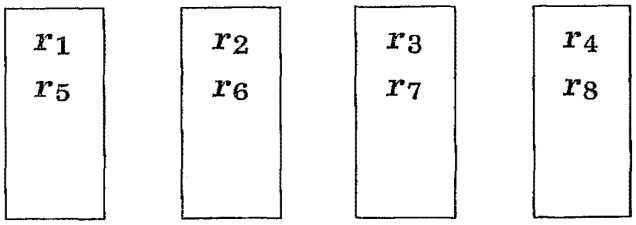

FIG. 15A

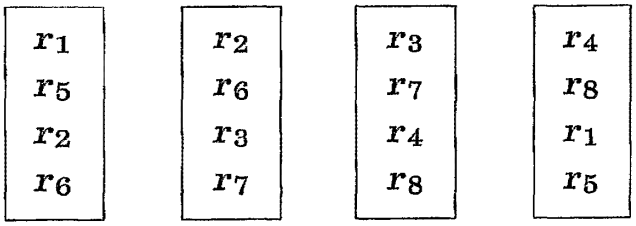

FIG. 15B

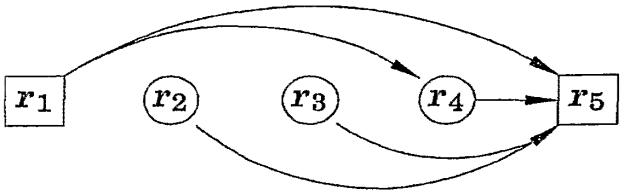

FIG. 16A

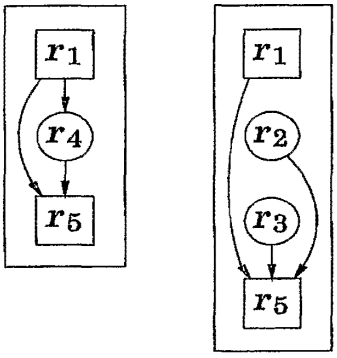

FIG. 16B

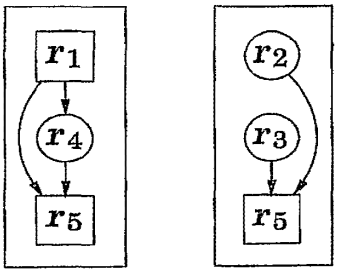

FIG. 16C

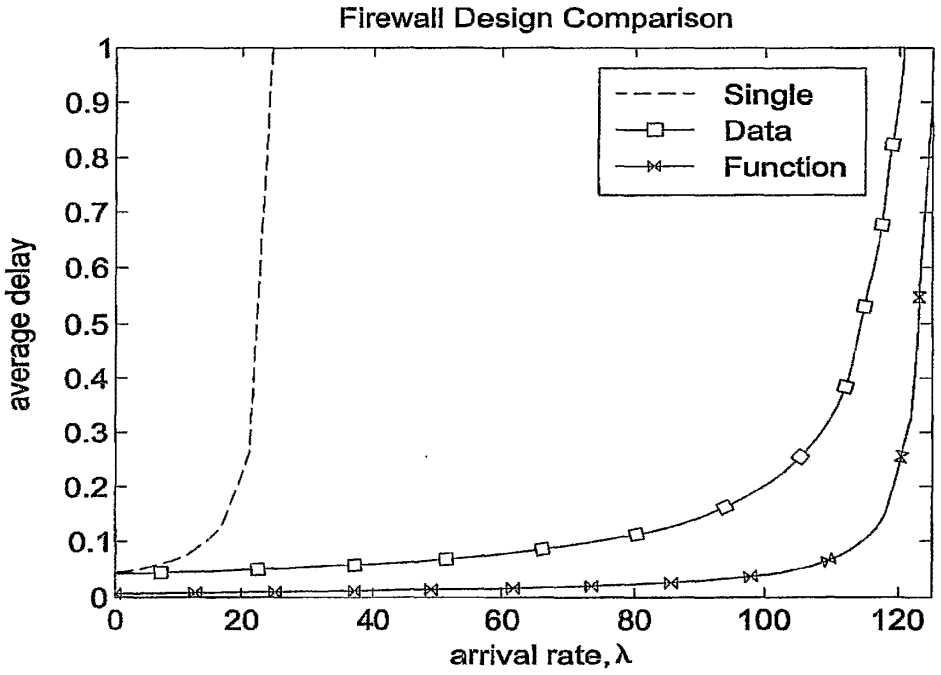
Firewall Design Comparison
Single
Data
Function
average delay
arrival rate, λ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

FIG. 17A

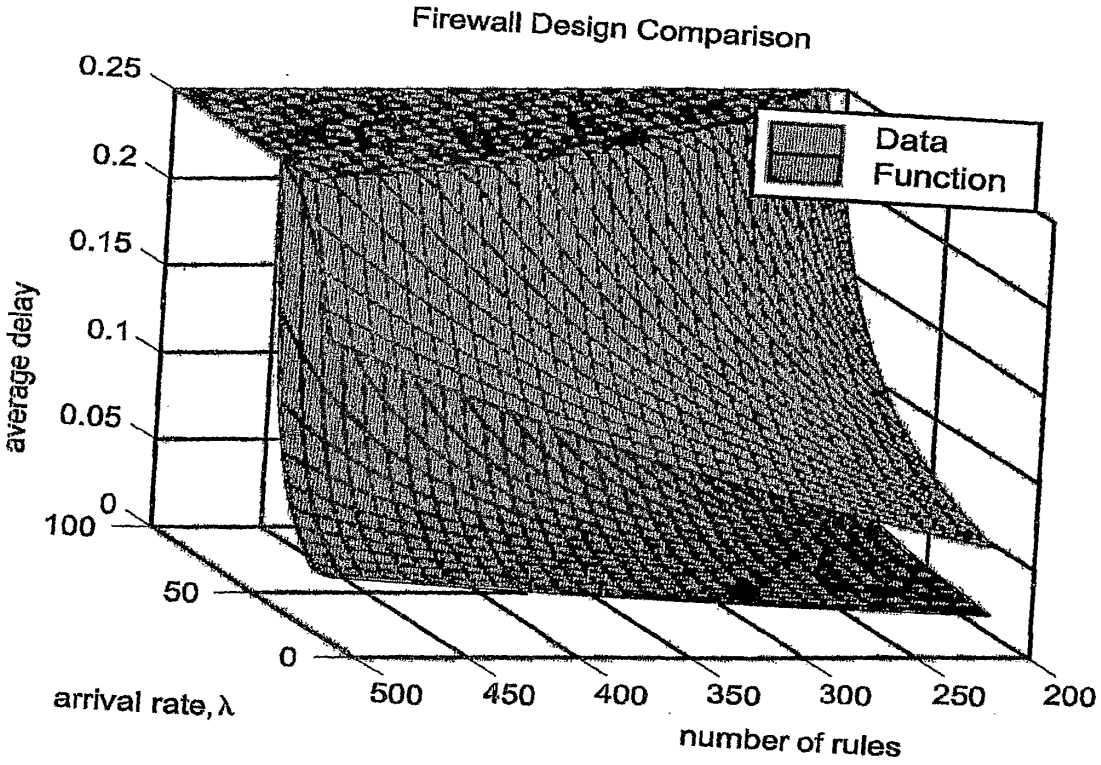
Firewall Design Comparison
0.25
0.2
0.15
0.1
0.05
0
average delay
Data Function
100
50
0
arrival rate, λ
500
450
400
350
300
250
200
number of rules

FIG. 17B

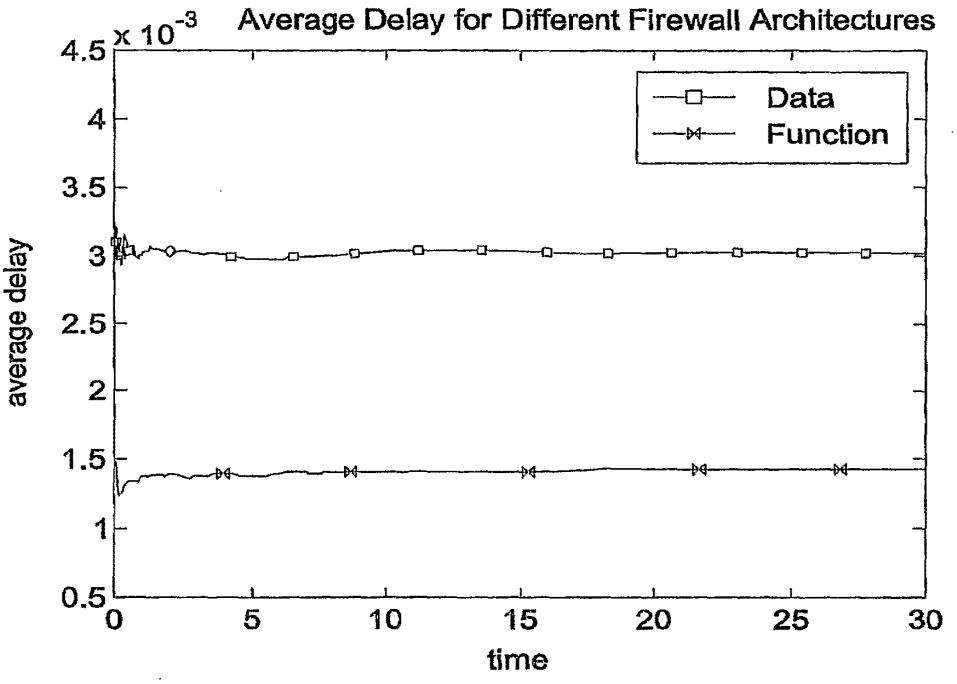
Average Delay for Different Firewall Architectures
x 10^-3
4.5
4
3.5
3
2.5
2
1.5
1
0.5
average delay
0
5
10
15
20
25
30
time
Data
Function

FIG. 18A

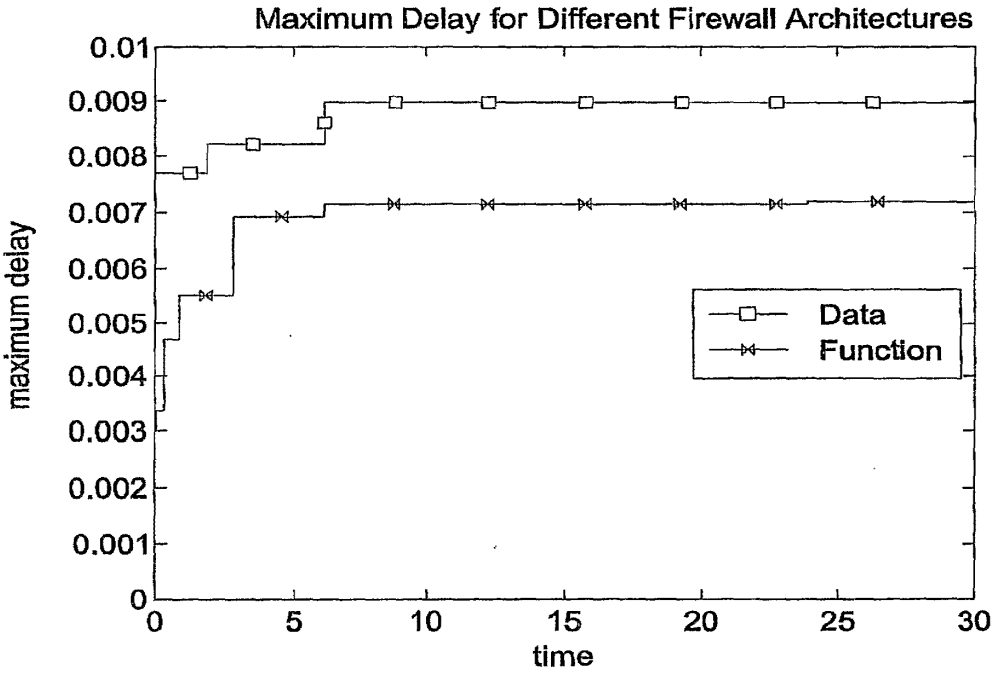
Maximum Delay for Different Firewall Architectures
maximum delay
time
Data
Function
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
5
10
15
20
25
30

FIG. 18B

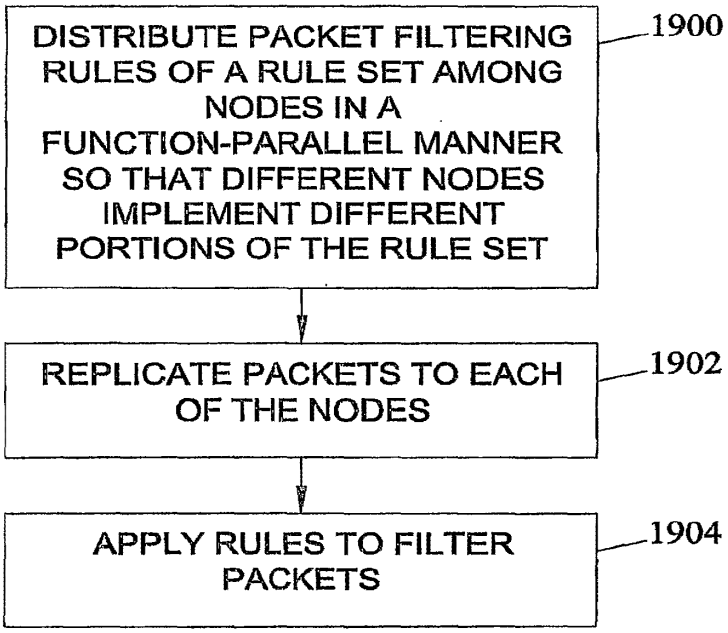
DISTRIBUTE PACKET FILTERING RULES OF A RULE SET AMONG NODES IN A FUNCTION-PARALLEL MANNER SO THAT DIFFERENT NODES IMPLEMENT DIFFERENT PORTIONS OF THE RULE SET
1900
REPLICATE PACKETS TO EACH OF THE NODES
1902
APPLY RULES TO FILTER PACKETS
1904

FIG. 19

Australian Government

IP Australia

LETTERS PATENT

STANDARD PATENT

2005328336

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Name and Address of Patentee(s):

Wake Forest University
Office of Technology Asset Management, Wake Forest University Health Services, 200 East First Street, Suite 101, Winston Salem, North Carolina, 27101, United States of America

Name of Actual Inventor(s):

Fulp, Errin W. and Farley, Ryan J..

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(71) Applicant(s)
Wake Forest University

(72) Inventor(s)
Fulp, Errin W.;Farley, Ryan J.

(74) Agent / Attorney
Griffith Hack, Level 10 167 Eagle Street, Brisbane, QLD, 4001

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(71) Applicant *(for all designated States except US)*: **WAKE FOREST UNIVERSITY** [US/US]; OFFICE OF TECHNOLOGY ASSET MANAGEMENT, WAKE FOREST UNIVERSITY HEALTH SCIENCES, 200 East First Street, Suite 101, Winston Salem, North Carolina 27101 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **FULP, Errin, W.** [US/US]; 308 N. Hawthorne Road, Winston-salem, North Carolina 27104 (US). **FARLEY, Ryan, J.** [US/US]; 212 Radford Street, Winston-salem, North Carolina 27106 (US).

(74) Agent: **HUNT, Gregory, A.**; JENKINS, WILSON & TAYLOR, P.A., SUITE 1400 UNIVERSITY TOWER, 3100 Tower Boulevard, Durham, North Carolina 27707 (US).

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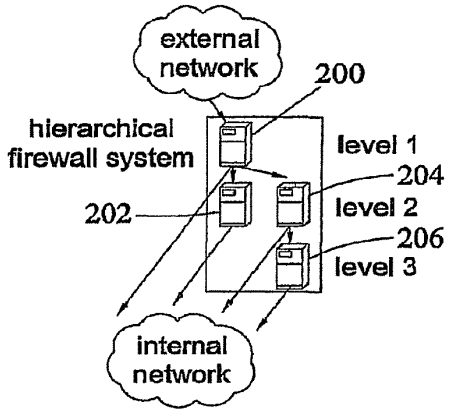
(54) Title: METHOD, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR IMPLEMENTING FUNCTION-PARALLEL NETWORK FIREWALL



(57) Abstract: Methods, systems, and computer program products for providing function-paralell firewalls are disclosed. According to one aspect, a function-parallel firewall includes a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules. The first portion includes less than all of the rules in the rule set. At least one second firewall node filters packets using a second portion of the rule set. The second portion includes at least one rule in the rule set that is not present in the first portion. The first and second portions together include all of the rules in the rule set.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

DESCRIPTION

METHOD, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR IMPLEMENTING FUNCTION-PARALLEL NETWORK FIREWALL

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/638,436, filed December 22, 2004; the disclosure of which is incorporated herein by reference in its entirety.

GOVERNMENT INTEREST

This invention was made with Government support under Grant No. DE-FG02-03ER25581 awarded by U.S. Department of Energy, Mathematical and Computational Information Sciences Division. The U.S. Government has certain rights in the invention.

TECHNICAL FIELD

The subject matter described herein relates to implementing network firewalls. More particularly, the subject matter described herein relates to methods, systems, and computer program products for implementing a function-parallel network firewall.

BACKGROUND ART

Firewalls remain the frontier defense for securing networks that are vital to private industry, government agencies, and the military. They enforce a security policy by inspecting and filtering traffic arriving at or departing from a secure network [3, 21, 22]. Meaningful inspections often involve a complex process, and if firewalls are to remain effective, they must adapt to constantly changing network demands, technology, and security threats.

As firewall technology evolves to meet new demands and threats, it must continue to act transparently to legitimate users, with little or no effect on the perceived network performance. The networks between two communicating machines should be invisible, especially if traffic requires specific network Quality of Service (QoS), such as bounds on the packet delay, jitter, and throughput. The firewall should process the legitimate traffic quickly, efficiently,

and never violate the desired QoS. Unfortunately, the firewall can easily become a bottleneck, given increasing traffic loads and network speeds [12, 14, 18, 20, 21]. Packets must be inspected and compared against complex rule sets and tables, which is a time-consuming process. In addition, audit files must be updated with current connection information. As a result, current firewalls have difficulty maintaining QoS guarantees. Since a firewall can be overwhelmed with traffic, it is also susceptible to Denial of Service (DoS) attacks [21]. Such attacks merely overload/saturate the firewall with illegitimate traffic. Audit files and state tables quickly fill available storage space and legitimate traffic queued behind suspicious traffic encounters long delays. Legitimate users notice poor network performance, and, in the worst case, the secure network is disconnected from the outside world.

Inspecting traffic sent between networks, a firewall provides access control, auditing, and traffic control based on a security policy [3, 21, 22]. The security policy is a list of ordered rules, as seen in Table 1, that defines the action to perform on matching packets. A rule r can be viewed as a k-tuple ($r[1]$, $r[2]$, $r[3]$, ..., $r[k]$), where $r[i]$ is specified as a variable length prefix.

No.	Proto.	Source		Destination		Action
		IP	Port	IP	Port	
1	TCP	140.*	*	*	80	accept
2	TCP	150.*	*	120	80	accept
3	TCP	140.*	*	130	20	accept
4	UDP	150.*	*	*	3030	accept
5	*	*	*	*	*	deny

Table 1: Example Security Policy Consisting of Multiple Ordered Rules

In the examples described herein, rules will initially be represented as the 5-tuple (protocol, IP source address, source port number, IP destination address, destination port number). Fields can be fully specified or contain wildcards '*' in standard prefix format. For example the prefix 192.* would represent any IP address that has 192 as the first dotted-decimal number. In addition to the prefixes, each filter rule has an action, which is to accept or deny. An accept action passes the packet into or from the secure network,

while deny causes the packet to be discarded. Rules are applied in order to every arriving packet until a match is found; otherwise, a default action is performed [21, 22].

Unfortunately, security policies may contain anomalies, such as a packet that matches multiple rules, where the matching rules specify conflicting actions. Security policy anomaly detection and correction is the subject of continued research [13, 21] and is not the focus of the present subject matter. Given the type of security policy required, rule sets can become quite large and complex. Security can be further enhanced with connection state and packet audit information. For example, a table can be used to record the state of each connection, which is useful for preventing certain types of attacks (e.g., TCP SYN flood) [21, 22].

Traditional firewall implementations consist of a single dedicated machine, similar to a router, that sequentially applies the rule set to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [15, 18, 22]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [21]. Successfully handling this high traffic becomes more difficult as rule sets become more complex [4, 14, 22]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 7, 10, 12]. An attacker could simply inundate the firewall with traffic, delaying or preventing legitimate packets from being processed. Building a faster single firewall is possible [8, 15, 18, 19, 20]; however, the benefits are temporary (traffic loads and interface speeds are increasing); it is not scalable; it is a single point of failure; and it is generally not cost-effective for all installations.

A data-parallel firewall (or firewall sandwich) where each firewall node implements an entire firewall rule set is another approach to increase the speed of processing traffic [4, 12, 14, 22]. As shown in Figure 1, the system consists of multiple identical firewalls **100** connected in parallel. Each machine implements the complete security policy and arriving packets are distributed across the machines for processing in parallel [4]. A packet distributor **102**

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implements a load balancing algorithm to distribute different packets to different firewall nodes. How the load-balancing algorithm distributes packets is vital to the system and is typically implemented as a high-speed switch in commercial products [11,12]. Although data-parallel firewalls achieve higher throughput than traditional firewalls [4] and have a redundant design, they have difficulty maintaining QoS across networks. For example, legitimate traffic can encounter delays if it is queued behind traffic that requires more processing. Under these circumstances, users notice poor network performance, which is growing concern as more network applications require QoS assurances. Furthermore, stateful inspection requires all traffic from a certain connection or exchange to traverse the same parallel machine, which is difficult to perform at high speeds [14]. Therefore, new firewall architectures are needed to meet the demands of future networks and the challenges of increasing security threats.

SUMMARY

In accordance with the present invention, there is provided a function-parallel firewall system comprising (a) a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules, the first portion including less than all of the rules in the rule set; and (b) at least one second firewall node for filtering packets using a second portion of the rule set, the second portion including at least one rule in the rule set that is not present in the first portion, wherein the first and second portions together include all of the rules in the rule set, wherein the first and second firewall nodes are configured to implement a gateless design wherein the rules are distributed among the first and second firewall nodes such that for a given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet.

In accordance with the present invention, there is provided a method for controlling access to a network based on a set of packet filtering rules distributed in a function-parallel manner, the method comprising (a) distributing packet filtering rules of a rule set among a plurality of different nodes in a function-parallel manner so that at least some of the different nodes implement different portions of the rule set; (b) replicating packets to each of the nodes; and (c) applying the rules to filter the packet using a gateless design wherein the rules are distributed among first and second firewall nodes such that for a given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet.

In accordance with the present invention, there is provided a computer program product comprising computer executable instructions embodied in a computer readable medium for performing steps comprising (a) a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules, the first portion including less than all of the rules in the rule set; and (b) at least one second firewall node for filtering packets using a second portion of the rule set, the second portion including at least one rule in the rule set that is not present in the first portion, wherein the first and second portions together include all of the rules in the rule set, wherein the first and second firewall nodes are configured to implement a gateless design wherein the rules are distributed among the first and second firewall nodes such that for any given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet.

According to one aspect, the subject matter described herein includes a function-parallel firewall. The function-parallel firewall includes a first firewall node for filtering received packets using a portion of a rule set. The portion of the rule set may be less than all of the rules in the rule set. At least one second firewall node filters packets using at least one rule in the rule set that is not present in the portion implemented by the first firewall node. The first and second potions together include all of the rules in the rule set.

The term "firewall node," as used herein refers to a physical entity that implements one or more packet filtering rules. For example, a firewall node may be a single-processor computing device that implements the packet filtering rules. Alternatively, a firewall node may be a processor within a multi-processor computing device that implements one or more packet filtering rules. Thus, a multi-processor device may include multiple firewall nodes.

According to another aspect, the subject matter described herein includes a stateful function-parallel firewall system. The system includes a first function-parallel firewall subsystem including a plurality of firewall nodes implementing a first rule set for filtering packets arriving at a network. The first function-parallel firewall subsystem includes at least first and second firewall nodes respectively implementing first and second portions of the first rule set.

The first portion includes at least one rule that is not present in the second portion. A second function-parallel firewall subsystem includes a second set of firewall nodes. The second set of firewall nodes implements a firewall rule set for filtering packets departing from the network. The second function-parallel firewall subsystem includes at least third and fourth firewall nodes. The third and fourth firewall nodes implement at least one rule that is not present in the second portion of the second rule set. The function-parallel firewall subsystems share state information regarding connections established through the first and second sets of firewall nodes.

According to another aspect, the subject matter described herein includes a firewall grid. The firewall grid includes a plurality of firewall nodes that are physically connected to each other via a network for filtering packets. A controller controls logical connections between the firewall nodes. The controller is adapted to configure the firewall nodes in a logical firewall hierarchy without changing physical connections between the firewall nodes.

According to yet another aspect, the subject matter described herein includes a method for distributing rules in a function-parallel firewall. The method includes defining a rule set for a function-parallel firewall. The method further includes assigning rules in the rule set to nodes and branches in a trie data structure. Each node in the trie data structure corresponds to a data field and each branch represents a value for each data field to be compared to be values in corresponding fields of received packets. The trie data structure is pruned in a manner that preserves ordering of the rules in the rule set.

According to yet another aspect, the subject matter described herein includes a method for assigning rules to a plurality of firewall nodes. The method includes assigning rules to nodes in a directed acyclical graph (DAG). Relationships between rules are represented by edges in the DAG. Rules are distributed among a plurality of firewall nodes using the DAG in a function-parallel manner and such that relationships between the rules specified in the DAG are preserved.

As used herein, the term "firewall" refers to a logical entity that is adapted to filter packets at the ingress and/or egress portions of a network based on a policy. The term "firewall" is intended to include systems that block packets from entering or leaving a network and systems that perform intrusion

detection and intrusion protection functions for packets entering or leaving a network. Thus, the term "function-parallel firewall" is also intended to include an intrusion detection system or an intrusion protection system that operates in a function-parallel manner as described herein.

The subject matter described herein can be implemented using any combination of hardware, software, or firmware. In one exemplary implementation, the subject matter described herein may be implemented using a computer program product comprising computer executable instructions embodied in a computer readable medium. Exemplary computer readable media suitable for implementing the subject matter described herein include disk memory devices, chip memory devices, programmable logic devices, application specific integrated circuits, and downloadable electrical signals. In addition, a computer program product that implements the subject matter described herein may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

One objective of the subject matter described herein is to provide a new security architecture, referred to herein as a hierarchical firewall, that provides the functionality of a traditional firewall (enforcing a security policy) and includes the following improvements:

1. **Suitable for high speed networks and scalable for large traffic loads**. Firewalls must continue to perform security tasks quickly and efficiently, appearing transparent to legitimate users under varying traffic loads.

2. **Maintains QoS requirements and traffic differentiation.** A growing number of network applications require QoS for their operation. Firewalls must not violate these guarantees while performing their security tasks.

3. **Greatly lessens the impact of DoS attacks**. Firewalls are candidates for DoS attacks, since they serve as the point of entry between two networks. New architectures must be capable of handling these new threats.

4. **Highly available**. Firewalls introduce a single point of failure between two networks. New firewall architectures must provide redundancy that prevents segmenting the secure network from the external network.

According to one aspect, the subject matter described herein includes a set of hierarchically configured computers that collectively enforce a desired security policy. Given this distributed configuration, traffic is quickly divided among the machines based on perceived threat. In one exemplary implementation, traffic that is considered safe may be promptly forwarded into the secure network, while the remaining traffic may be forwarded to different machines in the hierarchy for further scrutiny. Hence, traffic is segregated and queued based on security threat, yielding minimal delays for legitimate traffic. The system is also robust and highly available, since multiple machines are employed for the architecture and low cost, since Linux-installed PCs and open source software can be used for its implementation [21]. The proposed architecture is believed to be applicable to a wide variety of agencies in the public and private sectors.

The firewall architecture described herein will provide a scalable solution to varying traffic loads and QoS requirements, which are increasingly important as computing becomes more ubiquitous and applications become more diverse. The architecture is of interest to the networking community, since the architecture will result in new security policy models and optimization methods. The architecture is also relevant to the military and business community, since it provides a new, robust and cost-effective solution to security threats.

Some of the objects of the subject matter described herein having been stated hereinabove, and which are addressed in whole or in part by the subject matter described herein, other objects will become evident as the description proceeds when taken in connection with the accompanying drawings as best described hereinbelow.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings of which:

Figure 1 is a block diagram of a conventional data-parallel firewall;

Figure 2 is a block diagram illustrating an exemplary function-parallel firewall architecture according to an embodiment of the subject matter described herein;

Figure 3A is graph comparing simulation results for average packet delay for different firewall architectures;

Figure 3B is a graph comparing simulation results for maximum packet delay for different firewall architectures;

Figure 4A is a graph illustrating average packet delay for different packet types for a data-parallel firewall;

Figure 4B is a graph illustrating simulation results for packet delay for different packet types for a function-parallel hierarchical firewall according to an embodiment of the subject matter described herein;

Figure 5 is a data structure diagram illustrating a full trie representation of the security policy illustrated in Table 1;

Figure 6 is a data structure diagram illustrating a pruned trie representation of the security policy given in Table 1 where each packet is processed within four field comparisons;

Figure 7A is a data structure diagram illustrating a trie representing two security rules assuming that the default action per node is deny;

Figure 7B is a data structure diagram illustrating a reordered version of the trie data structure illustrated in Figure 7A;

Figure 8A is a diagram illustrating a Jackson model for a function-parallel hierarchical firewall according to an embodiment of the subject matter described herein;

Figure 8B is a diagram illustrating a Jackson model for a data-parallel firewall;

Figure 9 is a graph illustrating simulation results for average delay for different firewall architectures;

Figure 10 is a block diagram illustrating a stateful hierarchical firewall according to an embodiment of the subject matter described herein;

Figure 11A is a block diagram illustrating physical connections of a firewall grid according to an embodiment of the subject matter described herein;

Figure 11B is a block diagram illustrating logical connections of the firewall grid illustrated in Figure 11A according to an embodiment of the subject matter described herein;

Figure 12 is a policy directed acyclical graph (DAG) representation of the firewall rules given in Table 2;

Figure 13A is a block diagram illustrating rule distribution among a data-parallel firewall;

Figure 13B is a block diagram illustrating a function-parallel firewall and rule distribution among nodes in the function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 14A is a block diagram illustrating one exemplary rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 14B illustrates another distribution of rules among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 14C illustrates an illegal rule distribution among nodes in a function-parallel firewall;

Figure 15A is a block diagram illustrating non-redundant rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 15B is a block diagram illustrating redundant rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 16A illustrates a policy DAG where deny rules are indicated by a square node;

Figure 16B is a block diagram illustrating initial gateless rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 16C is a block diagram illustrating final gateless rule distribution among nodes in a function-parallel firewall according to an embodiment of the subject matter described herein;

Figure 17A is a graph illustrating simulation results for average packet delay as packet arrival rate increases for different firewall designs;

Figure 17B is a graph illustrating simulation results for packet delay as the arrival rate and number of rules increase for different firewall designs;

Figure 18A is a graph illustrating simulation results for average packet delay for different firewall architectures;

Figure 18B is a graph illustrating simulation results for maximum packet delay for different firewall architectures; and

Figure 19 is a flow chart illustrating exemplary steps for filtering packets using a rule set distributed among nodes in a function-parallel manner according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION OF THE INVENTION

According to one aspect of the subject matter described herein may include multiple firewall machines configured in a hierarchy, as shown in Figure 2. In the example illustrated in Figure 2, a plurality of firewall nodes **200**, **202**, **204**, and **206** collectively implement a firewall policy. Each firewall node or set of nodes implements a different level of the firewall policy in a hierarchy. For example, firewall node **200** may implement a first level of a firewall policy that includes rules that are not present in subsequent levels. If a packet passes the first level of screening, the packet may be forwarded immediately to the internal network without impacting other firewall nodes. If the packet is identified as requiring further scrutiny, the packet may be forwarded to the next level where it is screened by firewall node **202** or **204** using rules that were not applied by firewall node **200**. If the packet passes level 2 screening, the packet may be forwarded directly to the internal network. If the packet is indicated as requiring further screening, the packet will be passed to level 3 where level 3 screening is applied by firewall node **206**.

At each level in the firewall hierarchy illustrated in Figure 2, firewall nodes may implement different portions of a packet filtering rule set. An architecture in which different firewall nodes implement different portions of a firewall rule set is referred to herein as a function-parallel architecture. A function-parallel firewall architecture in which packet filtering rules are distributed among firewall nodes such that if a packet passes or fails at a

certain level, the packet may bypass later levels is referred to herein as a hierarchical firewall architecture.

In the architecture illustrated in Figure 2, at each level, machines may be configured to perform a specific security task quickly and efficiently. In one implementation, the firewall rules may be distributed across the different hierarchy levels such that increased scrutiny is placed at lower levels. Since the rules are distributed among the levels, no machine in the hierarchy is required to implement the entire rule set. In contrast, a data-parallel firewall architecture requires all machines to implement the complete rule set.

As described above, in the exemplary architecture illustrated in Figure 2, packets start at the highest level and progress downward through the hierarchy. At each level, a packet can be forwarded to the internal network if deemed safe, forwarded to the next lower level for more processing, or dropped. The benefit of this divide-and-conquer approach is that traffic will incur delays consistent with its perceived security threat; therefore, traffic that is deemed safe will not be delayed by traffic that requires more processing. As a result, the hierarchical firewall can provide differentiated service and support QoS guarantees, unlike current designs. Furthermore, traffic that is forwarded to the internal network can be shaped at the particular firewall level, constraining the amount of traffic entering the network and lessening the effect of DoS attacks.

For example, in the hierarchical firewall depicted in Figure 2, packets are forwarded from the external network to the first level, where initial security checks are performed, such as a quick validity check and comparisons of IP addresses. Packets with trusted IP addresses are immediately forwarded to the internal network, while the remaining packets are sent to the next level. At the second level, packets are separated based on transport protocols and/or port numbers. Again, if a packet is deemed safe it is immediately forwarded to the secure network; otherwise, they are sent to the next level for auditing. Log files may be used at one or more of the firewall nodes indicate which connections are open and have been requested. Each level may also drop packets based on perceived threat.

The preceding example illustrates a simple hierarchical firewall; however, the size and complexity can vary. In general, the hierarchy attempts to quickly divide traffic and provide differentiated service. More levels can be used for

stronger security policies and to distribute traffic more efficiently. Determining the appropriate number of levels, the number of machines per level, and how to distribute the rule set are implementation details that may be used to optimize a function-parallel firewall according to an embodiment of the subject matter described herein.

Preliminary Experimental Results

In this section, simulation is used to compare a hierarchical firewall with a traditional single-machine firewall and a data-parallel firewall [4, 22]. Each architecture implemented the same 325-rule security policy, where each rule required 1 unit of time to complete. The single firewall architecture consisted of one machine that processed each packet received from the external network. The data-parallel architecture consisted of four machines, as shown in Figure 1, each implementing the same 325-rule set. The hierarchical firewall consisted of four machines configured in three levels, as shown in Figure 2. Rules were distributed across the levels such that the first level implemented 25 rules; the second level implemented 50 rules each; and the third level implemented 75 rules. The group of rules performed at a certain machine will be referred to as a security task. The hierarchical firewall incurred an additional delay of one time unit when a packet was transmitted from machine to machine. Packets randomly arrived to the system using a Poisson distribution with a mean of 30 units and would randomly match one of the 325 rules based on a uniform distribution. For classification purposes, each packet was associated with the security task it matched (which group of rules). In this experiment, the performance parameters analyzed are the overall average packet delay, the maximum packet delay, and the average delay experienced by each packet type.

Experimental results for the different architectures are shown in Figures 3 and 4. More particularly, Figure 3A illustrates average packet delay for a single firewall design, for the data-parallel firewall design illustrated in Figure 1, and for the hierarchical firewall design illustrated in Figure 2. Figure 3B illustrates maximum packet delay for the single, data-parallel, and hierarchical firewall designs. Figure 4A illustrates average packet delay for the data-parallel firewall design for different packet types. Figure 4B illustrates average packet

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delay for the hierarchical firewall design for different packet types. Packet types refer to packets of a classified based on which security task was satisfied. Unlike the data-parallel firewall, the hierarchical design consistently yields different delays for each packet type.

For both delay measurements, the hierarchical architecture performed better than the single firewall and the data-parallel firewall. The single firewall had an average delay 31 times greater than the hierarchical architecture, which demonstrates how a single firewall machine can quickly become a bottleneck. Although the data-parallel firewall performed better than the single firewall, it had an average and maximum delay 6 times longer than the hierarchical architecture. In the parallel configuration, traffic that needed little processing often queued behind traffic that required more processing, which resulted in longer delays. In contrast, the hierarchical system consistently yielded better results, since traffic was distributed among the levels based on processing requirements.

The average delay experienced by each packet type is also important and is illustrated in Figures 4A and 4B. Delays in the hierarchical firewall were proportional to the amount of processing required; for example, security task 1 traffic had the shortest delay, security task 2 traffic had the second shortest delay, security task 3 traffic had the third shortest delay; and security task 4 traffic had the highest delay. Even though security tasks 2 and 3 were on the same level, security task 3 traffic had a delay slightly higher that security task 2 traffic, since it was queued with security task 4 traffic. Therefore, the hierarchical firewall is capable of providing differentiated service to multiple packet types/classes. In contrast, the delays varied for each packet type in the data-parallel firewall. Packets were constantly delayed by lower type/class traffic (e.g., security task 1 packets delayed by security task 4 packets); thus, no differentiation was achieved. Although these results are preliminary, they indicate the hierarchical architecture has merit, offering significantly better performance than current firewall systems.

Refinements

The previous section described an initial hierarchical firewall architecture for employing a security policy. Although preliminary results indicate the architecture has merit, refinements can be made so that the design can achieve its full potential. One refinement relates to the hierarchical architecture. Important questions include determining the appropriate number of levels and how to effectively distribute the security policy rules. Another refinement may include providing stateful packet inspection (maintaining connection tables) and increasing redundancy. Finally, another refinement may include examining other high-speed firewall architectures, such as a dynamic firewall grid. Analytical models and simulation will be used for design and analysis; in addition, a prototype will be implemented along with analysis tools and software.

Architecture Design and Rule Set Distribution

Important questions about the firewall architecture include the number of levels, the number of machines per level, and the number of security tasks per machine. The security policy is central for addressing these questions and, for this reason, will be formally defined and modeled. The model will be optimized to reduce the physical size, minimize the traversal time, and provide differentiated service. Afterward, the optimized policy model will be used to implement the actual hierarchical firewall.

One method for designing the hierarchy is to represent the security policy graphically as a tree data structure. This representation will aid the translation to the actual firewall, since it has a hierarchical form. Although a variety of tree data structures exist, a trie will be initially investigated [1]. A trie is a special type of data structure that has the advantages of fast retrievals and quick unsuccessful search determination, which are important for enforcing a security policy. In a security policy trie, each path from the root node to a leaf corresponds to one rule. The nodes of the trie correspond to the rule fields, while branches are possible values. Figure 5 is a trie data structure for the rules in Table 1. For example, in Figure 5, the root node is the protocol field. The next level represents the source IP address, while the leaf nodes represent

the rule action. Rules that have the same field value at a node will share a branch for that value.

The trie in Figure 5 referred to as full trie, since every noncycle path from the root to a leaf has the same length, and every leaf lies at the same depth [6]. Unlike other policy models, the rule order must be preserved if the trie is to be successfully translated to a hierarchical firewall. The action to apply to a packet is determined by a preorder traversal. Starting at the root node, branches are compared to the fields of the packet. Since multiple branches may match a packet, they are traversed in order from left to right. If a packet field does not match any possible branches, it moves back to the previous node (parent), where the next branch is tested. Once the policy trie is developed, it can be translated into a hierarchical firewall. The nodes of the trie represent the machines in the hierarchy, while the branches represent the links between nodes. The value associated with each branch indicates the packet field value required to traverse it. Although a full trie representation of a security policy can be created, it is not necessarily optimal. Further trie manipulation is required create an effective hierarchical firewall, such as preventing routing to parents and limiting trie traversal time.

Pruning yields a trie that never requires routing to parent nodes, which provides faster packet processing [1, 15]. Assuming a full trie consists of n nodes and k levels (where k <= n), the worst case packet processing would be O(n*k) tuple-compares. In contrast, a pruned trie requires only O(k + n) tuple-compares in the worst case which is a processing reduction of 1/k.. Pruning is accomplished by replacing general rules with descendants. Rule r_1 is a descendant of rule r_2, if $r_2[i]$ is a prefix of $r_1[i]$ for $i = 1, ..., k$. Therefore, pruning occurs by pushing a rule down to all its descendents, then deleting the rule. An example of a pruned version of the trie illustrated in Figure 5 is given in Figure 6, where [*, *, *, deny] is a general rule that can be pushed down to every other rule. Although the original branch has been removed and added to the other branches, the order is preserved, if branches are tested from left to right. Current pruning algorithms do not consider rule order, since tries were primarily developed for storing data [6]. New pruning techniques that preserve order may be developed and used to distribute rules among nodes in a functional-parallel firewall according to an embodiment of the subject matter described

herein. Pruning may also cause the number of nodes in the hierarchy to increase, since a general rule is duplicated at different levels. For this reason, other techniques are needed to reduce the trie size.

Reducing the trie size is important, since delay increases each time a packet is forwarded from one node to another. The trie can be reduced by compressing nodes, which is achieved by removing single branching paths or consolidating sub-ties into one node [2, 6, 15]. As a result, a node may compare multiple rule fields or perform multiple security tasks per packet. For example, in Figure 5, the rule [UDP, 150.*, *, 3030, accept] is considered a leaf chain [6] and can be compressed into one node (a single machine). Two other methods commonly used to reduce the size of a trie are Directed Acyclic Graphs (DAG) and level reordering [1, 6, 15]. If the same sub-trie appears in multiple places, then the trie structure can be changed to a DAG. The possible use of DAG is seen in Figure 6, where nodes labeled $Port^a$ and $Port^b$ are equivalent sub-tries. Parent nodes of both sub-tries could point to just one, eliminating the need for the other.

Another method for reducing the trie size is level reordering. As seen in Figures 7A and 7B, the order of the levels can significantly affect the number of nodes in the trie. More particularly, in Figure 7A, an original trie representing the security rule [TCP, 120.*, 210.*, 90, accept] and [TCP, 130.*, 210.*, 90, accept] is illustrated. Both Figures 7A and 7B assume that the default action per node is deny. Since some of the rules in the original trie in Figure 7A include common elements, the rules can be reordered so that the number of branches in the subtrie are reduced. For example, in Figure 7A, the destination IP address and port for each branch of the subtrie are the same. Accordingly, if these common portions of the rule are implemented at higher levels, the duplicate nodes in the trie can be reduced, as illustrated by Figure 7B. More particularly, in Figure 7B, the nodes for destination IP and port are placed before the node for source IP address. As can be seen from Figure 7B, reordering the levels produces a smaller trie. Using a DAG can also reduce the number of nodes.

The problem of finding an ordering that guarantees a minimum size trie has been shown to be NP-complete; however, several heuristics have been developed [2, 6]. It should be noted that DAGs and reordering only reduce the

number of nodes in the hierarchy and do not reduce the depth of the trie, which influences the traversal time.

Regardless of the applicability of these different trie modifications, they must be performed in concert to achieve an optimal hierarchical design. For example, the architecture utilizes multiple nodes to distribute traffic load and provide differentiated service; however, the trie path length (depth) impacts the packet traversal time. Therefore, compression and ordering must be performed together to provide differentiated service and optimize packet delay.

To achieve these goals, information not explicitly given in the security policy (e.g., QoS, level of trust, and processing time) may be used. For example, it is advantageous to place security tasks that require the most time at the lowest levels. This prevents packets from queueing behind traffic that requires more processing time; thus, lowering delay. A weight w_i can be assigned to each security task s_i (a single rule or multiple rules) based on the amount of time it requires. For example, an auditing security task requires more time (updating system files) than those that only perform field comparisons. Using these weights, the trie can be ordered to minimize the average traversal time. For example assuming i and j are hierarchy levels, where $i < j$, the trie can be ordered such that the average weight per level increases from the highest to the lowest level $\overline{w}_i < \overline{w}_j, \forall i \neq j$. In addition, the trie can be designed to separate traffic based on QoS or level of trust. Traffic would traverse different sub-tries, based on the type of service required, providing class isolation and different delays. The algorithms described in this section can then be applied to these sub-tries independently to reduce size and traversal time. These ideas were used to design the hierarchical firewall simulated in the preceding section, which showed excellent results. New algorithms for trie compression based on traversal time with constraints on QoS will be developed for optimizing function-parallel firewall design.

Packet traversal time remains a key performance metric for firewall systems. For this reason, queueing models will be used to analyze the delay of different firewall designs. The node delay encountered by a packet consists of the processing time, queueing delay, and transmission time. The processing delay is the time required to perform the security task. Assume node i must

process R_i rules per packet and can perform xi rules per unit time, then the service rate is x_i/R_i packets per unit time. Queueing is the delay associated with waiting for processing and depends on the system state. The transmission delay is the time required to transmit the packet, which depends on the packet's length and the line speed. The maximum delay experienced by a packet traversing the firewall is the sum of the node delays along the path from the root to a leaf.

If it is assumed the packet arrival and processing (transmission and security task) rates are exponentially distributed, the node can be modeled as an M/M/1 queue [5, 17]. The firewall can then be considered an open network of M/M/1 queues, where probabilities are assigned to each link to indicate the likelihood of moving to the next node. This is a Jackson network model, which has a product-form solution for the average delay [5, 17]. The average end-to-end delay for N cascading nodes (traversal path) can be computed as

$$E(T) = \sum_{i=1}^{N} \frac{1}{\mu_i - \lambda_i} \quad (1)$$

where $1/\mu_i$ is the service time (processing and transmission) and λ_i is the arrival rate to node i. Figures 8A and 8B respectively illustrate Jackson models for hierarchical and data-parallel firewalls. In Figures 8A and 8B, it is assumed that the total arrival rate to each system is λ packets per unit time, each system implements the same R rule security policy, and each node can perform x rules per unit time. For the hierarchical firewall, shown in Figure 8A, the policy rules are evenly distributed to each node; therefore, the service rate is $3x/R$ per node. The traffic arrival rate to node A is λ packets per unit time, half of the packets are forwarded to node B, while the other half is forwarded to node C. Although not considered in this example, some traffic may be forwarded into the secure network or dropped by node A; therefore in this case, the sum of the rates to nodes B and C would be less than λ. Using these values, the average end-to-end delay for either path in the hierarchical firewall is

$$E_h(T) = \frac{1}{\frac{3x}{R} - \lambda} + \frac{1}{\frac{3x}{R} - \frac{\lambda}{2}} \quad (2)$$

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For the data-parallel configuration, illustrated in Figure 8B, traffic arrives at the packet distributor, which evenly distributes the traffic to each node. Each node implements the complete rule set *R*; therefore, the service rate is *x/R*. The end-to-end delay across any node in the data-parallel firewall is

$$E_p(T) = \frac{1}{\frac{x}{R} - \frac{\lambda}{3}} \quad (3)$$

Using these models, the effect of increasing traffic load λ on the average end-to-end delay, for the two architectures is shown in Figure 9. For this example, the arrival rate λ ranged from 1 to 50 packets per unit time. The rule set *R* consisted of 240 rules, while *x* equaled 5000 rules per unit time. Each of the hierarchical nodes incurred an additional delay of five time units to compensate for inter-node transmission. As expected, the average delay increases as the network load increases for both architectures; however, the average delay is consistently lower for the hierarchical firewall. This is due to the decreased rule set per node and the reduced arrival rates for nodes B and C. The average is an upper bound for the hierarchical firewall. Allowing node A to forward packets to the secure network or to drop packets would reduce the load on the second level and decrease delays. The arrival rate is less per node in the data-parallel firewall; however, the system has a higher end-to-end delay because each node must implement the complete rule set. The theoretical results are consistent with the experimental results described above. These models provide an important tool for analyzing the effect of load and rule distribution on end-to-end delay. In addition to analytical results, simulation will be used to measure the performance of the hierarchical designs under various conditions.

Stateful Firewalls

Another aspect of the subject matter described herein includes a stateful hierarchical firewall. The preceding design is considered stateless, or static, since the security action taken is based solely on the packet currently inspected. A stateful firewall provides better security by tracking and controlling network flows (packets belonging to a particular network connection or

exchange) [16, 21, 22]. In one exemplary implementation, a stateful firewall can be achieved by storing state information concerning each flow in a table, and then according it with the security policy. For example, each time a TCP connection is established from the internal network to the external network, it is logged in a table. The table may contain the source and destination addresses, port numbers, sequencing information, and connection flags. Afterwards, packets arriving from the external network claiming to be part of an existing TCP connection can be checked against the table. If a packet belongs to an existing connection or exchange, it can be accepted. Otherwise, it is dropped. Table entries expire, if packets belonging to an exchange are not observed by the firewall over a period of time [21].

Therefore, a stateful firewall is dynamic and limits the hackers' opportunity to exploit certain services. The increased security does require additional memory and time for table manipulation, which is problematic for high-speed networks. Furthermore, the firewall must process all traffic arriving and departing the secure network to adequately maintain the connection tables 21]. To solve these problems, the proposed firewall system will be divided into two hierarchies, one for arriving traffic and another for departing traffic, as illustrated in Figure 10. In Figure 10, a stateful firewall system includes first and second hierarchical firewall subsystems **1000** and **1002** and a control node **1004**. First and second hierarchical firewall subsystems **1000** and **1002** may be function-parallel firewall systems including a plurality of firewall nodes with different rules distributed among different nodes as described above. In one exemplary implementation, hierarchical firewall subsystem **1000** may include at least two firewall nodes that implement different portions of a first firewall rule set. Similarly, hierarchical firewall subsystem **1002** may include at least two firewall nodes that implement different portions of a second firewall rule set. Firewall subsystem **1000** may filter packets entering the network. Firewall subsystem **1002** may filter packets departing from the network. Firewall subsystems **1000** and **1002** may share state information regarding connections established through the nodes within each system. Control node **1004** may store the state information and may be accessible by the nodes in hierarchical firewall subsystems **1000** and **1002.** Rules can be distributed to the

hierarchies and the designs can be optimized using the methods described in preceding section.

However, a new problem with the stateful model is the need to distribute state information across nodes. For example, nodes that scrutinize arriving traffic must be aware of any new connections permitted by nodes that inspect departing traffic. Furthermore, nodes must be informed of table entries that expire over time. To communicate state information, a central database machine, such as control node **1004**, may collect and distribute the information (table entries) to the appropriate nodes. In one exemplary implementation, control node **1004** may not perform table queries on behalf of nodes. Individual nodes will only query their local tables, which prevents the central machine from becoming a bottleneck. In addition, the central machine will only send information (table entries) to nodes that might require it. As a result of this policy, the table searched by an individual node is reduced (contains only relevant information) as well as the search time. In an alternate implementation, control node **1004** may store the connection table and may perform queries for packets received by firewall subsystems **1000** and **1002**.

Survivability and Firewall Grids

Another aspect of the subject matter described herein focuses on increasing the survivability of the hierarchical design. Although the proposed design has the benefit of increased packet throughput and minimal delay, the reliability of the system is decreased, since more machines (nodes) are deployed. For example, if the highest level node fails (is unable to inspect more traffic or goes off-line), then the entire hierarchy is unable to process packets. For this reason, the hierarchy is considered an n of n system, where all *n* machines must be functioning for the system to operate correctly [4, 12].

Survivability of the system can be improved with the use of redundant (parallel) nodes at different levels. For example, the first level may include multiple machines in parallel, where each machine implements the same security task (e.g., an IP check). An arriving packet would be sent to only one of the parallel machines, where it would be accepted, dropped, or forwarded to the next level for further processing. If one of the parallel nodes fails, then the

remaining nodes can process the traffic. An additional benefit of parallel processing is the equal distribution of traffic among nodes, which can result in higher throughput and lower delays. Details such as where to locate parallel nodes and the number of machines required for each parallel configuration may depend on the desired degree of reliability versus cost of deploying redundant machines.

Yet another aspect of the subject matter described herein includes a grid of configurable firewalls (nodes) that can be used to efficiently process traffic, while being highly available. In one exemplary implementation, the grid may include a network of highly interconnected nodes (possibly via a high-speed switch or router) that can be logically deployed in various configurations (e.g., parallel, hierarchical, or hybrid). The advantage of the firewall grid is its ability to quickly adapt to new demands. When security needs change (e.g., due to policy changes, increased traffic volume, or node failure), these machines can be deployed or configured to maintain throughput and QoS requirements. For example, in a logical hierarchy, if a higher level encounters an increased traffic load, less frequently used redundant machines at lower levels can be reconfigured to process packets at the higher level. Unlike the hierarchical model, physical changes are not required, since all the machines are interconnected. Only the logical connection between nodes must be updated, which can be performed quickly. Like the stateful hierarchical firewall, the initial grid model will use a central machine to coordinate node configuration and communication. This central machine will play an important role in the system (balancing processing demand per node) and may constrain the efficiency of the firewall grid. Future versions of the firewall grid will attempt to place more intelligence in the nodes and allow them to interact independently and adapt dynamically under the guidance of a general security policy.

Figures 11A and 11B illustrate an example of a firewall grid according to an embodiment of the subject matter described herein. Referring to Figure 11A, a plurality of firewall nodes **1100**-**1114** are connected via a control node **1116**. Each firewall node **1100**-**1114** may be configured to implement different portions of a firewall rule set, as controlled by control node **1116**. Each of the firewall nodes is physically connected to the other firewall nodes via physical

connections **1118**. Physical connections **1118** may be local area network connections, such as Ethernet connections. As such, control node **1116** may be an Ethernet switch.

In Figure 11B, firewall nodes **1100-1114** are connected via logical connections **1120**. Logical connections **1120** may be implemented by control node **1116** without changing physical connections **1118**. For example, control node **1116** may configure the output port to which firewall **1106** is connected to receive frames from firewalls **1100**, **1102**, and **1104**. Similar internal configurations can be implemented for the remaining firewalls illustrated in Figure 11B. In Figure 11B, logical connections **1120** between the firewalls implement a hierarchical, function-parallel firewall design, such as that illustrated in Figure 1. In addition, the design illustrated in Figure 11B is also data-parallel at each level. For example, each firewall node at each level may implement a common rule or rule set. For example, the rule set implemented by the firewall nodes in level 1 is illustrated in Figure 11B as R1. The firewall nodes in level 2 implement a rule set represented by R2, and the firewall nodes in level 3 implement a rule set represented by R3. If any of the firewall nodes in a given level fails, the remaining firewall nodes in that level may take over operation for the failed firewall. Alternatively, as described above, if a failure or a bottleneck occurs at one level, a less-used firewall at another level may be logically configured to operate at the level where the failure or congestion occurred. Packet distributors **1122** may be configured to distribute the firewall rules between the firewalls at each level. Thus, as illustrated by Figures 11A and 11B, logical connections between firewall nodes and a firewall grid may be dynamically altered (i.e., changed on the fly without ceasing packet filtering operation) by a controller node without changing the physical connections between the firewalls.

Firewall Implementation

In addition to the analytical models and simulations described above, an implementation of a hierarchical firewall to measure performance will now be described. One exemplary implementation may utilize Linux-based PCs and Ethernet connections. Each PC will contain multiple Ethernet cards and be

loaded with the Linux 2.4 kernel. The 2.4 kernel has support for various packet queueing disciplines, traffic control methods, and packet processing (e.g., iproute2, tc, and iptable). Collectively, these functions are required for advanced packet filtering. For example, iproute2 and iptable can route packets based on information other than the destination address, while tc can mark and shape traffic. PCs will serve as hierarchical nodes, sources and receivers of network traffic, and hierarchy controllers.

Results from an initial implementation of a three-node hierarchical firewall indicate that these open-source components are suitable for high-speed networks. The Computer Science Department at Wake Forest University has 10 PCs available for this project, where each has a 600 Mhz processor and multiple 100 Mbps Ethernet cards. These machines will serve as an initial testbed for system development; however, faster machines and high-speed network connections are required for actual system testing. For this reason, this project requests the purchase of 6 additional PCs (2.4 Ghz processors), each with multiple Gigabit Ethernet cards (3 cards per machine). These new machines will be configured as the firewall, while the current machines will serve as traffic generators and receivers. For comparison purposes, parallel and single-machine firewalls will also be implemented using this equipment. Any software required will be developed and provided by the Computer Science Department.

Firewall Rule Distribution for Function-Parallel Firewall Design

As stated above, one aspect with creating an optimal function-parallel firewall design includes distributing rules among firewalls in the firewall rule set. Firewall rules are preferably distributed among firewall nodes in a manner that preserves firewall policy integrity. The following sections describe an exemplary firewall rule set and different options for distributing the firewall rule set among firewall nodes in a function-parallel firewall design.

Firewall Policy

In this section and the following sections, a rule r is modeled as an ordered tuple of sets, $r = (r[1], r[2], ..., r[k])$. Order is necessary among the tuples since comparing rules and packets requires the comparison of

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corresponding tuples. Each tuple $r[l]$ is a set that can be fully specified, specify a range, or contain wildcards '*' in standard prefix format. For the Internet, security rules are commonly represented as a 5-tuple consisting of: protocol type, IP source address, source port number, IP destination address, and destination port number [21, 22]. For example, the prefix 192.* would represent any IP address that has 192 as the first dotted-decimal number. Given this model, the ordered tuples can be supersets and subsets of each other, which forms the basis of precedence relationships. In addition to the prefixes, each filter rule has an action, which is to accept or deny. However, the action will not be considered when comparing packets and rules. Similar to a rule, a packet (IP datagram) d can be viewed as an ordered k-tuple $d = (d[1], d[2], ..., d[k])$; however, ranges and wildcards are not possible for any packet tuple.

Using the previous rule definition, a standard security policy can be modeled as an ordered set (list) of n rules, denoted as $R = \{r_1, r_2, ..., r_n\}$. A packet d is sequentially compared against each rule r_i starting with the first, until a match is found ($d \Rightarrow r_i$) then the associated action is performed. A match is found between a packet and rule when every tuple of the packet is a subset of the corresponding tuple in the rule.

Definition Packet d matches r_i if

$$d \Rightarrow r_i \text{ iff } d[l] \subseteq r_i[l],\ l = 1, ..., k$$

The rule list R is comprehensive if for every possible legal packet d a match is found using R. Furthermore, two rule lists R and R' are equivalent if for every possible legal packet d the same action is performed by the two rule lists. If R and R' are different (e.g. a reorder) and the lists are equivalent, then the policy integrity is maintained.

As described above, a rule list has an implied precedence relationship where certain rules must appear before others if the integrity of the policy is to be maintained. Table 2 shown below illustrates an exemplary rule set that will be used herein to illustrate precedence relationships and rule assignment according to an embodiment of the subject matter described herein.

No.	Proto.	Source		Destination		Action	Prob.
		IP	Port	IP	Port		
1	UDP	1.1.*	*	*	80	deny	0.01
2	TCP	1.*	*	1.*	90	accept	0.02
3	TCP	2.*	*	2.*	20	accept	0.25
4	UDP	1.*	*	*	*	accept	0.22
5	*	*	*	*	*	deny	0.50

Table 2: Example Security Policy Consisting of Multiple Ordered Rules

In Table 2, rule r_1 must appear before rule r_4, likewise rule r_5 must be the last rule in the policy. If for example, rule r_4 was moved to the beginning of the policy, then it will shadow [23] the original rule r_1. Shadowing is an anomaly that occurs when a rule r_j matches a preceding rule r_i, where $i < j$. As a result of the relative order r_j will never be utilized. However, there is no precedence relationship between rules r_1, r_2, or r_3 given in Table 2. Therefore, the relative order of these three rules will not impact the policy integrity and can be changed to improve firewall performance.

As described in [28], the precedence relationship between rules in a policy can be modeled as a Policy Directed Acyclical Graph (DAG). Let $G = (R,E)$ be a *policy DAG* for a rule list R, where vertices are rules and edges E are the precedence relationships (constraint). A precedence relationship, or edge, exists between rules r_i and r_j, if $i < j$ and the rules intersect [28].

Definition The intersection of rule r_i and r_j, denoted as $r_i \cap r_j$ is

$$r_i \cap r_j = (r_i[l] \cap r_j[l]),\ l = 1, \ldots, k$$

Therefore, the intersection of two rules results in an ordered set of tuples that collectively describes the packets that match both rules. The rules r_i and r_j intersect if every tuple of the resulting operation is non-empty. In contrast, the rules r_i and r_j do not intersect, denoted as $r_i \not\cap r_j$, if at least one tuple is the empty set. It should be noted that the intersection operation is symmetric; therefore, if r_i intersects r_j, then r_j will intersect r_i. The same is true for rules that do not intersect.

For example, for the rules given in Table 2, the intersection of r_1 and r_4 yields (UDP, 1.1.*, *, *, 80). Again, the rule actions are not considered in the

intersection or match operation. Since these two rules intersect, a packet can match both rules for example d = (UDP, 1.1.1.1, 80, 2.2.2.2, 80). The relative order must be maintained between these two rules and an edge drawn from r_1 to r_4 must be present in the DAG, as seen in Figure 12. In Figure 12, the policy DAG represents the rules in Table 2. Vertices **1200** indicate rules while edges **1202** indicate precedence relationships. Rules r_2 and r_3 in Table 2 provide an example of rules that can be re-ordered without changing the firewall policy. These two rules do not intersect due to the fifth tuple (destination port). A packet cannot match both rules indicating the relative order can change; therefore, an edge will not exist between them.

As described above, traditional firewall implementations consist of a single, dedicated machine, similar to a router, that applies the rule set to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [15, 18, 22]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [21]. Successfully handling these traffic loads becomes more difficult as rule sets become more complex [4, 14, 22]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 7, 10, 11]. Building a faster single firewall is possible [8, 15, 18, 19, 20]; however, the benefits are temporary (traffic loads and interface speeds are increasing); it is not scalable; it is a single point of failure; and it is generally not cost-effective for all installations.

Parallelization has been demonstrated to offer a scalable approach for improving the performance of network firewalls. As seen in Figure 13A, parallel designs consist of multiple firewalls, referred to as firewall nodes, connected in an array. In Figure 13A, firewall nodes **1300** each implement a common rule set. A packet distributor **1302** load shares packets among firewall nodes **1300**. In Figure 13B, a function-parallel design is illustrated where firewall nodes **1304** implement different portions of a firewall rule set. A packet duplicator **1306** duplicates each packet to each firewall node. A gate **1308** controls packets entering the network based on control information received from firewall nodes

1304. The operation of the system illustrated in Figure 13B will be described in more detail below.

The two designs depicted in Figures 13A and 13B are different based on what is distributed: packets or rules. For example, the design developed by Benecke et al consisted of multiple identical firewall nodes connected in parallel, as shown in Figure 13A. Each firewall node implements the complete security policy *R*, and arriving packets are distributed across the firewall nodes for processing (one packet is sent to one firewall node) [4]; therefore different packets are processed in parallel. Using terminology developed for parallel computing, this design is considered data-parallel since the data (packets) is distributed across the firewall nodes [25]. How the load-balancing algorithm distributes the packets is vital to the data-parallel system and typically implemented as a specialized high-speed switch [11, 12]. Although data-parallel firewalls have been shown to achieve higher throughput than traditional firewalls and have a redundant design [4], they suffer from two major disadvantages. First, these designs have difficulty maintaining QoS across networks. For example, legitimate traffic can encounter delays if it is queued behind traffic that requires more processing. Under these circumstances, users notice poor network performance, which is a growing concern as more network applications require QoS assurances. Second, stateful inspection requires all traffic from a certain connection or exchange to traverse the same firewall node, which is difficult to perform at high speeds using the data-parallel approach [4, 14].

Rule Distribution and Function-Parallel Firewall

As described above, new scalable firewall designs are needed to cope with increasing traffic loads, network speeds, and security threats. To address these issues, one implementation of the subject matter described herein includes a firewall design that consists of multiple firewalls connected in parallel and a gate machine, as shown in Figure 13B. Again in this design, the individual firewalls will be referred to as firewall nodes. However unlike the data-parallel design that distributes the packets, the function-parallel design distributes the policy rules across the firewall nodes. The distribution is done such that policy integrity is maintained. Therefore, a single traditional firewall

and a function-parallel firewall will always give the same result for any packet. The rules distributed to a firewall node will be referred to as the local rule set or local policy. Using parallel computing terminology this design will be referred to as function-parallel, since the rules are distributed across the firewall nodes [25].

The general operation of one exemplary function-parallel system can be described as follows. When a packet arrives to the function-parallel system, the packet is forwarded to every firewall node. Each firewall node processes the packet using its local rule list. The firewall node then signals the gate indicating either no match was found or provides the rule number and action if a match was found. Therefore, no match is a valid response and is required for this basic function-parallel design. The gate keeps track of the results and determines the final action to perform on the packet. For example, a first match policy can be implemented by applying the action of the lowest numbered matching rule to the packet.

The performance of this basic design can be improved by allowing the firewall nodes to pipeline packets [25]. For example, once a firewall node has completed processing a packet, it can immediately begin processing the next packet. This allows the firewall nodes to work independently, thus increasing the overall system performance. However, pipelining requires the gate to keep track of multiple packets simultaneously. Performance can also be increased if the gate can signal the firewall nodes that further processing of a certain packet is no longer needed (similar to short-circuit evaluation). This occurs when the appropriate match has been found by a firewall node before the other firewall nodes have completed processing the same packet. Short-circuit evaluation requires the gate to know how the rules are distributed as well as the dependencies, which is discussed in detail below.

The function-parallel design has several significant advantages over traditional and data-parallel firewalls. First, the function-parallel design results in the faster processing since every firewall node is utilized to process a single packet. Reducing the processing time, instead of the arrival rate (the data-parallel paradigm), yields better performance that will be proven theoretically and demonstrated experimentally. Second, unlike the data-parallel design, function-parallel can maintain state information about existing connections.

Maintaining state can be viewed as the addition of a new rule corresponding to a requested connection. Unlike the data-parallel design, the new rule can be placed in any firewall node since a packet will be processed by every firewall node. Third, the function-parallel design has the unique ability to provide service differentiation between classes of traffic; therefore, the design can provide QoS requirements. Finally, the function-parallel system can be implemented using any current firewall system (as discussed below, the gate can be removed), without any specialized hardware. The disadvantage of the system is the limited scalability, since the system cannot have more firewall nodes than rules, unless data-redundancy is provided. However, given the size of most firewall policies range in the thousands to hundred of thousands of rules, which is expected to increase, the scalability limit is not an important concern.

The operation and performance of the function-parallel design depends on the correct distribution of policy rules. Rule distribution techniques that maintain integrity, increase processing speed, allow redundancy and robustness, and eliminate the gate are described in the following sections.

Rule Distribution and Policy Integrity

As described above, the function-parallel design distributes the security policy rules across an array of firewall nodes. Using this design, all the firewall nodes process an arriving packet in parallel using its local rule set. The rules must be distributed such that the integrity of the policy is maintained. Again, it will be assumed in the examples described herein that a first-match policy is desired. Therefore, the distribution of the rules must not introduce any anomalies into the original rule list, such as shadowing.

Let m be the number of firewall nodes in the system and j be a firewall node $j = 1...m$. Each firewall node has a local rule set that is a portion of the security policy. Denote the local rule list for firewall node j as R_j that has n_j rules. The firewall node will process an arriving packet using the local rule list in a top-down fashion to find the first match. It should be noted that a software implementation of the firewall node according to the subject matter described herein is not required to have a rule list. The function-parallel design is independent of software implementation. In this scenario integrity is maintained

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under two conditions: every rule is assigned to at least one firewall node, and a policy DAG edge never traverses upward within a firewall node. The first condition assures every rule in the original policy exists in the function-parallel system, while the second condition prevents rule shadowing within a firewall node. Consider a two-firewall node system and the five-rule policy given in Table 2. Possible rule distributions are depicted in Figures 14A-14C. The distribution illustrated in Figure 14A will be referred to as vertical, while the distribution illustrated in Figure 14B will be referred to as horizontal. In both cases the five rules are present and all policy DAG edges are downward; thus integrity is maintained. In contrast, Figure 14C is an illegal distribution because rule r_4 shadows r_1 (upward policy DAG edge).

The gate can also utilize the policy DAG to determine the first match, and if a short-circuit evaluation can occur. For example consider the distribution illustrated in Figure 14A. Assume a packet matches r_3 in the second firewall node and this result is reported to the gate. Using the policy DAG, the gate can determine this is the first match, since it is impossible for a packet that matches r_3 to also match any rules that preceded it in the original policy (rules r_1 or r_2). The gate can inform the remaining firewall nodes to stop processing the packet.

Optimal Rule Distribution

The previous section described the distribution requirements for maintaining policy integrity. However it was proven in [27] that any linear arrangement of a policy DAG maintains integrity, which also holds for a local policy DAG. Furthermore as evident in the previous section, many different distributions are possible. Given the possible rule distributions for the function-parallel design, a distribution is sought that minimizes the average number of comparisons required per packet [27].

Achieving this goal will require information not present in the firewall rule list. Certain firewall rules have a higher probability of matching a packet than others. As a result, it is possible to develop a policy profile over time that indicates frequency of rule matches (similar to cache hit ratio). Let $P = \{p_1, p_2, ..., p_n\}$ be the policy profile, where p_i be the probability that a packet will match rule r_i (first match in the policy). Furthermore, assume a packet will always find

a match, $\sum_{i=1}^{n} p_i = 1$; therefore R is comprehensive. Using this information, the average number of rule comparisons required for the policy R using a standard single machine firewall is

$$E(R) = \sum_{i=1}^{n} i \cdot p_i \quad (4)$$

This equation also applies to firewall nodes. However, the rules of a local policy include rules of the original policy; therefore, a mapping between the local and original policy rules is needed. Let $r_{i,j}$ represent the ith rule of firewall node j, that corresponds a certain rule in the original rule list R. Consider the local rule list for the second firewall node depicted in Figure 14A. The local policy is $R_2 = \{r_4, r_5\}$, where $r_{1,2} = r_4$ and $r_{2,2} = r_5$. Similarly, let $p_{i,j}$ be the probability of matching the ith rule of firewall node j. Therefore the average number of comparisons required for firewall node j is

$$E(R_j) = \sum_{i=1}^{n_j} i \cdot p_{i,j} \quad (5)$$

Using the previous equation, the average number of comparisons required for the function-parallel system is

$$E_f(R) = \sum_{j=1}^{m} E(R_j) = \sum_{j=1}^{m} \sum_{i=1}^{n_j} i \cdot p_{i,j} \quad (6)$$

For example, the average number of comparisons required for the distribution given in Figure 14A is 2.24, while the average number of comparisons for the distribution given in Figure 14B is 2.45.

Given a policy DAG $G = (R,E)$ and policy profile P, a distribution is sought that minimizes Equation 6. In the absence of precedence relationships, the average number of comparisons is minimized if the rules are sorted in non-increasing order according to the probabilities [28], which is also referred to as Smith's algorithm [29]. The sorted rules are then distributed in a horizontal fashion, as depicted in Figure 14B. Precedence constraints cause the problem

to be more realistic; however, precedence constraints also make determining the optimal permutation more problematic. In [27] determining the optimal rule order for a single machine firewall is proven to be *NP*-complete; therefore, so is determining the optimal function-parallel rule distribution. However, [27] presents a simple sorting algorithm to improve the optimal order, that can be modified to apply to function-parallel rule distribution. This modified algorithm sorts the policy rules using the method described in [27], then distributes the rules in a horizontal fashion.

Redundancy

Similar to the traditional and data-parallel firewalls, a disadvantage of the current function-parallel design is its inability to withstand a single firewall node failure. If a single firewall node fails in the function-parallel system, then part of the policy is lost and integrity is not maintained. A simple solution commonly used for traditional firewalls is to duplicate the entire system; however, this solution is cost prohibitive, not efficient, and difficult to manage.

Redundancy can be provided in the function-parallel design by replicating rules, instead of firewall nodes. Consider the function-parallel system depicted in Figure 15A, that includes four firewall nodes and an eight-rule policy distributed in a horizontal manner. If the local rule list of the right neighbor is added to the end of every firewall node, as illustrated in Figure 15B, then any non-continuous firewall nodes can fail and integrity will be maintained. It should be noted that the criteria for maintaining integrity still apply: every rule must be implemented at a node and no upward edges in the local policy DAG. Furthermore, the redundant design requires short-circuit evaluations to prevent multiple firewall nodes from evaluating the same rule.

Gateless Design

The gate plays an important role in the function-parallel design. It accepts information from the firewall nodes to determine the correct action to apply to a packet. Unfortunately, the gate is a special device that must coordinate with the individual firewall nodes in the system, which may be problematic to implement. However, it is possible to eliminate the gate and allow the firewall nodes to operate independently without any coordination. The

significant advantage is that the gateless function-parallel design can be implemented with any firewall system (from open source to proprietary).

Eliminating the gate requires a rule distribution such that for any given packet, only one machine will ever accept and the remaining machines will always deny. As described above, rule actions are either accept or deny. This can be seen in the policy DAG by denoting deny rules with a square and accept rules with a circle. To assure only one machine will accept a packet, an accept rule in a firewall node cannot intersect with another accept rule in any other firewall node. As described above, the intersection of two rules describes the set of packets that can match both rules. If an edge spans the local rules of firewall nodes, then the set of packets would be accepted by both firewall nodes; thus, duplicate packets would be accepted. In addition, every drop rule must be present in each firewall node to assure the remaining firewall nodes will drop the packet. Given these two requirements a policy DAG edge will not span firewall nodes, as illustrated in Figures 16B and 16C.

For example, consider a two-firewall node function-parallel system that implements the five-rule policy given in Table 2. The policy DAG is given in Figure 16A, where the first and last rules are deny. An initial gateless rule distribution is given in Figure 16B which has no edges spanning the firewall nodes. Given the local policy DAG, deny rules can be removed if: no inbound edges exist for the deny rule; and all out-going edges for the deny rule connect to a superset deny rule. Using these constraints, the first rule in the second firewall node depicted in Figure 16B can be removed (it is a subset of r_5 and has no other edges). This gives the final gateless rule distribution shown in Figure 16C. As a result, the first firewall node in this distribution will only process UDP traffic, while the second machine only processes TCP. The rules can be divided with respect to other tuples, and can be done to provide QoS guarantees.

Theoretical Results

Assuming arrivals and service times are exponentially distributed, a firewall system can be considered an open network of M/M/1 queues (Jackson network) [5, 17]. Probabilities can be assigned to each link to indicate the likelihood of moving to the next node, which are given from the policy profile (hit

ratio) described above. The average end-to-end delay for q cascading machines (traversal path) can be computed as

$$E(T) = \sum_{i=1}^{q} \frac{1}{\mu_i - \lambda_i} \tag{7}$$

where $1/\mu_i$ is the service time (processing and transmission) and λi is the arrival rate to node i. As a result, we have a theoretical model for the average delay across a firewall system. Consider the data-parallel and functional-parallel firewall designs given in Figures 13A and 13B. Assume each system consists of m machines and implements the same n rule security policy. Let the total arrival rate to each system be λ packets per unit time and each node performs x rules per unit time.

For the data-parallel firewall, traffic arrives at the packet distributor, which evenly distributes the traffic. As a result the arrival rate to each machine is λ m. The service rate is x n, since each node implements the complete rule set. The end-to-end delay across any machine in the parallel firewall is

$$E_d(T) = \frac{1}{\frac{x}{n} - \frac{\lambda}{m}} \tag{8}$$

In contrast, rules are distributed across each machine, in the function-parallel firewall. Furthermore, all traffic arriving to the system is forwarded to each machine. If we assume the rules in each machine are independent (no policy DAG edges spanning machines), then the end-to-end delay across any machine in the functional-parallel firewall is

$$E_f(T) = \frac{1}{\frac{m \cdot x}{n} - \lambda} \tag{9}$$

The reduction in delay compared to a data-parallel firewall system is 1 m; therefore, the functional-parallel system has the potential to be m times faster than a (data) parallel system. However, the scalability of the functional-parallel system is dependent on the rule set.

Figures 17A and 17B compare the performance of function-parallel, data-parallel, and single firewall designs. More particularly, Figure 17A compares the average among the different firewall designs as the arrival rate λ increases. As can be seen from Figure 17A, the function-parallel design achieves lower average delay as the arrival rate increases than the data-parallel design. Figure 17B illustrates the average delay as arrival rate and the number of rules increase. In Figure 17B, the function-parallel design again achieves better simulated performance than the data-parallel design.

Experimental Results

The previous section described models that provide insight to the average delay across different firewall designs. This information is beneficial in guiding initial design; however, we are also interested in the maximum delay encountered. For this reason, a discrete event simulator has been developed to model the different systems.

The data-parallel firewall and function-parallel firewall designs were simulated, where both systems implemented a 50-rule policy and each consisted of 5 firewall nodes. Three classes of traffic were modeled, first, second, and background. The first and second classes represent legitimate traffic that was eventually accepted by the firewall system, while background traffic was typically dropped. The two designs were simulated under normal conditions, where each traffic type had the same volume. Figures 18A and 18B shows the simulation results. As seen in Figure 18A and predicted by the theoretical models, the average delay encountered by packets in the functional-parallel design was lower than the data-parallel designs. The function-parallel design also provided lower maximum delays than the data-parallel, as seen in Figure 18B. In summary, the theoretical models and simulation results indicate function-parallel is a better design than a traditional single firewall system or a data-parallel system; yet, function-parallel requires no more computing resources than data-parallel.

Summary

Thus, as described above, the subject matter described herein includes methods, systems, and computer program products for providing a function-

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parallel firewall where different portions of a firewall rule set are distributed among different firewall nodes. Figure 19 is a flow chart illustrating exemplary steps of a process for filtering packets using a rule set distributed among firewall nodes in a function-parallel manner. Referring to Figure 19, in step **1900**, packet filtering rules of a rule set are distributed among nodes in a function-parallel manner so that different nodes implement different portions of the rule set. In step **1902**, packets to be filtered are replicated to each of the nodes. In step **1904**, the packets to be filtered are replicated to each of the nodes. In a hierarchical design, step **1904** may be implemented at each level in the hierarchy. If a packet passes or fails at one level, the packet may be forwarded into a network or dropped, depending on the distribution of the rule set. In step **1904**, the rules are applied to filter the packets.

The steps illustrated in Figure 19 and in all of the examples described herein may be applied to firewall systems that filter packets based on packet header information, intrusion detection systems that filter packets based on packet payload information, or intrusion protection systems that filter packets based on a combination of packet header and packet payload information.

In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

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The following references correspond to the citations in this document. The disclosure of each of these references is hereby incorporated herein by reference it its entirety.

5

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It will be understood that various details of the present subject matter may be changed without departing from the scope of the present subject matter. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

2005328336 29 Jun 2007

CLAIMS

What is claimed is:

1. A function-parallel firewall system comprising:
   (a) a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules, the first portion including less than all of the rules in the rule set; and
   (b) at least one second firewall node for filtering packets using a second portion of the rule set, the second portion including at least one rule in the rule set that is not present in the first portion, wherein the first and second portions together include all of the rules in the rule set, wherein the first and second firewall nodes are configured to implement a gateless design wherein the rules are distributed among the first and second firewall nodes such that for a given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet.
2. The function-parallel firewall system of claim 1 wherein the first and second portions respectively include rules present in first and second levels of a firewall hierarchy.
3. The function-parallel firewall system of claim 2 wherein the first and second firewall nodes are connected to each other such that the rules in the first level are applied to received packets before the rules in the second level.
4. The function-parallel firewall system of claim 3 wherein the first firewall node is adapted to forward packets that pass one of the rules in the first portion to an internal network in a manner that bypasses the second firewall node.
5. The function-parallel firewall system of claim 3 wherein the first firewall node is adapted to discard packets that fail one of the rules in the first portion.
6. The function-parallel firewall system of claim 3 wherein the rules in the second portion are more processor-intensive than the rules in the first portion.

7. The function-parallel firewall system of claim 1 wherein the first and second firewall nodes implement rules of the same hierarchical level.

8. The function-parallel firewall system of claim 1 wherein the first and second firewall nodes are adapted to simultaneously process copies of the same packets.

9. The function-parallel firewall system of claim 1 wherein the rule set includes intrusion detection rules for filtering packets based on packet payloads.

10. The function-parallel firewall system of claim 1 wherein the rule set includes intrusion protection rules for filtering packets based on a combination of packet headers and packet payloads.

11. The function-parallel firewall system of claim 1 wherein the first and second firewall nodes are components of a first firewall subsystem for filtering packets entering a network and wherein the system further comprises a second function-parallel firewall sub-system including a second set of firewall nodes implementing a second rule set for filtering packets departing from the network, wherein the second function-parallel firewall subsystem includes at least third and fourth firewall nodes, the third and fourth firewall nodes implementing first and second portions of the second rule set, the first portion of the second rule set including at least one rule that is not present in the second portion of the second rule set, wherein the first and second function-parallel firewall subsystems share state information regarding connections established through the first and second sets of firewall nodes.

12. The function-parallel firewall system of claim 1 wherein the first and second firewall nodes are components of a firewall grid with logically configurable interconnections between the firewall nodes.

13. A method for controlling access to a network based on a set of packet filtering rules distributed in a function-parallel manner, the method comprising:

(a) distributing packet filtering rules of a rule set among a plurality of different nodes in a function-parallel manner so that at least some of the different nodes implement different portions of the rule set;

(b) replicating packets to each of the nodes; and

(c) applying the rules to filter the packets using a gateless design wherein the rules are distributed among first and second firewall nodes such that for a given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet.

14. The method of claim 13 wherein the packet filtering rules comprise intrusion detection rules for filtering packets based on packet payload information.

15. The method of claim 13 wherein the packet filtering rules comprise intrusion protection rules for filtering packets based on a combination of packet header and packet payload information.

16. The method of claim 13 comprising, receiving a first packet at a first node, determining whether the packet matches a first rule implemented by the first node, and, in response to determining that a match occurs, notifying the other nodes of the match.

17. The method of claim 16 comprising, at the other nodes, ceasing processing of the first packet.

18. A computer program product comprising computer executable instructions embodied in a computer readable medium for performing steps comprising:

(a) a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules, the first portion including less than all of the rules in the rule set; and

(b) at least one second firewall node for filtering packets using a second portion of the rule set, the second portion including at least one rule in the rule set that is not present in the first portion, wherein the first and second portions together include all of the rules in the rule set, wherein the first and second firewall nodes are configured to implement a gateless design

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wherein the rules are distributed among the first and second firewall nodes such that for any given packet, one of the first and second firewall nodes will accept the packet and the other of the first and second firewall nodes will deny the packet

19. The method of claim 13, or computer program product of claim 18, wherein distributing the rules in the rule set among a plurality of firewall nodes comprises:

(a) assigning rules in the rule set to nodes and branches in a trie data structure, wherein each node in the trie data structure corresponds to a data field and each branch represents a value for each data field to be compared to values in corresponding fields in received packets; and

(b) pruning the trie data structure in a manner that preserves ordering of the rules in the rule set.

20. The method or product of claim 19 wherein pruning the trie data structure includes pushing a rule to its descendants and deleting the original rule.

21. The method or product of claim 19 comprising reducing the depth of the trie using level reordering.

22. The method or product of claim 19 wherein assigning rules in the rule set to nodes and branches in the trie data structure includes assigning rules requiring longer processing time to lower levels in the trie.

23. The method of claim 13 or computer program product of claim 18, wherein distributing the rules in the rule set among a plurality of firewall nodes comprises:

(a) assigning packet filtering rules to nodes in a directed acyclical graph (DAG);

(b) representing relationships between rules by edges in the DAG; and

(c) distributing the rules among the plurality of firewall nodes using the DAG such that different firewall nodes implement different rules and such that relationships between the rules specified in the DAG are

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preserved.

24. The method or product of claim 23, wherein distributing the rules among the plurality of firewall nodes using the DAG includes distributing the rules such that intersecting accept rules are not present in more than one firewall node.

25. The method or product of claim 23, wherein distributing the rules among the plurality of firewall nodes using the DAG includes distributing the rules such that the edges to not span multiple firewall nodes.

26. The method or product of claim 23, wherein distributing the rules among the plurality of firewall nodes using the DAG includes replicating deny rules in each of the firewall nodes.

27. The method or product of claim 26, comprising eliminating a deny rule implemented by a first firewall node in response to determining that the deny rule for the first firewall node includes no inbound edges and outbound edges from the first deny rule terminate only in a superset deny rule.

28. A function-parallel firewall system, a method for controlling access to a network, or a computer program product, substantially as herein described with reference to Figures 2 to 19.

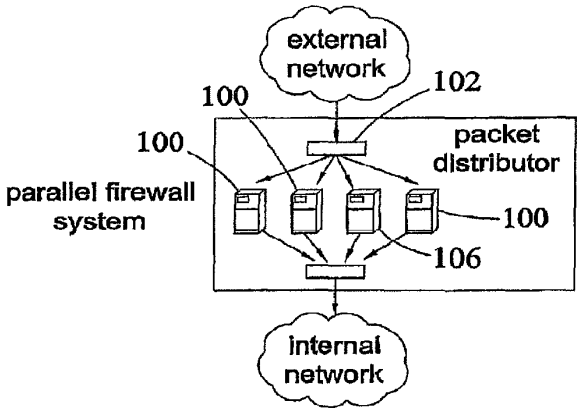


FIG. 1
(PRIOR ART)

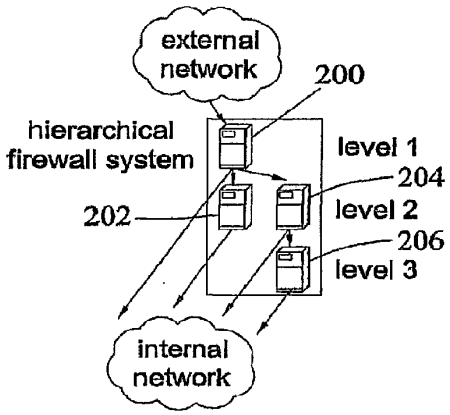

external network
200
hierarchical firewall system
level 1
204
level 2
202
206
level 3
internal network

FIG. 2

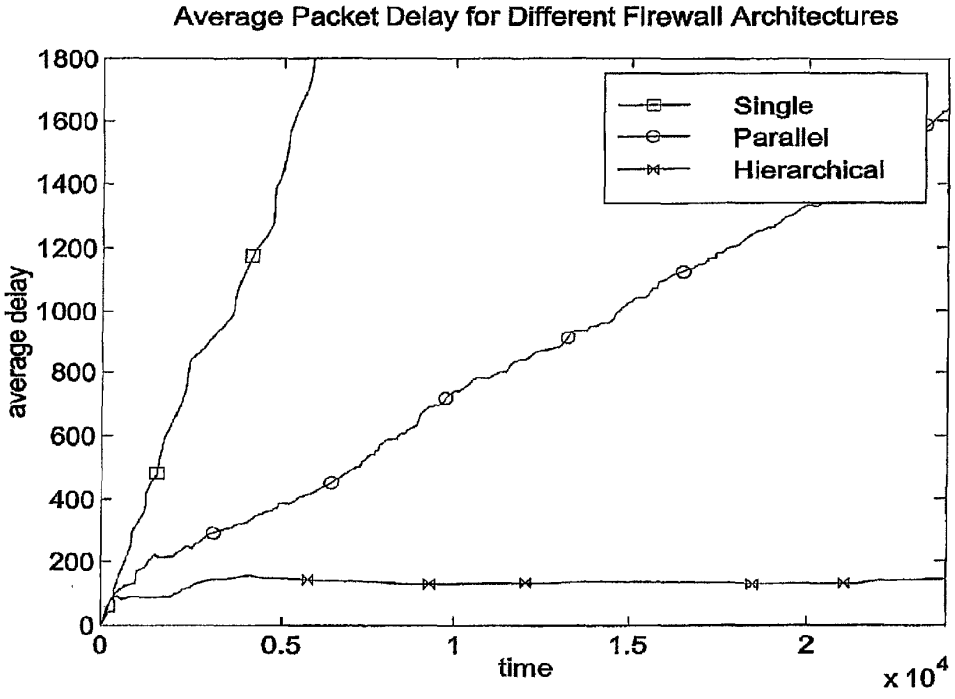

Average Packet Delay for Different Firewall Architectures
average delay
time
x 10^4
Single
Parallel
Hierarchical
0
200
400
600
800
1000
1200
1400
1600
1800
0
0.5
1
1.5
2

FIG. 3A

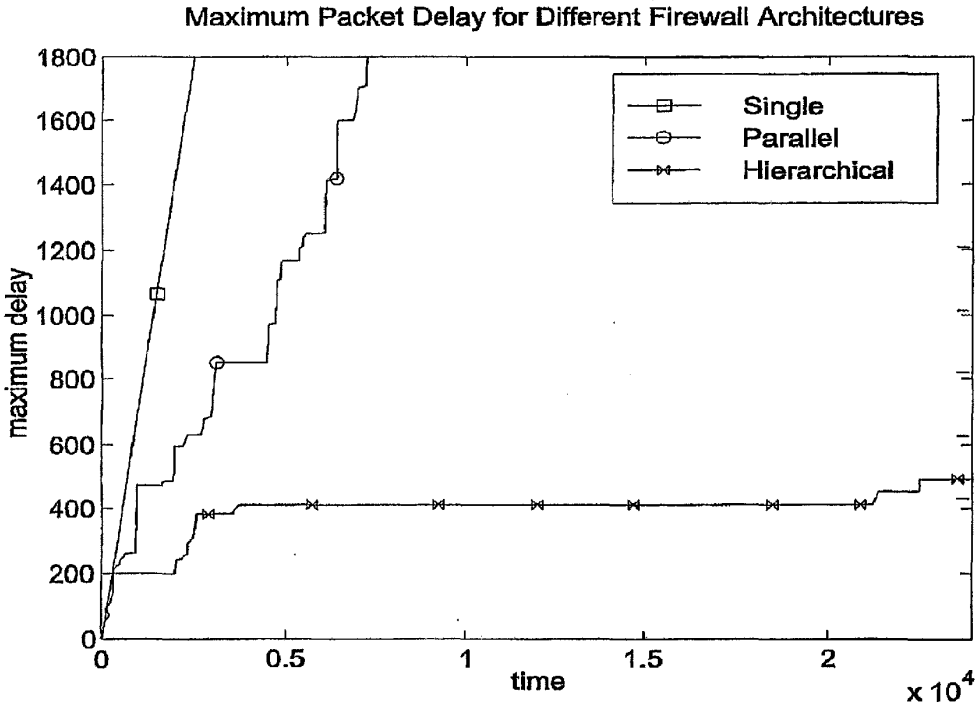

Maximum Packet Delay for Different Firewall Architectures
maximum delay
time
x 10^4
Single
Parallel
Hierarchical
0
200
400
600
800
1000
1200
1400
1600
1800
0
0.5
1
1.5
2

FIG. 3B

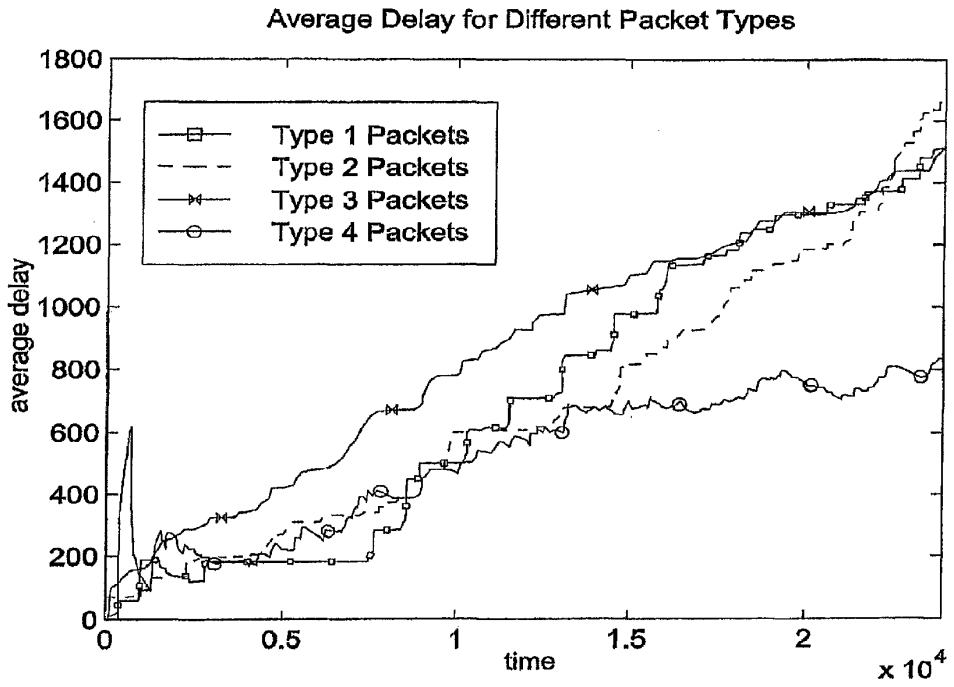

Average Delay for Different Packet Types
Type 1 Packets
Type 2 Packets
Type 3 Packets
Type 4 Packets
average delay
time
x 10^4
0
200
400
600
800
1000
1200
1400
1600
1800
0.5
1
1.5
2

FIG. 4A

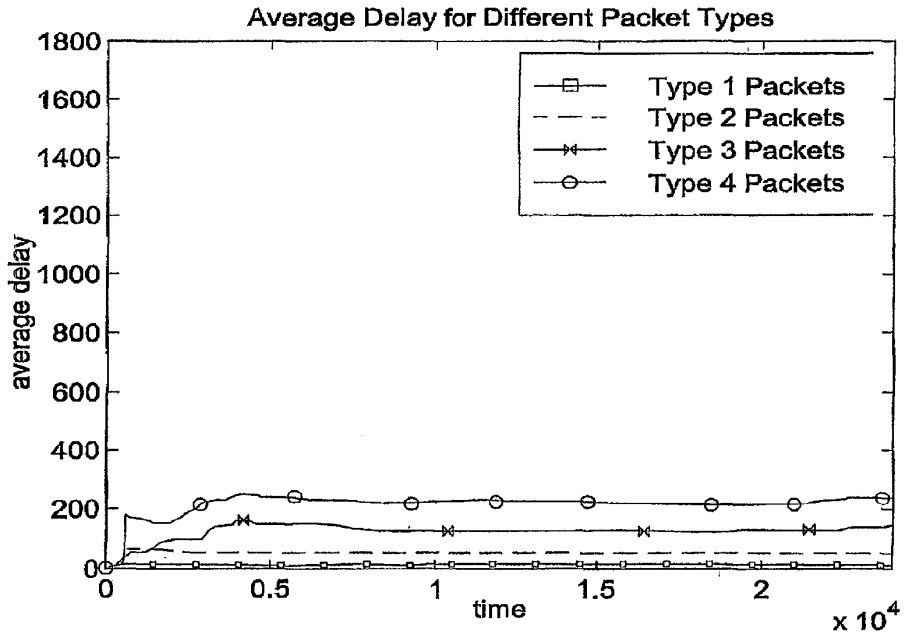

Average Delay for Different Packet Types
Type 1 Packets
Type 2 Packets
Type 3 Packets
Type 4 Packets
average delay
1800
1600
1400
1200
1000
800
600
400
200
0
0
0.5
1
1.5
2
time
x 10^4

FIG. 4B

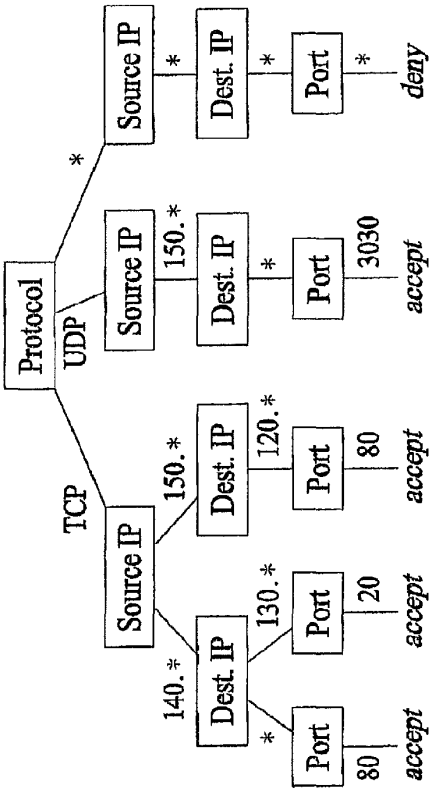

Protocol
TCP
UDP
Source IP
140.*
150.*
Dest. IP
130.*
120.*
Port
80
20
3030
*
accept
deny

FIG. 5

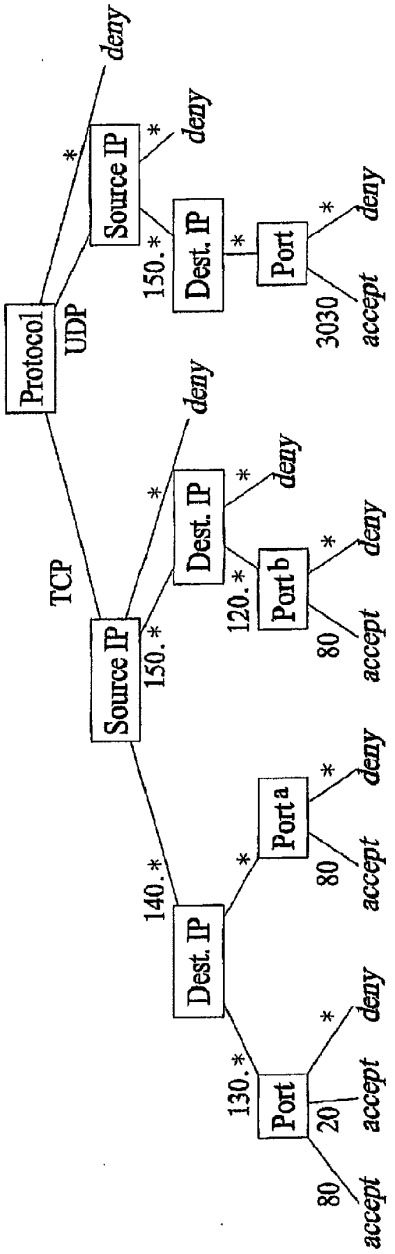

Protocol
TCP
UDP
Source IP
140.*
150.*
Dest. IP
130.*
120.*
Port
Port a
Port b
80
20
3030
*
accept
deny

FIG. 6

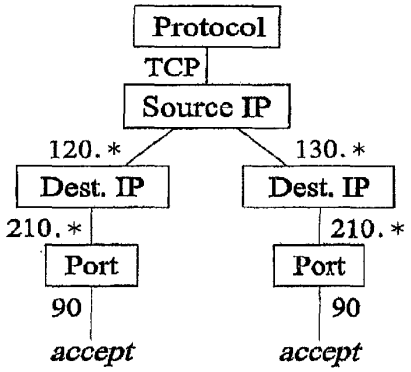

Protocol
TCP
Source IP
120.*
130.*
Dest. IP
Dest. IP
210.*
210.*
Port
Port
90
90
accept
accept

FIG. 7A

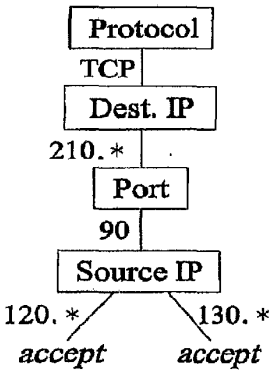

Protocol
TCP
Dest. IP
210.*
Port
90
Source IP
120.*
130.*
accept
accept

FIG. 7B

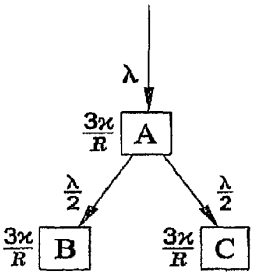

λ
3κ/R
A
λ/2
λ/2
3κ/R
B
3κ/R
C

FIG. 8A

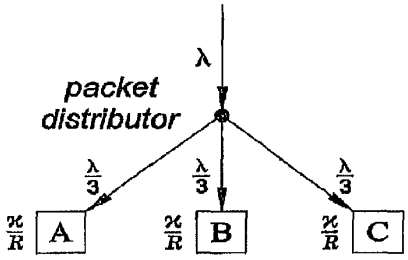

λ
packet distributor
λ/3
λ/3
λ/3
κ/R
A
κ/R
B
κ/R
C

FIG.8B

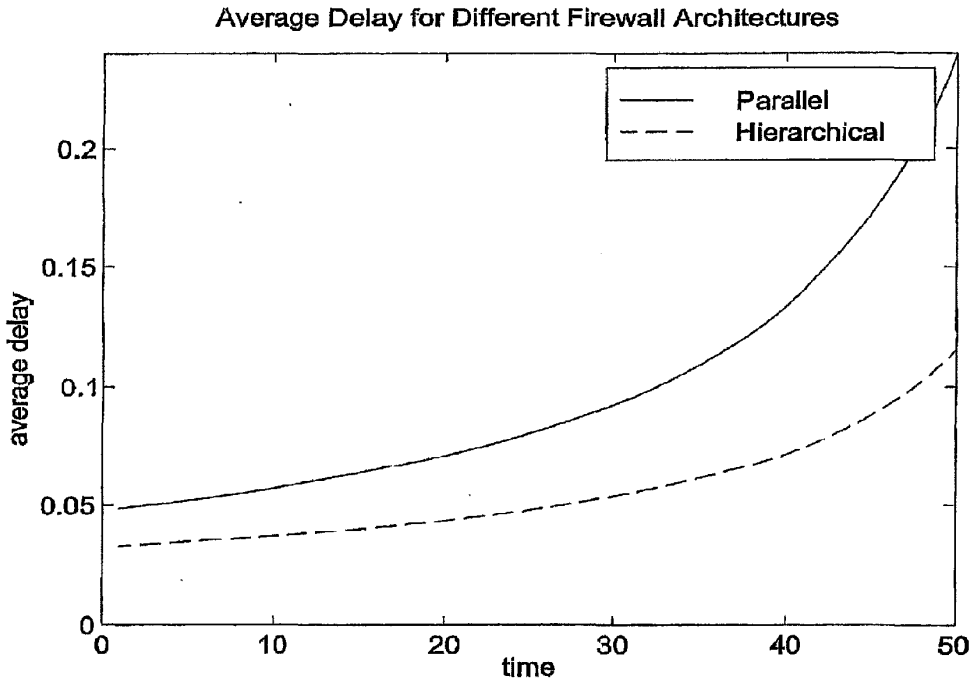

Average Delay for Different Firewall Architectures
Parallel
Hierarchical
average delay
0
0.05
0.1
0.15
0.2
0
10
20
30
40
50
time

FIG. 9

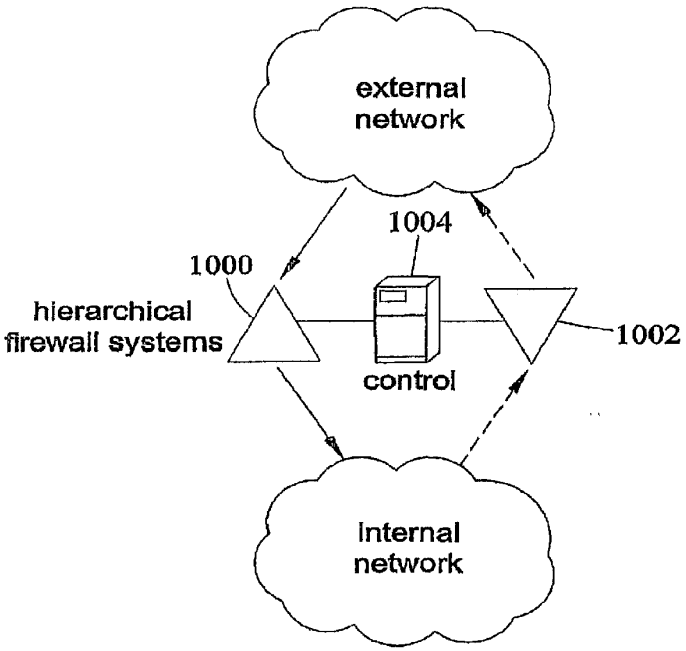

external network
1004
1000
hierarchical firewall systems
1002
control
internal network

FIG. 10

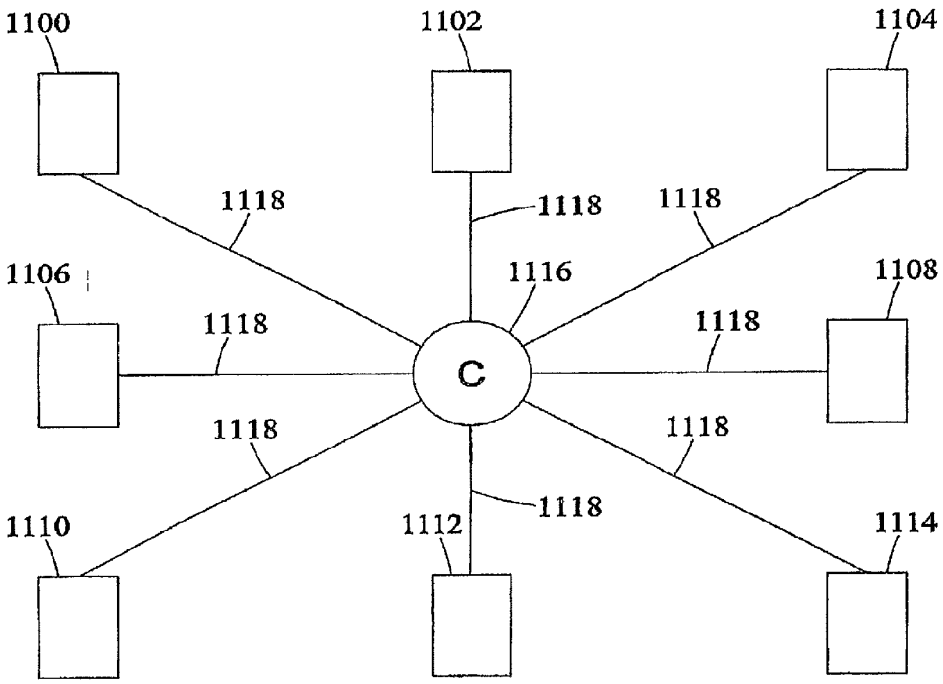

1100
1102
1104
1118
1118
1118
1106
1116
1108
1118
1118
C
1118
1118
1110
1112
1118
1114

FIG. 11A

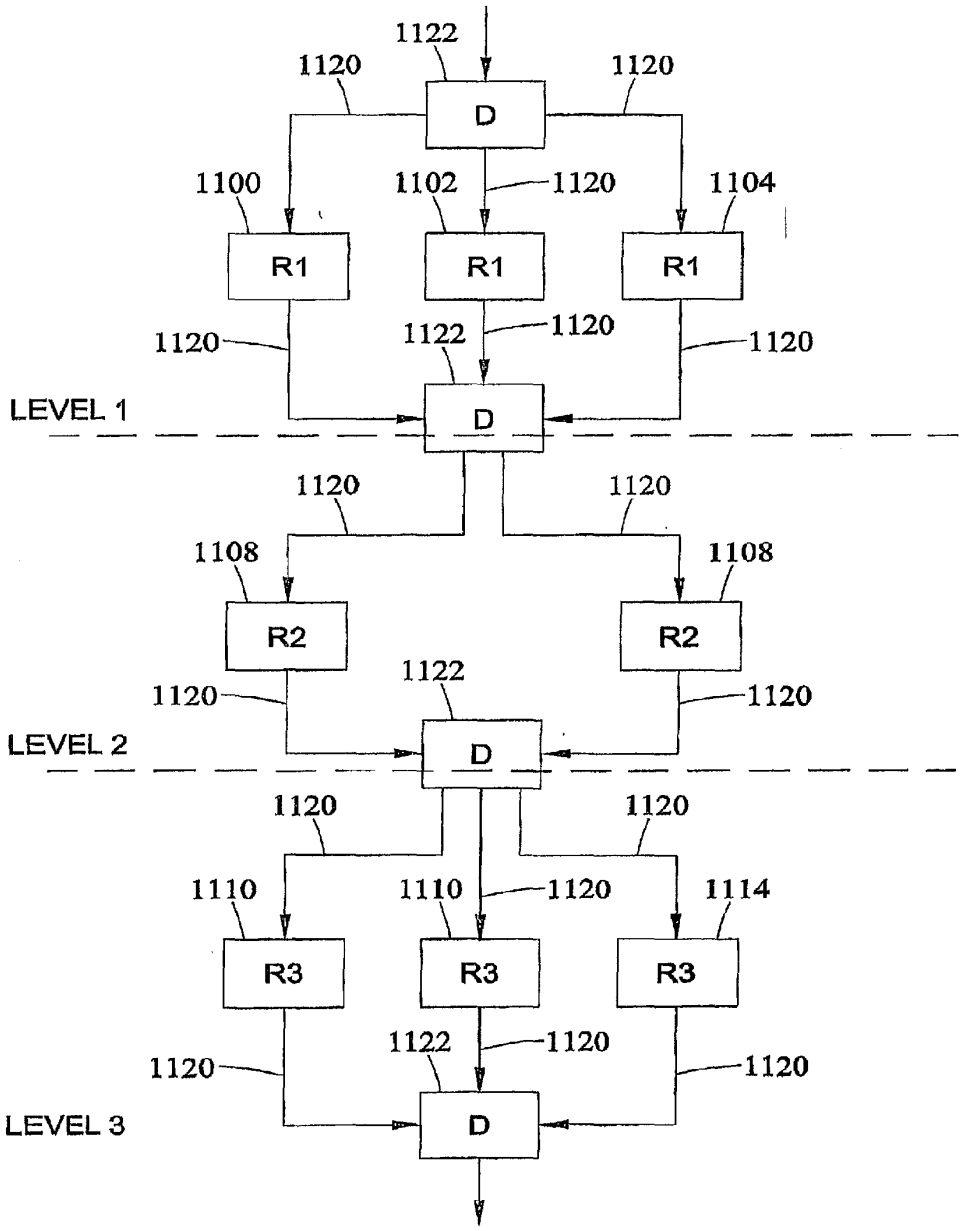

1122
1120
1120
D
1100
1102
1120
1104
R1
R1
R1
1120
1122
1120
1120
LEVEL 1
D
1120
1120
1108
1108
R2
R2
1122
1120
1120
LEVEL 2
D
1120
1120
1110
1110
1120
1114
R3
R3
R3
1122
1120
1120
1120
LEVEL 3
D

FIG. 11B

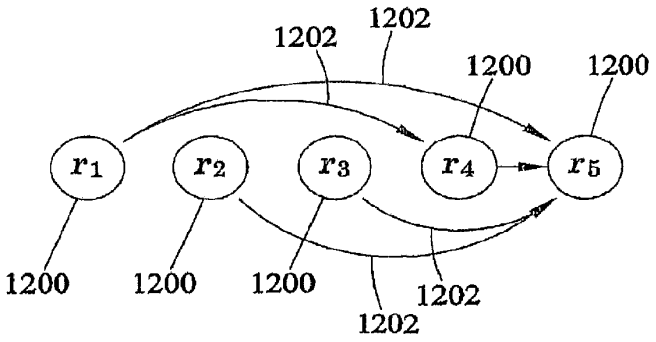


FIG. 12

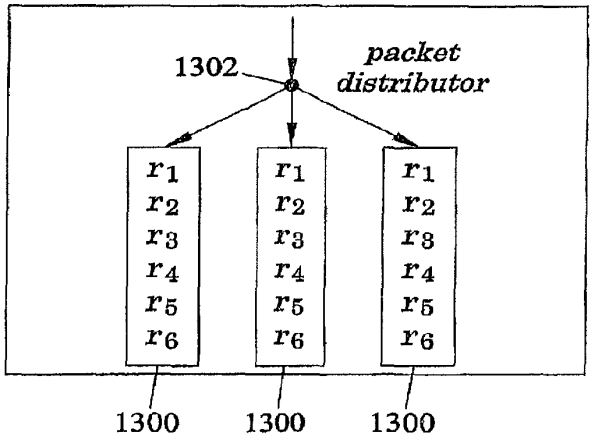


FIG. 13A

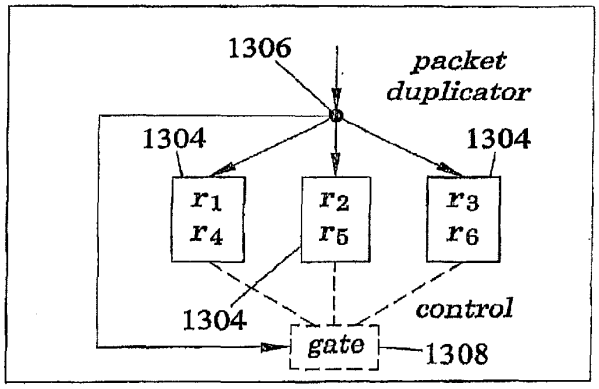


FIG. 13B

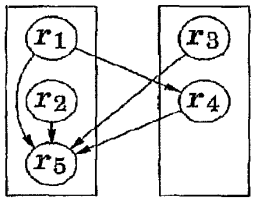


FIG. 14A

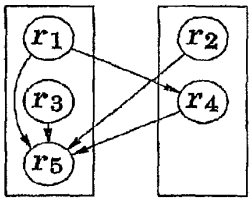


FIG. 14B

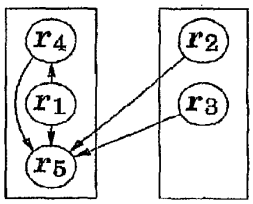


FIG. 14C

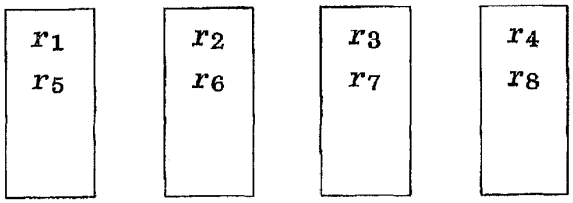


FIG. 15A

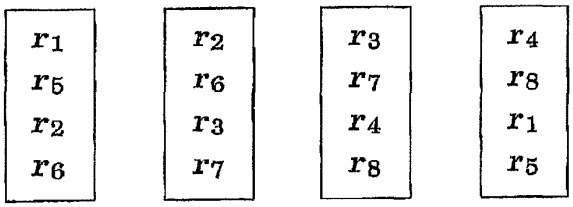


FIG. 15B

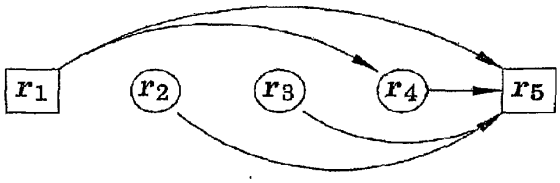


FIG. 16A

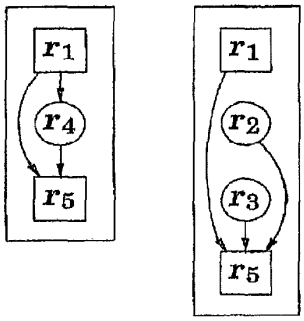


FIG. 16B

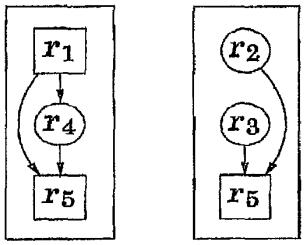


FIG. 16C

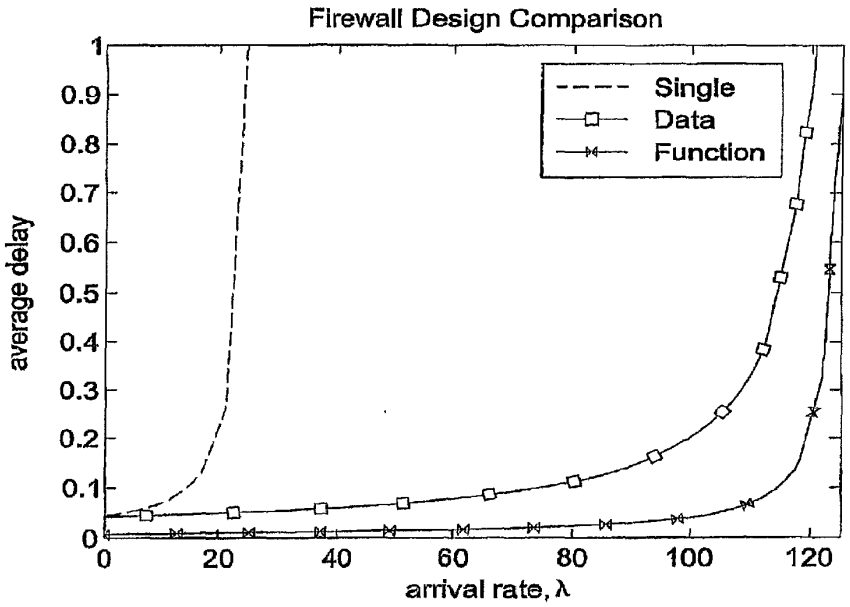

Firewall Design Comparison
Single
Data
Function
average delay
arrival rate, λ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

FIG. 17A

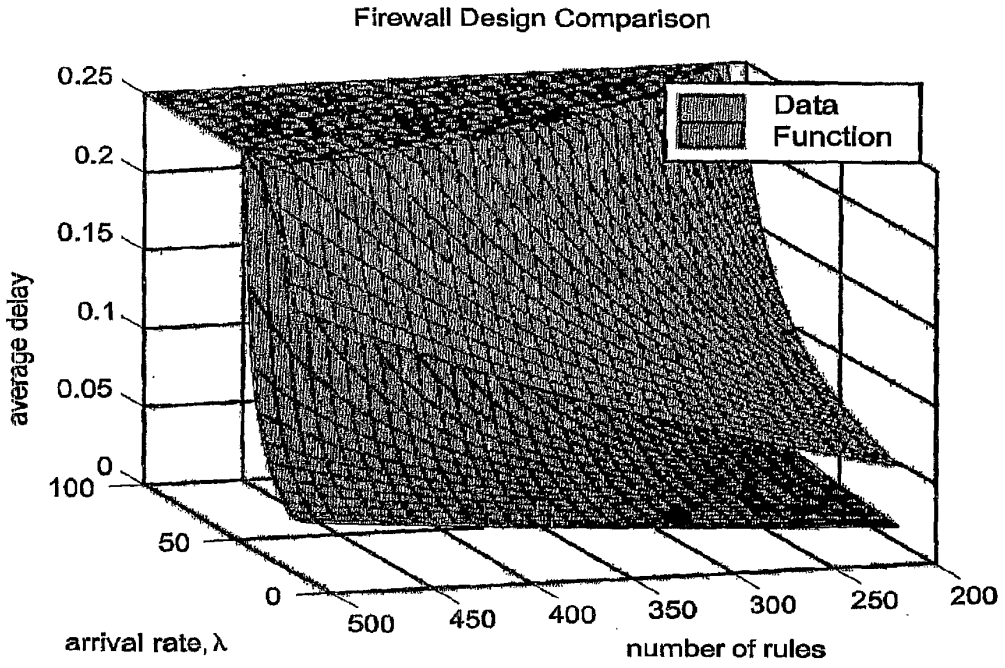

Firewall Design Comparison
Data
Function
average delay
0.25
0.2
0.15
0.1
0.05
0
100
50
0
arrival rate, λ
500
450
400
350
300
250
200
number of rules

FIG. 17B

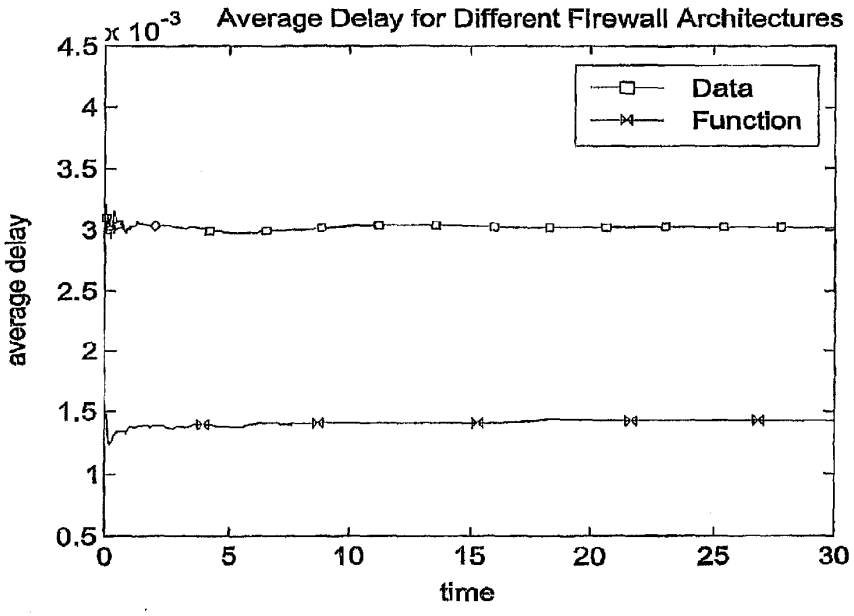

Average Delay for Different Firewall Architectures
x 10^-3
4.5
4
3.5
3
2.5
2
1.5
1
0.5
average delay
0
5
10
15
20
25
30
time
Data
Function

FIG. 18A

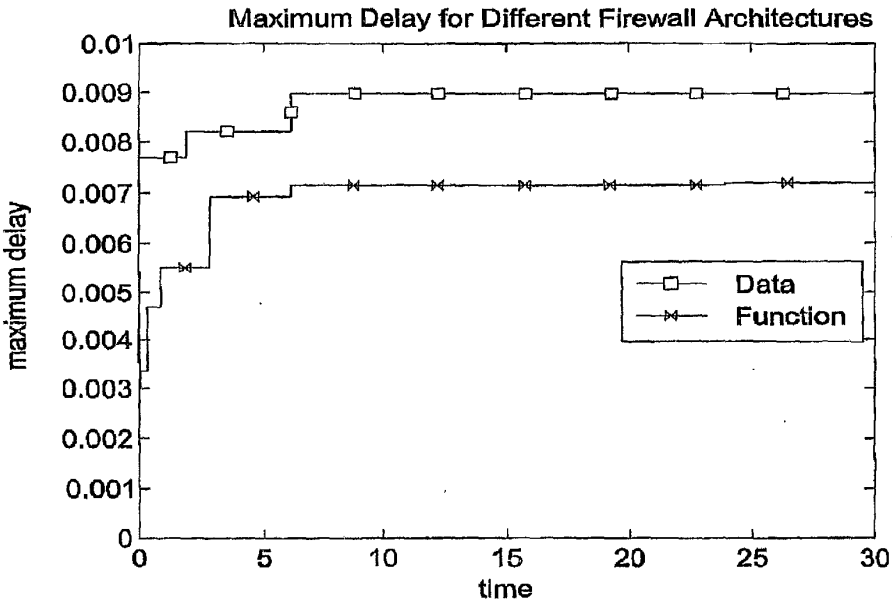

Maximum Delay for Different Firewall Architectures
maximum delay
time
Data
Function
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
5
10
15
20
25
30

FIG. 18B

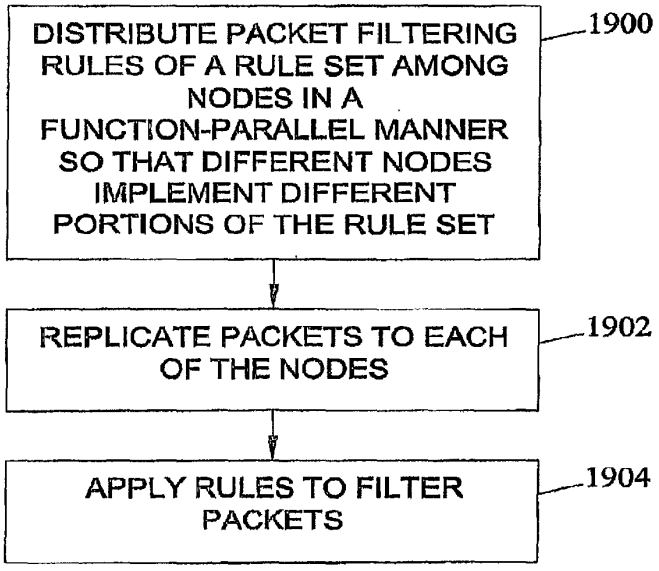

DISTRIBUTE PACKET FILTERING RULES OF A RULE SET AMONG NODES IN A FUNCTION-PARALLEL MANNER SO THAT DIFFERENT NODES IMPLEMENT DIFFERENT PORTIONS OF THE RULE SET
1900
REPLICATE PACKETS TO EACH OF THE NODES
1902
APPLY RULES TO FILTER PACKETS
1904

FIG. 19

Espacenet

Bibliographic data: WO2011038420 (A2) — 2011-03-31

METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR ADAPTIVE PACKET FILTERING

Inventor(s): AHN DAVID K [US] ± (AHN, DAVID, K)

Applicant(s): GREAT WALL SYSTEMS [US]; AHN DAVID K [US] ± (GREAT WALL SYSTEMS, ; AHN, DAVID, K)

Classification: - international: ***H04L12/22; H04L12/26; H04L12/56; H04L29/06***
- cooperative: **G06F21/562**; **H04L63/0227**; **H04L63/0263**; H04L63/1416

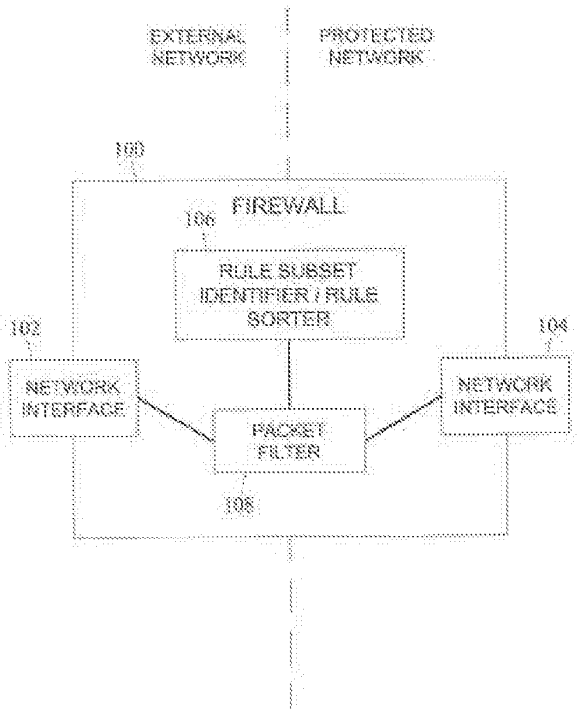
Application number: WO2010US54520 20101028

Priority number (s): US20090237974P 20090828 ; US20100871806 20100830

Also published as: WO2011038420 (A3) US2011055916 (A1) US8495725 (B2) US2014007216 (A1) EP2471218 (A2) more

Abstract of WO2011038420 (A2)

The subject matter described herein includes methods, systems, and computer readable media for adaptive packet filtering. One method includes identifying at least one subset of rules and an ordered set of firewall packet filtering rules that defines a firewall policy such that the subset contains disjoint rules. Disjoint rules are defined as rules whose order can be changed without changing integrity of the firewall policy. Rules in the subset are sorted to statistically decrease the number of comparisons that will be applied to each packet that a firewall encounters.; Packets are filtered at the firewall using the sorted rules in the subset by comparing each packet to each of the sorted rules in the subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and



thereby achieving sub-linear searching for packets filtered using the sorted rules in the subset.

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PCT

(10) International Publication Number
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12/871,806 30 August 2010 (30.08.2010) US

(71) Applicant *(for all designated States except US)*: **GREAT WALL SYSTEMS** [US/US]; 635 W 4th St., Ste 200, Winston-Salem, NC 27101-2740 (US).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: **AHN, David, K.** [US/US]; 740 N. Pine Valley Road, Winston-salem, NC 27106-5508 (US).

(74) Agent: **HUNT, Gregory, A.**; Jenkins, Wilson, Taylor & Hunt, P.A., Suite 1200, University Tower, 3100 Tower Boulevard, Durham, NC 27707 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,

[Continued on next page]

(54) Title: METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR ADAPTIVE PACKET FILTERING

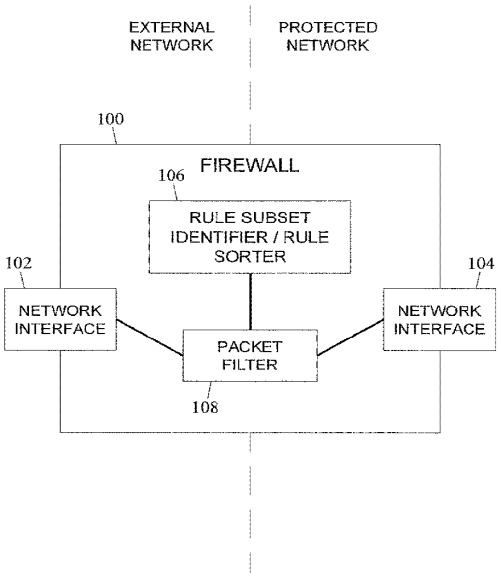

FIG. 1

(57) Abstract: The subject matter described herein includes methods, systems, and computer readable media for adaptive packet filtering. One method includes identifying at least one subset of rules and an ordered set of firewall packet filtering rules that defines a firewall policy such that the subset contains disjoint rules. Disjoint rules are defined as rules whose order can be changed without changing integrity of the firewall policy. Rules in the subset are sorted to statistically decrease the number of comparisons that will be applied to each packet that a firewall encounters. Packets are filtered at the firewall using the sorted rules in the subset by comparing each packet to each of the sorted rules in the subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and thereby achieving sub-linear searching for packets filtered using the sorted rules in the subset.

WO 2011/038420 A2

SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

— *with information concerning request for restoration of the right of priority in respect of one or more priority claims (Rules 26bis.3 and 48.2(b)(vii))*

DESCRIPTION

METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR ADAPTIVE PACKET FILTERING

PRIORITY CLAIM

This application claims the benefit of U.S. Provisional Patent Application Serial No. 61/237,974, filed August 28, 2009 and U.S. Patent Application Serial No. 12/871,806, filed August 30, 2010; the disclosures of which are incorporated herein by reference in their entireties.

TECHNICAL FIELD

The subject matter described herein relates to network firewall filtering. More particularly, the subject matter described herein relates to methods, systems, and computer readable media for adaptive packet filtering.

BACKGROUND

A firewall generally processes a packet against a list of ordered rules to find the first rule match. The list of ordered rules represents an aggregate security policy, and arbitrarily changing the order of the rules can result in a violation of the aggregate security policy. The Wake Forest University (WFU) techniques described in U.S. patent application publication nos. 2006/0248580 and 2006/0195896 provide the methods to optimally reorder the list while preserving the aggregate security policy, thereby improving the performance of the firewall. The WFU techniques also include methods to break apart rules into functionally independent lists containing (groups of) dependent rules such that a function parallel firewall can simultaneously process one packet against multiple lists, which can substantially improve the performance of the firewall. However, these improvements provided by WFU techniques can be dwarfed by the performance degradation as the number of rules in the list becomes very large.

A key reason for the lack of scalability of most firewall implementations is due to the common use of linear search algorithms for comparing packets against a list of rules. In the worst case, a packet is matched at the last N^{th} rule in the list, so it must also be compared against all *N-1* prior rules for a total of *N*

comparisons. This poses a computational resource problem when the size of *N* is very large on a single processing node (including when such nodes are arranged in a data-, function-, hierarchical- or hybrid-parallel system), where the time required for processing each packet can quickly increase latency and reduce throughput to unacceptable levels. In fact, the WFU techniques provide good results in part because the reordering of, or the reduction in size of, rules on each processing node allows for a larger percentage of the total rules to reside in each processor's cache(s), which then substantially increases their performance relative to when only a small portion of those rules are cached.

The problem of searching firewall rule sets is well understood and highly researched, and there are some published techniques for sub-linear (substantially faster than linear) techniques applicable to firewall rules. However, these sub-linear techniques generally involve changing the underlying representation of rules. Examples of such an approach might be to use a graph, trie- or tree-like structure instead of a list to represent a set of rules, which would allow a match to be determined using tree search algorithms by traversing down the graph, trie or tree (see E. Fulp, Trie-Based Policy Representations for Network Firewalls, Proceedings of the IEEE International Symposium on Computer Communications, 2005 and Al-Shaer et al., Modeling and Management of Firewall Policies, IEEE Transactions on Network and Service Management, 2004). These approaches have potential but can add complexity or limitations that may reduce their practical usefulness in a commercial high performance firewall product.

SUMMARY

Adaptive packet filtering (APF), a set of techniques for processing firewall rules and packets, is described herein. APF offers improved processing performance compared to the WFU techniques in most cases, and can be combined with the WFU techniques or other parallel, pipelining and optimization techniques to achieve even greater performance.

The subject matter described herein includes methods, systems, and computer readable media for adaptive packet filtering. One method includes identifying at least one subset of rules in an ordered set of firewall packet

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filtering rules that defines a firewall policy such that the subset contains disjoint rules. Disjoint rules are defined as rules whose order can be changed without changing the integrity of the firewall policy. Rules in the subset are sorted to statistically decrease the number of comparisons that will be applied to each packet that a firewall encounters. Packets are filtered at the firewall using the sorted rules in the subset by using binary search, interpolated search, informed search, or hash lookup search algorithms to compare each packet to the sorted rules in the subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and thereby achieving sub-linear searching for packets filtered using the sorted rules in the subset.

The subject matter described herein for adaptive packet filtering can be implemented in a non-transitory computer readable medium having stored thereon executable instructions that when executed by the processor of a computer control the computer to perform steps. Exemplary computer readable media suitable for implementing the subject matter described herein include chip memory devices, disk memory devices, programmable logic devices and application specific integrated circuits. In addition, a computer readable medium that implements a subject matter described herein may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

Further, the subject matter described herein for adaptive packet filtering can be implemented on a particular machine, such as a network firewall including one or more network interfaces for receiving packets and packet filtering hardware and software for optimizing rules as described herein and for filtering packets using the optimized arrangement of rules.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the subject matter described herein will now be described with reference to the accompanying drawings of which:

Figure 1 is a block diagram of a system for adaptive packet filtering according to an embodiment of the subject matter described herein;

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Figure 2 is a block diagram of application of the present subject matter to a pipelined processing approach according to an embodiment of the subject matter described herein;

Figure 3 is a block diagram illustrating application of the present subject matter to a combination of pipelined and data parallel processing approaches according to an embodiment of the subject matter described herein; and

Figure 4 is a block diagram illustrating application of the present subject matter to a short-circuiting pipelined processing approach according to an embodiment of the subject matter described herein; and

Figure 5 is a block diagram illustrating application of the present subject matter to a combination of pipelined and function parallel processing approaches according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION

Methods, systems, and computer readable media for adaptive packet filtering are disclosed. Figure 1 is a block diagram illustrating an exemplary system for adaptive packet filtering according to an embodiment of the subject matter described herein. Referring to Figure 1, a firewall **100** may function at the boundary between an external network and a protected network. Firewall **100** may include one or more network interfaces **102** for receiving packets from the external network. Firewall **100** may also include one or more network interfaces **104** for transmitting allowed packets to the protective network. In one implementation, firewall **100** may filter Internet protocol (IP) packets based on a combination of source and destination addresses in the IP headers of the packets. However, the subject matter described herein is not limited to filtering any particular protocol. Any packet network protocol with parameters for which firewall filtering rules can be defined is intended to be within the scope of the subject matter described herein.

As used herein, the term "firewall" includes any network security device or system of devices that inspects network traffic data that originates, terminates, or traverses the device system in any capacity and compares that

traffic data (headers, payload, raw bits, etc.) to a set of one or more rules, signatures, or conditions, either inline (i.e., in real time) or offline (i.e., capture and replay of the traffic data). The term "firewall" is also intended to include an intrusion detection device that analyzes network traffic in real time or historically to detect the presence of intrusion events in a network. The term "firewall" is also intended to include a deep packet inspection device that analyzes network traffic in real time or historically to detect the presence of certain packet content in a network.

Firewall **100** includes a firewall rule subset identifier/rule sorter **106** for identifying at least one subset of rules in an ordered set of firewall packet filtering rules that defines a firewall policy such that the subset contains disjoint rules, where disjoint rules are defined as rules whose order can be changed without changing the firewall policy. Firewall rule subset identifier/rule sorter **106** may sort the rules in the subset or subsets to statistically decrease the number of comparison that will be applied to each packet that the firewall encounters. Exemplary methods for grouping and sorting rules will be described below.

Although in the example illustrated in Figure 1 rule subset identifier/rule sorter **106** is illustrated as a component of firewall **100**, the subject matter described herein is not limited to such an implementation. Rule subset identifier/rule sorter **106** can be implemented on any computing platform capable of sorting firewall rules using the methods described herein, and the sorted rule set can be provided to firewall **100** through any suitable means, such as communication over a network. In one implementation, rule subset identifier/rule sorter **106** may be implemented on a management platform separate from firewall **100**.

Firewall **100** further includes a packet filter **108** for filtering packets at the firewall using the rules in the subset by using binary search, interpolated search, informed search, hash lookup search algorithms, or other sub-linear algorithms to compare each packet to each of the sorted rules in the subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and thereby achieving

sub-linear searching for the packets filtered using the sorted rules in the subset.

Once the subsets of disjoint rules have been identified by rule subset identifier/rule sorter **106**, the rule subsets can be distributed across plural firewall processors in order to improve packet filtering efficiency. Figure 2 is a block diagram illustrating an exemplary pipelined approach where rules and different subsets are distributed across plural firewall processors for processing packets in a pipelined manner. Referring to Figure 2, firewalls **200** and **202** each include separate processors **204** and **206** for executing packet filters **108**. In this example, rule subset identifier/rule sorter **106** identifies two rule subsets, subset A **208** and subset B **210**. The rules within each subset **208** and **210** are disjoint and sorted to statistically decrease the number of comparisons that will be applied to each packet using the methods described herein. However, the rules in subset B **210** are dependent on the rules in rule subset A **208**. Accordingly, rule subset identifier/rule sorter **106** distributes the rule across firewall processors **204** such that the rules in rule subset A **208** are applied before the rules in rule subset B **210**. Because the rules in different subsets are distributed across plural processors in a pipeline manner, packet filtering efficiency is improved over a single-processor approach because the different processors can simultaneously apply rules to different packets. In the example illustrated in Figure 2, packets that pass the filtering of rule subset A **208** are processed by processor **206**, which applies rule subset B **210**, at the same time that processor **204** applies rule subset A to new incoming packets.

In yet another embodiment, rule subset identifier/rule sorter **106** may distribute the grouped, sorted rules across firewall processors such that a combination of pipelined and data parallel processing techniques are used. Figure 3 illustrates an example where firewalls **300**, **302**, **304**, and **306** each include separate processors **308**, **310**, **312**, and **314** for applying their respective packet filters. In the illustrated example, rule subset identifier/rule sorter **106** distributes rule subset A **316** to firewall **300**, rule subset B **318** to firewalls **302** and **304**, and rule subset C **320** to firewall **306**. The rules within each subset A, B and C are disjoint. The rules in subset B are dependent

upon the rules in subset A. The rules in subset C are dependent upon the rules in subsets A and B.

In operation, packets entering firewall **300** are filtered using rule subset A **316**. The packets that are allowed by rule subset A **316** are divided between firewalls **302** and **304** such that the application of the rules in rule subset B **318** to different packets is performed in parallel. This is referred to as a data parallel approach. The packets that pass the filtering by rule subset B **318** are passed to firewall **306** for application of the rules in rule subset C **320**. Accordingly, Figure 3 illustrates an example where the rule subsets that are identified and sorted by rule subset identifier/rule sorter **106** are distributed across the firewall processors for a combination of pipelined and data parallel processing.

In yet another embodiment, the rules subsets that are identified and in which the rules are sorted using rule subset identifier/rule sorter **106** may be distributed across firewall processors in a short-circuiting pipelined manner. Figure 4 is an example of short-circuiting pipelined filtering using rule subsets that are identified and sorted by rule subset identifier/rule sorter **106**. Referring to Figure 4, a first firewall **400** and a second firewall **402,** respectively including processors **404** and **406,** filter packets using packet filters **108**. In the illustrated example, packet filter **108** uses rule subset A **408** and packet filter **108** uses rule subset B **410**. Rule subsets A and B **408** and **410** may respectively implement different levels of a firewall hierarchy such that packets that pass the filtering by rule subset A **408** are allowed into the protected network. Packets that are identified by rule subset A **408** is requiring further filtering are distributed to rule subset B **410** for that filtering. Thus, rule subset identifier/rule sorter **106** can also be used with short-circuiting pipelined firewall techniques without departing from the scope of the subject matter described herein.

In yet another embodiment, rule subset identifier/rule sorter **106** may distribute the grouped, sorted rules across firewall processors such that a combination of pipelined and function parallel processing techniques are used. Figure 5 illustrates an example where firewalls **500**, **502**, **504**, and **506** each include separate processors **508**, **510**, **512**, and **514** for applying their

respective packet filters. In the illustrated example, rule subset identifier/rule sorter **106** distributes rule subset A **516** to firewall **500**, rule subset B **518** to firewalls **502**, and rule subset C **520** to firewall **504**, and rule subset D **522** to firewall **506**. The rules within each subset A, B, C and D are disjoint. The rules in subset B and C are dependent upon the rules in subset A. The rules in subset D are dependent upon the rules in subsets A, B and C.

In operation, packets entering firewall **500** are filtered using rule subset A **516**. The packets that are allowed by rule subset A **516** are copied to both firewalls **502** and **504** such that the application of the rules in rule subsets B **518** and C **520** to the packets is performed in parallel. This is referred to as a function parallel approach. The packets that pass the filtering by rule subsets B **518** and C **520** are passed to firewall **506** for application of the rules in rule subset D **522**. Accordingly, Figure 5 illustrates an example where the rule subsets that are identified and sorted by rule subset identifier/rule sorter **106** are distributed across the firewall processors for a combination of pipelined and function parallel processing.

Technique

APF analyzes and orders the list of firewall rules in-place to contain functionally dependent groups, where each group contains a subset of rules that are disjoint, dependent or both, without substantially changing the underlying representation of rules and while preserving the aggregate security policy. APF then uses varying criteria to sort each group containing disjoint rules, then uses sub-linear search algorithms when comparing packets against the rules within that group. APF uses linear search algorithms when comparing packets within a group containing dependent rules or when otherwise appropriate. A detailed computational complexity analysis of APF would need to be completed. However, on average, it is hypothesized that only $O(log(N))$ comparisons would be needed to process a rule list of size N. In the theoretical best case when all rules are disjoint, this translates to about 20 comparisons (instead of 1,000,000) for a list of N = 1,000,000 rules and about 30 comparisons for a list of N = 1,000,000,000 rules. In the worst case when all rules are dependent, APF performs the same as linear search firewall

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cores. In practice, APF should process a packet against a very large list of rules (*N* = millions) in the same amount of time that other techniques can process against a very small list (*N* = hundreds, or thousands). APF does not inherently use parallel techniques; therefore, it can be combined with WFU techniques or other parallel/pipelining techniques to increase performance.

The following table shows preliminary results comparing a single linear search firewall) with a single APF core as the number of rules is increased.

	linear firewall core		APF core	
N = # rules in the core	PPS = packets per second at max throughout with 0 loss	Latency in microseconds at max throughput with 0 loss	PPS = packets per second at max throughout with 0 loss	Latency in microseconds at max throughput with 0 loss
1	844,595	12.3	811,688	12.3
10	730,994	11.9	766,871	12.3
100	314,861	13.9	718,391	12.0
1,000	29,357	44.6	683,060	12.0
10,000	930	1,112.4	464,684	12.0
100,000	Fail	Fail	292,740	17.4
1,000,000			252,525	14.3
10,000,000			132,556	18.6

Detailed Technique

This section describes an exemplary algorithm for implementing the subject matter described herein.

A firewall *rule* is defined as an *n*-tuple criteria and an associated action for matching packets. For example, a 5-tuple rule that matches Internet Protocol version 4 (IPv4) packets might consist of 5 IPv4 header fields (source address, source port, destination address, destination port and protocol) and an action (allow, deny), and might specify the rule ***R1*** as:

Rule	Source Addr	Source Port	Dest Addr	Dest Port	Protocol	Action
R1	192.168.1.1	12345	10.1.1.1	80	TCP	DENY

A firewall *rule set* is defined as an ordered list of *n* rules *R1,R2,R3,...,Rn* where the *i* in *Ri* is the index of the rule in the list. Packets that traverse the firewall are checked against each rule in the rule set until the

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first matching rule is found and its associated action is applied. An example rule set is ***S1*** which contains:

Rule	Source Addr	Source Port	Dest Addr	Dest Port	Protocol	Action
R1	192.168.1.1	12345	10.1.1.1	80	TCP	DENY
R2	192.168.2.2	ANY	10.2.2.2	25	TCP	ALLOW
R3	192.168.3.3	ANY	10.3.3.3	53	UDP	ALLOW
R4	ANY	ANY	10.1.1.1	ANY	ANY	ALLOW
R5	ANY	ANY	ANY	ANY	ANY	DENY

An example TCP packet from source 192.168.4.4 port 54321 to destination 10.1.1.1 port 80 would be checked against but not match *R1*, *R2* and *R3*; would be checked against and match *R4* and be allowed; and, would not be checked against *R5* because *R4* was the first matching rule.

A firewall *security policy* is defined as the set of all possible packets that can traverse the firewall along with their specified outcomes as defined by the rule set. Changing the rules in a rule set usually results in a change of its security policy.

Within a rule set, a firewall rule is *dependent* on another rule if swapping the order of the two rules results in a change in the security policy of the rule set. Otherwise, the two rules are *disjoint* if swapping the order does **not** result in a change the security policy. For example, in rule set ***S1*** above, rules ***R1*** and ***R4*** are dependent because placing ***R4*** ahead of ***R1*** would render ***R1*** ineffective, thereby changing the security policy. Rules ***R1*** and ***R2*** are disjoint because placing ***R2*** ahead of ***R1*** does not change the security policy.

A *permutation* of a rule set is defined as a new rule set which contains the same rules as the original rule set, but which lists a different ordering of the rules from the original rule set without changing the original security policy. For example, in the rule set ***S1*** above, swapping the order of the disjoint rules ***R1*** and ***R2*** would result in a permutation rule set ***S1'***:

Rule	Source Addr	Source Port	Dest Addr	Dest Port	Protocol	Action
R2	192.168.2.2	ANY	10.2.2.2	25	TCP	ALLOW
R1	192.168.1.1	12345	10.1.1.1	80	TCP	DENY
R3	192.168.3.3	ANY	10.3.3.3	53	UDP	ALLOW

R4	ANY	ANY	10.1.1.1	ANY	ANY	ALLOW
R5	ANY	ANY	ANY	ANY	ANY	DENY

Two rules are *spatially disjoint* if they are disjoint and their corresponding tuples are either identical or do not overlap. For example, in the rule set ***S1*** above, rules ***R1*** and ***R2*** are disjoint but not spatially disjoint because the source ports 12345 and ANY overlap. However, rules ***R2*** and ***R3*** are both disjoint and spatially disjoint because the source ports ANY and ANY are identical, and the other 4 tuples do not overlap. (Other examples follow.)

A *transform function* is an algorithm that can be applied to a rule to create a *sortable key* for that rule, which can then be used to sort the rules by their keys using a *key comparison function*. For example, the transform function ***Tfn*** could concatenate the tuples of a rule into a bit array that is interpreted as a large integer, and a corresponding comparison function ***Cfn*** could be a simple integer comparison function. (Other examples follow.)

A *rule subset* is defined as an ordered grouping of one or more rules within a rule set. For example, in rule set ***S1*** above, the rule subsets might be:

Subset	Rules
T1	*R1, R2, R3*
T2	*R4*
T3	*R5*

A *rule group* is defined as a rule subset with a *group type* (dependent, disjoint), *transform function*, *comparison function*, and a *search algorithm hint* (linear, sub-linear). The *group type* can be *dependent* if the group contains dependent rules, or can be *disjoint* if the group strictly contains disjoint rules. For example, the rule set ***S1*** above might contain the following disjoint rule group:

Group	Group Type	Rules	Transform Fn	Comparison Fn	Hint
G1	Disjoint	*R1, R2, R3*	*Tfn*	*Cfn*	Sub-linear

A rule set may be partitioned into a list of ordered rule groups such that the security policy of the rule set is not changed when each rule group is decomposed in the listed order. This partitioning is accomplished by applying

a rule subset identification method to a given rule set. An example of such a method is:

1. For a given rule set *S* containing *n* rules *R1,R2,...,Rn*:
    a. Create a new empty disjoint rule group *Gj* (initially G1) in *S*.
    b. Place the first ungrouped rule *Ri* (initially R1) into *Gj*.
    c. For each remaining ungrouped rule *Ri* in *S*:
        i. If *Ri* is disjoint from rules in *Gj* and placing *Ri* into *Gj* does not modify the security policy of *S*, then place *Ri* into *Gj*.
        ii. Otherwise, leave *Ri* ungrouped.
    d. If *S* contains ungrouped rules, then go to step 1.a.
2. The rule set *S* now contains *m* disjoint rule groups *G1,G2,G3,...,Gm* which group together the *n* (possibly reordered) rules *R1,R2,...,Rn*.

Applying the above method to rule set ***S1*** might result in its partitioning into the following list of disjoint ordered rule groups:

Group	Group Type	Rules	Transform Fn	Comparison Fn	Hint
G1	Disjoint	*R1, R2, R3*			Linear
G2	Disjoint	*R4*			Linear
G3	Disjoint	*R5*			Linear

Decomposing the disjoint rule groups would result in ***G1,G2,G3*** = [***R1,R2,R3***], [***R4***], [***R5***] = ***R1,R2,R3,R4,R5*** = ***S1***.

A partitioned rule set containing disjoint rule groups may then be sorted by applying a transform function to each rule within each disjoint group to derive a sortable key for each rule. Then, the rules may be reordered within their disjoint groups using their sortable keys. The resulting sorted groups may be searched using sub-linear searching algorithms. An example of the sorting method is:

1. For each disjoint group *Gj* in rule set *S*:
    a. For each rule *Ri* in *Gj*:
        i. Apply Transform *Tfn* to *Ri* to derive a sortable key *Ki*.
    b. Sort the rules in *Gj* using the comparison function *Cfn* on the sortable keys *K*.

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3. The rule set *S* now contains *m* sorted disjoint rule groups *G1*,*G2*,*G3*,...,*Gm*.

Applying the above method to the partitioned rule set ***S1*** might result in a new permutation rule set ***S1'*** that contains the following list of sorted rule groups where the ordering of rules within ***G1*** might change from ***R1,R2,R3*** to ***R3,R1,R2***:

Group	Group Type	Rules	Transform Fn	Comparison Fn	Hint
G1	Disjoint	*R3, R1, R2*	*Tfn*	*Cfn*	Sub-linear
G2	Disjoint	*R4*	*Tfn*	*Cfn*	Sub-linear
G3	Disjoint	*R5*	*Tfn*	*Cfn*	Sub-linear

The permutated rule set containing disjoint rule groups may be consolidated to reduce the number of groups that contain a rule count at or below a certain threshold, such as 1 rule, by merging two or more consecutive disjoint groups into a larger dependent group that may be searched using linear searching algorithms. An example of the consolidation method is:

1. For each group *Gj* in rule set S:
    a. If the sum of the number of rules in *Gj* and its subsequent group *Gj+1* is less than or equal to a specified threshold (e.g. 1), then the two groups are merged, their rules are concatenated, and the group type is set to *dependent.*
2. The rule set *S* now contains *m* or fewer rule groups of both dependent and disjoint types.

Applying the above method to the permuted rule set ***S1'*** might merge the disjoint group ***G3*** into ***G2***:

Group	Group Type	Rules	Transform Fn	Comparison Fn	Hint
G1	Disjoint	*R3, R1, R2*	*Tfn*	*Cfn*	Sub-linear
G2	Dependent	*R4, R5*	(none)	(none)	Linear

The APF packet filtering method matches packets against a given rule set by sequentially iterating over each of the ordered rule groups, then performing the specified sub-linear or linear search within each group. An example of a rule filtering method is:

1. For each packet that traverses the firewall:
    b. For each group *Gj* in rule set *S*:
        i. If *Gj* is a dependent group, then perform linear search within that group until there is a first rule match.
        ii. If *Gj* is a disjoint group:
            1. Apply transform *T* to the packet to derive a lookup key *K*.
            2. Use the comparison function *C* and sub-linear search within the group until there is a first rule match on key *K*.
        iii. If there is a first rule match, then process the packet according to its specified action. Otherwise, continue to the next group *Gj+1*.

Additional Notes

- The primary purpose of the partitioning of rules is to create rule groups that, in aggregate, enable the fastest possible searching of each packet against the rules in the rule set. In most cases, the optimal partitioning should be the grouping of maximal subsets of spatially disjoint rules. However, in some cases where these disjoint groups are small (e.g. less than 10 rules), consolidating the disjoint groups into a single larger group containing rules that are ordered using other criteria (such as hit probabilities or hardware cache friendliness) and employing linear or interpolated search algorithms may improve performance. A critical concept is the flexibility to organize the rules within the rule set in different ways that enable the use of the most efficient and applicable search algorithm that is available that accounts for the hardware capabilities, which is the motivation behind the term "adaptive" in Adaptive Packet Filtering.
- Rule sets may be partitioned, sorted and consolidated in-place.
- When partitioning a rule set into rule groups, each disjoint group should generally contain the maximal subsets of disjoint rules in order to reduce the number of disjoint groups in the rule set.

- When partitioning a rule set into rule groups and/or sorting those groups, the transform and comparison functions may be different for each rule group.
- When partitioning a rule set into rule groups and/or sorting those groups, the algorithms may account for the hit probabilities of each rule and the aggregate hit probabilities of each group.
- When filtering packets, the search performed within any given rule group may employ the fastest available search algorithm applicable to that group even if it may be different from the specified search algorithm hint.
- When filtering packets, a sub-linear binary search within a disjoint rule group may account for hit probabilities at each pivot so that each recursion could maximize the probability of a rule match.
- When filtering packets, a constant-time search within a disjoint rule group is possible by defining a hashing function as the transform function such that the hash values for all rules within a group are unique within that group.

Examples

This section provides examples of the following items described in the algorithm in the previous section.

1) Example of the rule breakup

2) Example of transform function

3) Definition of rule representation

4) Difference between sub-linear and linear

5) Explanation of disjoint rules

1) Examples of the rule breakup

Define

```
S1 = (R1, R2, R3, R4, R5)
```

and

```
R1 = from 1.2.3.4 to 3.4.5.6 deny
R2 = from 2.3.4.5 to 4.5.6.7 allow
```


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```
R3 = from 3.4.5.6 to 5.6.7.8 allow
R4 = from *.*.*.* to 3.4.5.6 allow
R5 = from *.*.*.* to *.*.*.* deny
```

Then S1' contains 3 groups of disjoint rules:

```
S1' = (G1, G2, G3)
G1 = (R1, R2, R3)
G2 = (R4)
G3 = (R5)
```

Or, S1' can contain 2 groups of disjoint and dependent rules:

```
S1' = (G1, G2)
G1 = (R1, R2, R3), disjoint, sub-linear
G2 = (R4, R5), dependent, linear
```

or

Define

```
S2 = (R1, R2, R3, R4, R5, R6, R7, R8, R9)
```

and

```
R1 = from 1.2.3.4 to 3.4.5.6 deny
R2 = from 2.3.4.5 to 4.5.6.7 allow
R3 = from 1.2.3.4 to 4.5.6.7 deny
R4 = from 1.*.*.* to *.*.*.* allow
R5 = from 3.4.5.6 to 5.6.7.8 deny
R6 = from 2.*.*.* to *.*.*.* deny
R7 = from *.*.*.* to 3.4.5.6 allow
R8 - from *.*.*.* to 5.6.7.8 allow
R9 = from *.*.*.* to *.*.*.* deny
```

Then S2' contains 4 groups of "spatially disjoint" rules:

```
S2' = (G1, G2, G3, G4)
G1 = (R1, R2, R3, R5)
G2 = (R4, R6)
G3 = (R7, R8)
G4 = (R9)
```

Or, S2' can contain 2 groups of disjoint and dependent rules:

```
S2' = (G1, G2)
G1 = (R1, R2, R3, R5), disjoint, sub-linear
G2 = (R4, R6, R7, R8, R9), dependent, linear
```

---

2) Example of transform function

A rule R usually consists of an N-tuple, most basically a 3-tuple such as "from 1.2.3.4 to 3.4.5.6 deny"

* tuple a = source IP address, e.g. "1.2.3.4"
* tuple b = destination IP address, e.g. "3.4.5.6"
* tuple c = action, e.g. "deny"

Each of these tuples have underlying scalar integer/bit vector representation, so in the above example:
* source IP address = "1.2.3.4" = 32 bit integer 0016909060
* destination IP address = "3.4.5.6" = 32 bit integer 0050595078
* action = "deny" = 8 bit integer 000

One possible transform function is a transform to scalar key which concatenates the digits of each of the tuples into a large integer value:
* T(a, b, c) = abc
* T(1.2.3.4, 3.4.5.6, deny) = 0016909060 0050595078 000 = 001690906000050595078000

Another possible transform function is a transform to scalar key which concatenates the bits of each of the tuples into a large integer/bit vector:
* a = 1.2.3.4 = 00000001000000100000001100000100 (32 bits)
* b = 3.4.5.6 = 00000011000001000000010100000110 (32 bits)
* c = 0 = 00000000 (8 bits)

T(a, b, c) = abc = 000000010000001000000011000001000000001100000100000001010000011000000000

Another possible transform function is an identity function (i.e. transformation function that does not do anything), then defining a multi-dimensional comparison function for sorting purposes. An example of this is a comparison function that is radix-based for each tuple, which would essentially result in a rule set that is radix sorted by each tuple.

Note that the transform function must convert the rule into a sortable key, which does not necessarily have to be a scalar key (i.e. it can be a multi-dimensional key that uses a multi-dimensional comparison function for sorting).

---

3) Definition of rule representation.
Rule representation is the way a rule and a rule set are conceptually represented in software. The most common representation of a rule is as an N-tuple object or structure that simply holds all the tuples together:

```
struct rule {
      unsigned char ip_proto;
      unsigned int ip_src_addr;
      unsigned int ip_dst_addr;
      unsigned short ip_src_port;
```

```
    unsigned short ip_dst_port;
    ...
    unsigned char action;
};
```

The most common representation of a rule set is an array or linked list that hold the rules in a fixed order, and allows for iteration forwards and backwards in the array or list.

Example of array:

memory location	0	1	2	3	4	5	6	7	8
value	R1	R2	R3	R4	R5	R6	R7	R8	R9

Example of linked list:

memory location	0	1	2	3	4	5	6	7	8
value	R1	R9	R2	R8	R3	R5	R4	R6	R7
linked list prev	-	0	2	4	6	5	7	8	3
rule	R1	R2	R3	R4	R5	R6	R7	R8	R9
next	2	4	6	5	7	8	3	1	-

An alternate rule representation is to hold the rule and rule set in a trie or other graph structure. An example of this is described in "Balancing Trie-Based Policy Representations for Network Firewalls."Stephen J. Tarsa and Errin W. Fulp. Proceedings of the IEEE International Symposium on Computer Communications, 2006

Another alternate rule set representation is a hierarchical one as described in OPTWALL, described in Acharya et al., "OPTWALL: A Hierarchical Traffic-Ware Firewall," available at:

http://www.isoc.org/isoc/conferences/ndss/07/papers/OPTWALL.pdf,

where rule sets are broken down into mutually exclusive rule subsets which are arranged in a hierarchical order. Despite some similarities in terminology, OPTWALL and APF are different. For example, APF does not change the underlying rule or rule set representation. It simply reorders the rules in place and keeps track of the beginning and ending rules in each subset T externally from the rule or rule set. For example, say that a given rule is a standard structure and the rule set is an array form so that the rule set contains the following in the computer's memory:

Rule set S:

Location	0	1	2	3	4	5	6	7	8
value	R1	R2	R3	R4	R5	R6	R7	R8	R9

Suppose that the above rule set S can be divided into subsets containing disjoint rules:

```
T1 = R2, R9, R1, R3
```

```
T2 = R5, R7
T3 = R2, R4, R8
```

so that

```
S' = T1, T2, T3 = R2, R9, R1, R3, R5, R7, R2, R4, R8
```

Then the order of the rules in memory can be changed in place:

Rule set S':

```
location  0  1  2  3  4  5  6  7  8
value     R2 R9 R1 R3 R5 R7 R2 R4 R8
          |---------| |---| |------|
               T1       T2     T3
```

The memory ranges for T1 (0-3), T2 (4-5) and T3 (6-8) are stored outside of the rule and rule set data structures.

---

4) Difference between linear and sub-linear.

A linear algorithm is one whose computational time increases linearly as the size of the set is increased. The best example of this is when looking up a word in a dictionary. If the dictionary is unsorted, then the order of the words would be arbitrary. Therefore, when looking up the word "zebra," one could start from the beginning and search until the end to find it. If the dictionary contains 1,000 entries, you would need to examine all 1,000 words in the worst case.

A sub-linear algorithm is one whose computational time increases sub-linearly as the size of the set is increased. In the above example, if the dictionary were sorted alphabetically, then one could still use a linear search by starting from the beginning and searching until the end to find "zebra." However, one could also use a sub-linear binary search algorithm by looking in the middle of the dictionary, then seeing if the middle entry comes alphabetically before or after (or is equal), then recursively selecting the middle of the appropriate half again and again to find the word "zebra." Since at each recursion 1/2 of the remaining words are eliminated, it would take about $\log_2(1{,}000)$ or about 10 examinations to find the entry in the worst case.

Another example of a sub-linear algorithm is hashing. Suppose that the above dictionary contains only 5 letter words. If we define a hash function that sums the alphabet order of each letter in the word (z = 26, e = 05, b = 02, r = 18, a = 01), then hash("zebra") = 26 + 05 + 02 + 18 + 01 = 52. The computer could have an array containing all the words in the dictionary where each word's position in the array is the hash value of the word (subject to collisions). In the above example, the array's 52nd position would have the word "zebra," so it would take only 1 comparison to determine a match without collision. This hash technique can be selectively used in APF.

---

5) Explanation of disjoint rules.

A rule R1 is "disjoint" from another rule R2 if their positions in the rule set S can be exchanged without altering the overall security policy. An example of this is rule set S containing:

```
R1 = from 1.*.*.* to 2.3.4.5 deny
R2 = from 1.2.3.4 to 1.2.3.4 allow
```

has the same security policy as rule set S' containing:

```
R2 = from 1.2.3.4 to 1.2.3.4 allow
R1 = from 1.*.*.* to 2.3.4.5 deny
```

because P = P'; therefore, R1 and R2 are disjoint.

The technique set forth above does not explain the concept of "spatially disjoint" rules. This is important if the transform function T cannot account for overlapping tuple values, which can be very common in practical settings.

A rule R1 is "spatially disjoint" from another rule R2 if they are "disjoint" and their corresponding tuples do not unevenly overlap (must be exactly equal, or do not overlap at all). In the above example, R1 and R2 are disjoint but not spatially disjoint because the first tuple of R1 (1.*.*.*) and R2 (1.2.3.4) are not equal but do overlap, i.e. the value of 1.2.3.4 would match the first tuple of both R1 and R2. An example of spatially disjoint rules are:

```
R3 = from 1.2.3.4 to 3.4.5.6 deny
R4 = from 2.3.4.5 to 3.4.5.6 allow
```

Here, the first tuple of R1 (1.2.3.4) and the first tuple of R2 (2.3.4.5) do not overlap, the second tuple of R1 (3.4.5.6) and R2 (3.4.5.6) are equal, and the >> third tuple of R1 (deny) and R2 (allow) do not overlap.

The importance of "spatially disjoint" rules is dependent upon the definition of a transform function T, so it may be possible to define T such that rules need not be "spatially disjoint" so long as rules are "disjoint."

The disclosure of each of the publications referenced herein is hereby incorporated by reference in its entirety.

It will be understood that various details of the presently disclosed subject matter may be changed without departing from the scope of the presently disclosed subject matter. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

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CLAIMS

What is claimed is:

1. A method for adaptive packet filtering, the method comprising:

identifying at least one subset of rules in an ordered set of firewall packet filtering rules that defines a firewall policy such that the at least one subset contains disjoint rules, where disjoint rules are defined as rules whose order can be changed without changing the integrity of the firewall policy;

sorting the rules in the at least one subset to statistically decrease the number of comparisons that will be applied to each packet that a firewall encounters; and

filtering packets at the firewall using the sorted rules in the at least one subset by comparing each packet to each of the sorted rules in the at least one subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and thereby achieving sub-linear searching for the packets filtered using the sorted rules in at least one subset.

2. The method of claim 1 comprising, for the disjoint rules within the at least one subset, identifying spatially disjoint rules and grouping the spatially disjoint rules together within the at least one subset and wherein sorting the rules includes sorting the rules within each of the spatially disjoint groupings.

3. The method of claim 1 comprising identifying at least another subset of rules in the ordered set of firewall rules that are non-disjoint and refraining from sorting the rules in the at least another subset and wherein filtering the packets includes filtering the packets using the sorted, disjoint rules and the non-sorted, non-disjoint rules, thereby achieving sub-linear searching for the sorted, disjoint rules and achieving linear searching for the non-sorted, non-disjoint rules.

4. The method of claim 1 wherein sorting the rules includes applying a transform function to each rule in the at least one subset to compute a sortable key for each of the rules and sorting the rules according to the keys.

5. The method of claim 1 wherein sorting the rules includes sorting the rules according to hit probabilities.

6. The method of claim 1 wherein sorting the rules includes sorting the rules in a binary search tree.

7. The method of claim 1 wherein filtering packets by comparing each packet to the sorted rules includes comparing each packet to the sorted rules using a binary search algorithm.

8. The method of claim 1 wherein filtering packets by comparing each packet to the sorted rules includes comparing each packet to the sorted rules using an interpolated search algorithm.

9. The method of claim 1 wherein filtering packets by comparing each packet to the sorted rules includes comparing each packet to the sorted rules using an informed search algorithm.

10. The method of claim 1 wherein filtering packets by comparing each packet to the sorted rules includes comparing each packet to the sorted rules using a hash lookup algorithm.

11. The method of claim 1 wherein each rule includes an IP source address and an IP destination address.

12. The method of claim 1 wherein the firewall includes a plurality of processors, the at least one subset comprises a plurality of subsets and further comprising distributing the subsets across the plurality of processors to implement at least one of pipelined processing, data parallel processing, and function parallel processing.

13. The method of claim 12 wherein the firewall implements a combination of pipelined and function parallel processing.

14. The method of claim 12 wherein the firewall implements a combination of pipelined and data parallel processing.

15. The method of claim 12 wherein the firewall implements a combination of pipelined, function parallel, and data parallel processing.

16. A system for adaptive packet filtering, the system comprising:

a firewall rule subset identifier/rule sorter for identifying at least one subset of rules in an ordered set of firewall packet filtering rules that defines a firewall policy such that the at least one subset contains

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disjoint rules, where disjoint rules are defined as rules whose order can be changed without changing integrity of the firewall policy, and for sorting the rules in the at least one subset to statistically decrease the number of comparisons that will be applied to each packet that a firewall encounters; and

a packet filter for filtering packets at the firewall using the sorted rules in the at least one subset by comparing each packet to each of the sorted rules in the at least one subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and thereby achieving sub-linear searching for the packets filtered using the sorted rules in at least one subset.

17. The system of claim 16 comprising, for the disjoint rules within the at least one subset, the firewall rule subset identifier/rule sorter identifies spatially disjoint rules and groups the spatially disjoint rules together within the at least one subset and wherein the firewall rule subset identifier/rule sorter the rules within each of the spatially disjoint groupings.

18. The system of claim 16 wherein the firewall rule subset identifier/rule sorter identifies at least another subset of rules in the ordered set of firewall rules that are non-disjoint and refrains from sorting the rules in the at least another subset and wherein the firewall packet filter filters the packets using the sorted, disjoint rules and the non-sorted, non-disjoint rules, thereby achieving sub-linear searching for the sorted, disjoint rules and achieving linear searching for the non-sorted, non-disjoint rules.

19. The system of claim 16 wherein the firewall rule subset identifier/rule sorter applies a transform function to each rule in the at least one subset to compute a sortable key for each of the rules and sorting the rules according to the keys.

20. The system of claim 16 wherein the firewall rule subset identifier/rule sorter sorts the rules includes sorting the rules according to hit probabilities.

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21. The system of claim 16 wherein the firewall rule subset identifier/rule sorter sorts the rules includes sorting the rules in a binary search tree.

22. The system of claim 16 wherein the packet filter compares each packet to the sorted rules using a binary search algorithm.

23. The system of claim 16 wherein the packet filter compares each packet to the sorted rules using an interpolated search algorithm.

24. The system of claim 16 wherein the packet filter compares each packet to the sorted rules using an informed search algorithm.

25. The system of claim 16 wherein the packet filter compares each packet to the sorted rules using a hash lookup algorithm.

26. The system of claim 16 wherein each rule includes an IP source address and an IP destination address.

27. The system of claim 16 wherein the firewall includes a plurality of processors, the at least one subset comprises a plurality of subsets and further comprising distributing the subsets across the plurality of processors to implement at least one of pipelined processing, data parallel processing, and function parallel processing.

28. The system of claim 27 wherein the firewall implements a combination of pipelined and function parallel processing.

29. The system of claim 27 wherein the firewall implements a combination of pipelined and data parallel processing.

30. The system of claim 27 wherein the firewall implements a combination of pipelined, data parallel, and function parallel processing.

31. A non-transitory computer readable medium having stored thereon on executable instructions that when implemented by a processor of a computer controls the computer to perform steps comprising:

identifying at least one subset of rules in an ordered set of firewall packet filtering rules that defines a firewall policy such that the at least one subset contains disjoint rules, where disjoint rules are defined as rules whose order can be changed without changing integrity of the firewall policy;

sorting the rules in the at least one subset to statistically decrease the number of comparisons that will be applied to each packet that a firewall encounters; and

filtering packets at the firewall using the sorted rules in the at least one subset by comparing each packet to each of the sorted rules in the at least one subset until the packet is allowed or denied and ceasing the comparing for the packet in response to the packet being allowed or denied and thereby achieving sub-linear searching for the packets filtered using the sorted rules in at least one subset.

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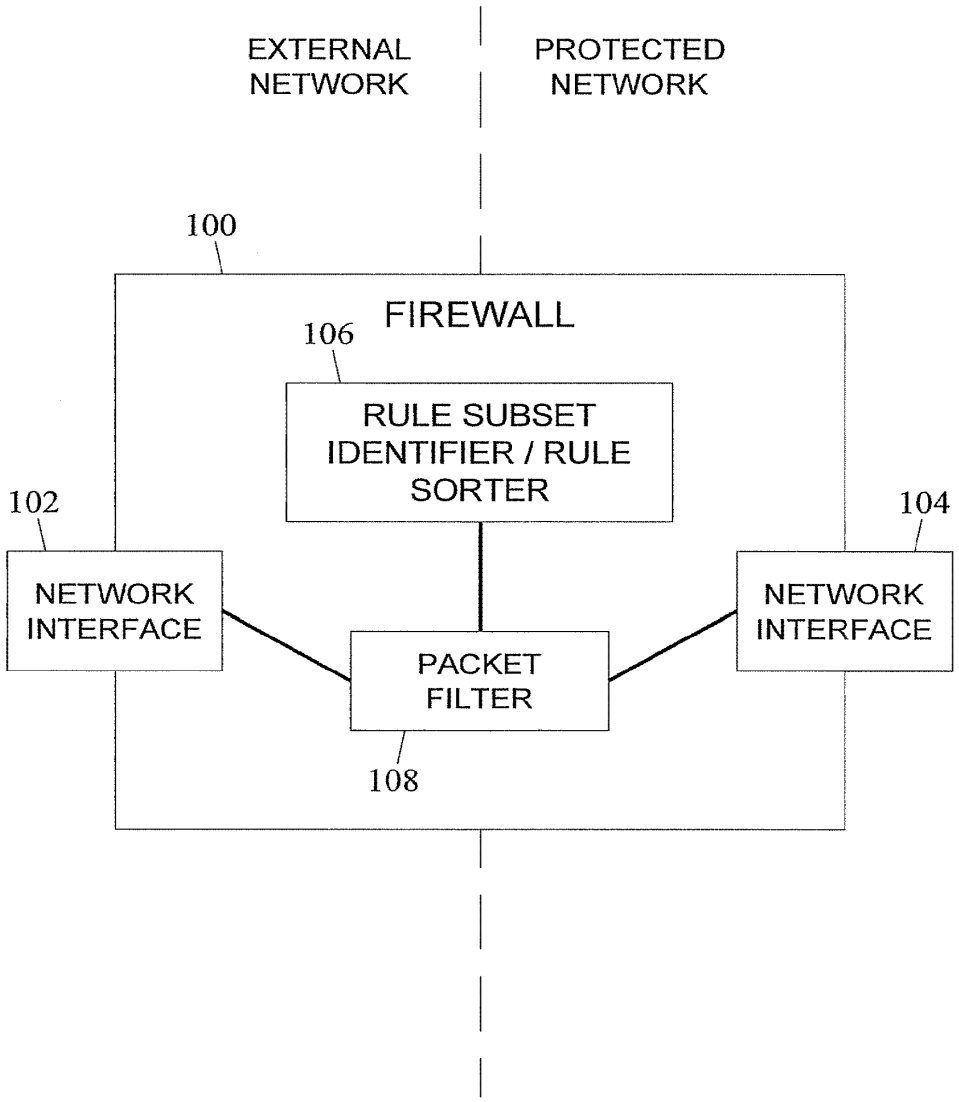
EXTERNAL NETWORK
PROTECTED NETWORK
100
FIREWALL
106
RULE SUBSET IDENTIFIER / RULE SORTER
102
104
NETWORK INTERFACE
NETWORK INTERFACE
PACKET FILTER
108

FIG. 1

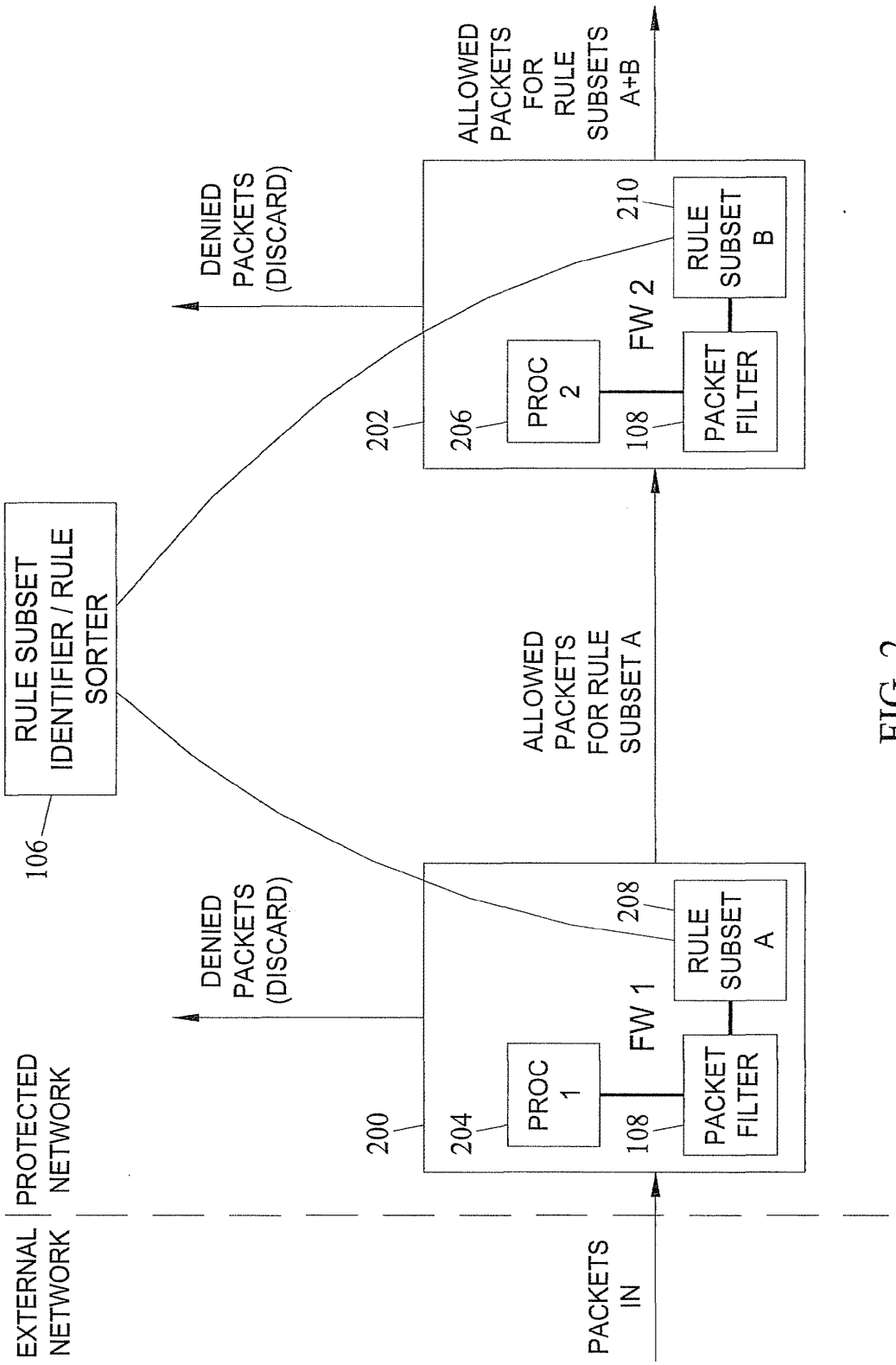
EXTERNAL NETWORK
PROTECTED NETWORK
PACKETS IN
RULE SUBSET IDENTIFIER / RULE SORTER
106
200
204
PROC 1
108
PACKET FILTER
FW 1
208
RULE SUBSET A
202
206
PROC 2
108
PACKET FILTER
FW 2
210
RULE SUBSET B
DENIED PACKETS (DISCARD)
DENIED PACKETS (DISCARD)
ALLOWED PACKETS FOR RULE SUBSET A
ALLOWED PACKETS FOR RULE SUBSETS A+B

FIG. 2

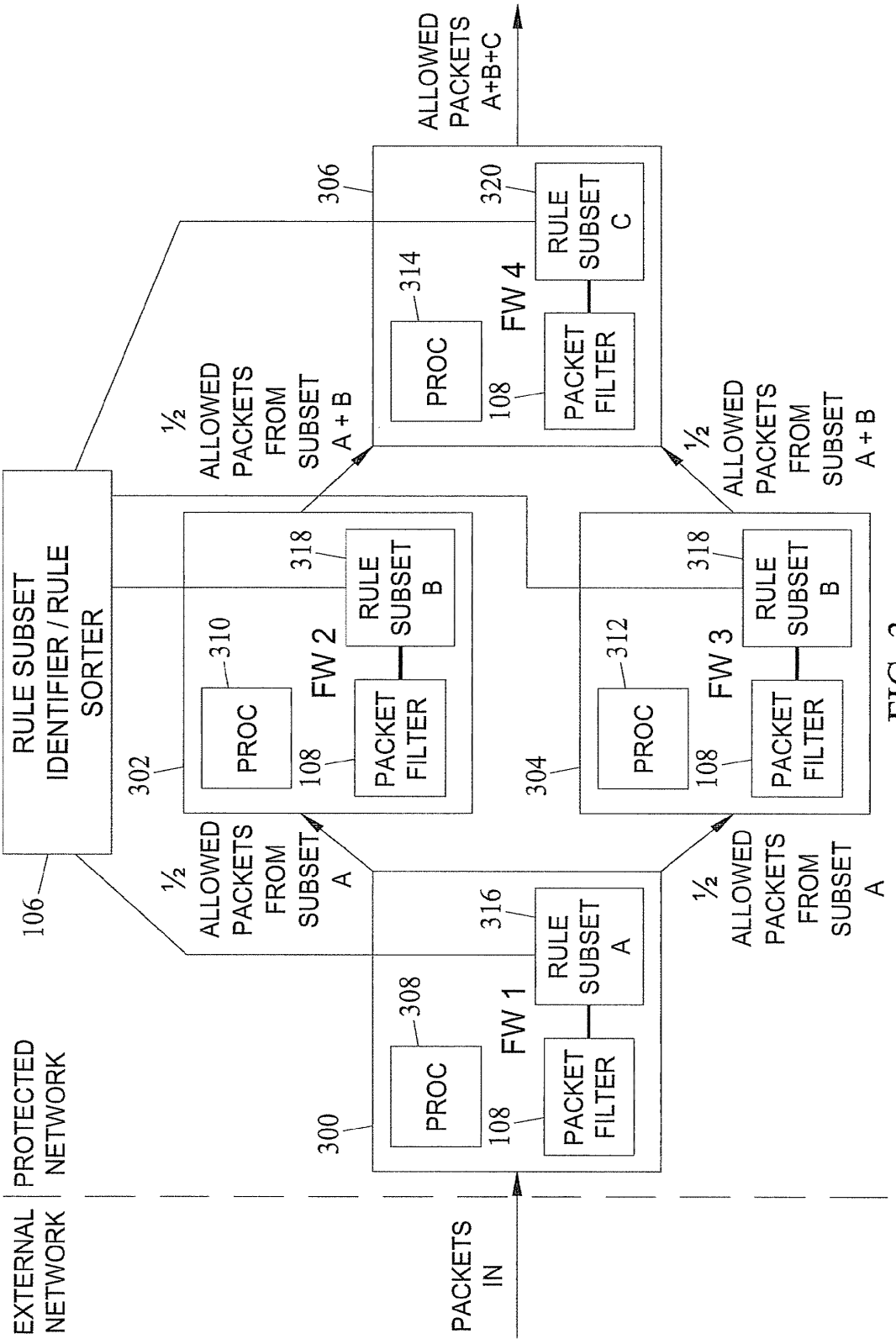
EXTERNAL NETWORK
PROTECTED NETWORK
PACKETS IN
106
RULE SUBSET IDENTIFIER / RULE SORTER
300
PROC
308
FW 1
PACKET FILTER
108
RULE SUBSET A
316
302
PROC
310
FW 2
PACKET FILTER
108
RULE SUBSET B
318
304
PROC
312
FW 3
PACKET FILTER
108
RULE SUBSET B
318
306
PROC
314
FW 4
PACKET FILTER
108
RULE SUBSET C
320
½ ALLOWED PACKETS FROM SUBSET A
½ ALLOWED PACKETS FROM SUBSET A
½ ALLOWED PACKETS FROM SUBSET A + B
½ ALLOWED PACKETS FROM SUBSET A + B
ALLOWED PACKETS A+B+C

FIG. 3

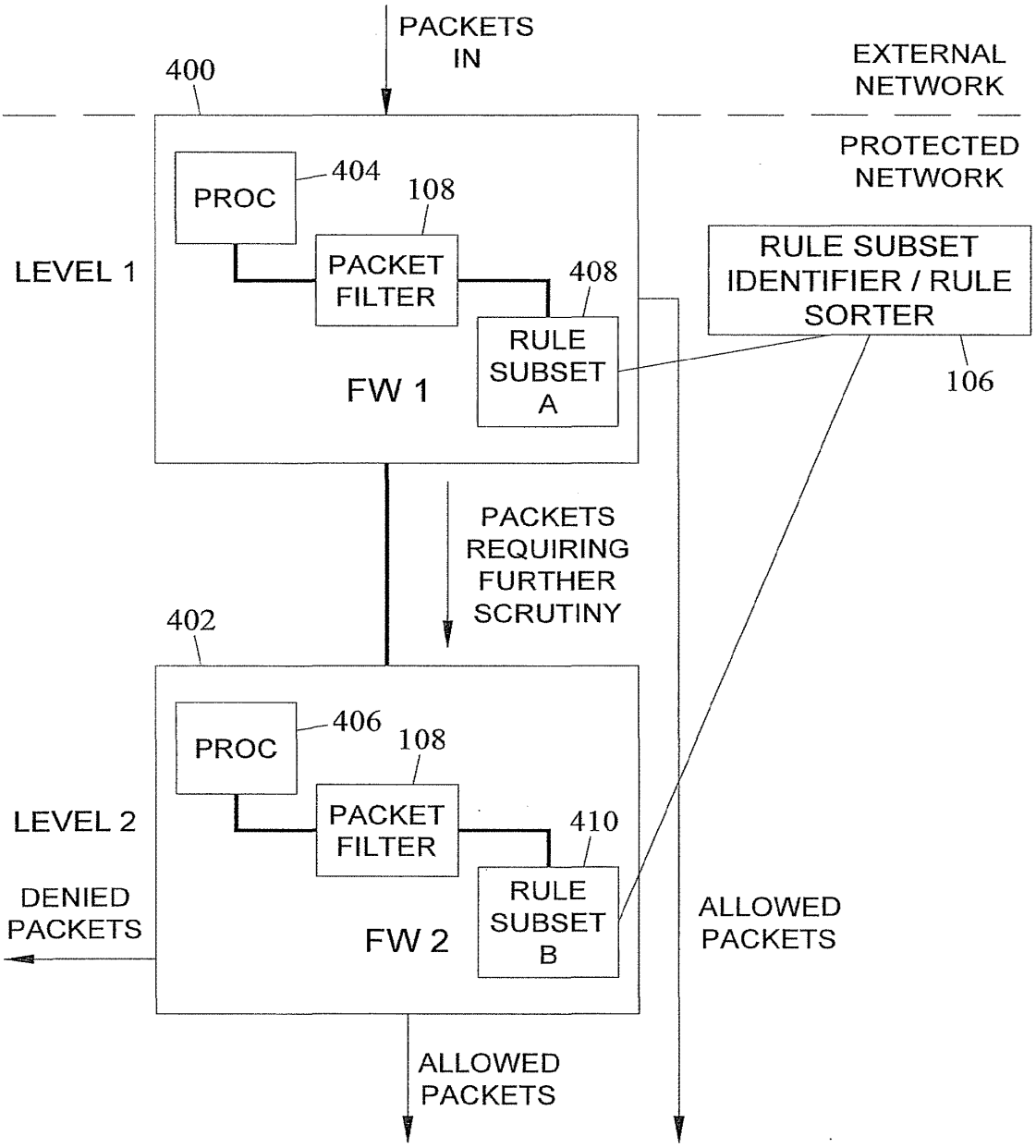
PACKETS IN
400
EXTERNAL NETWORK
PROTECTED NETWORK
PROC
404
108
PACKET FILTER
408
RULE SUBSET A
FW 1
LEVEL 1
RULE SUBSET IDENTIFIER / RULE SORTER
106
PACKETS REQUIRING FURTHER SCRUTINY
402
PROC
406
108
PACKET FILTER
410
RULE SUBSET B
FW 2
LEVEL 2
DENIED PACKETS
ALLOWED PACKETS
ALLOWED PACKETS

FIG. 4

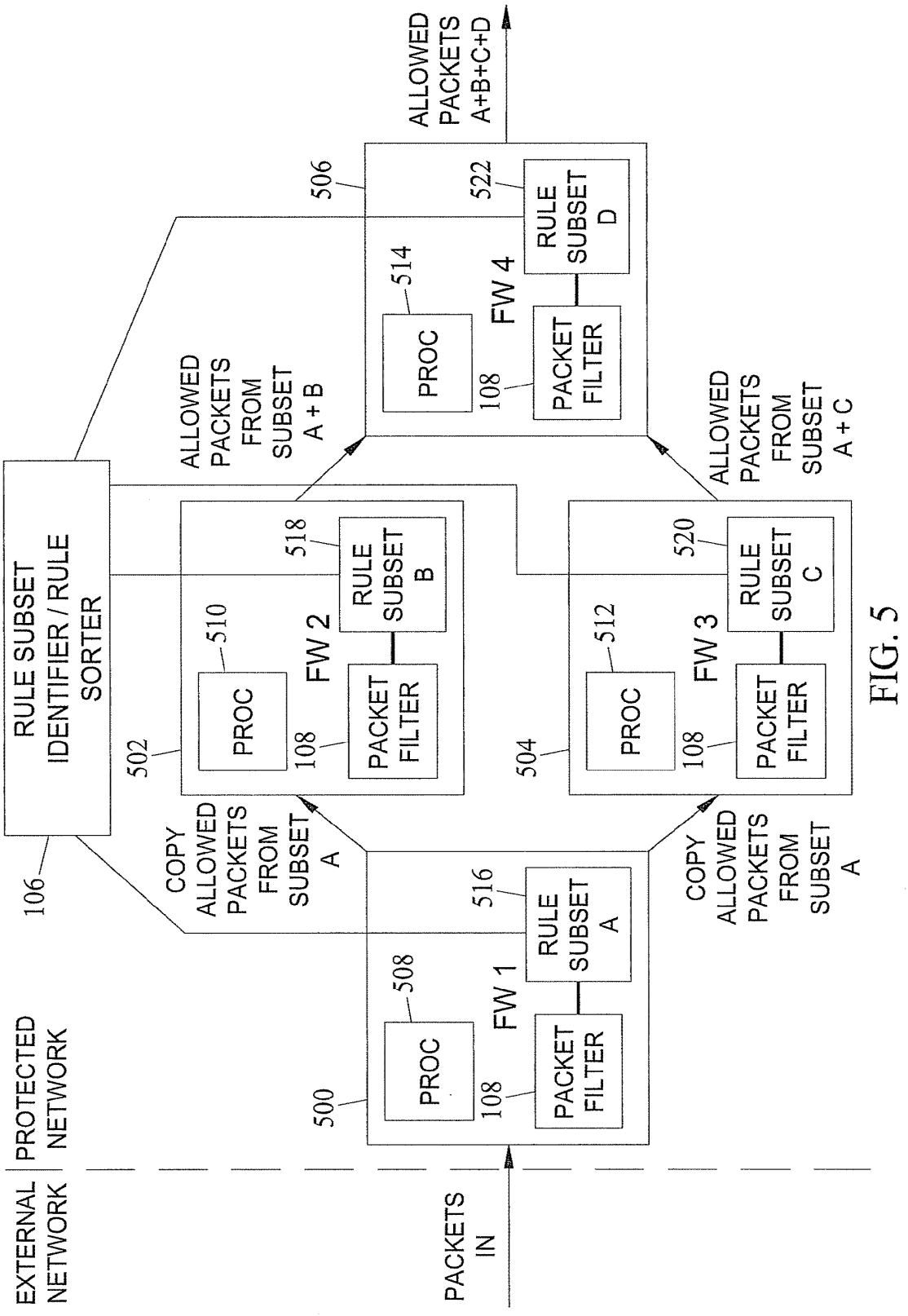
EXTERNAL NETWORK
PROTECTED NETWORK
PACKETS IN
RULE SUBSET IDENTIFIER / RULE SORTER
106
COPY ALLOWED PACKETS FROM SUBSET A
COPY ALLOWED PACKETS FROM SUBSET A
ALLOWED PACKETS FROM SUBSET A + B
ALLOWED PACKETS FROM SUBSET A + C
ALLOWED PACKETS A+B+C+D
500
FW 1
PROC
508
PACKET FILTER
108
RULE SUBSET A
516
502
FW 2
PROC
510
PACKET FILTER
108
RULE SUBSET B
518
504
FW 3
PROC
512
PACKET FILTER
108
RULE SUBSET C
520
506
FW 4
PROC
514
PACKET FILTER
108
RULE SUBSET D
522

FIG. 5

Espacenet

Bibliographic data: EP1484884 (A2) — 2004-12-08

Multi-layered firewall architecture

Inventor(s): SWANDER BRIAN D [US]; MAYFIELD PAUL G [US] ± (SWANDER, BRIAN D, ; MAYFIELD, PAUL G)

Applicant(s): MICROSOFT CORP [US] ± (MICROSOFT CORPORATION)

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- cooperative: **H04L63/0218**; **H04L63/0227**; **H04L63/0236**; **H04L63/0254**; H04L63/164

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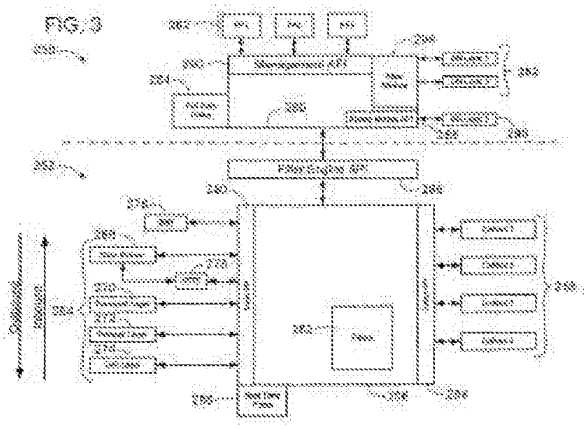
Abstract of EP1484884 (A2)



A method and system are provided for implementing a firewall architecture in a network device. The firewall architecture includes a plurality of network layers, a first firewall engine, and one or more callout modules. The layers send packets and packet information to the first firewall engine, maintain and pass packet context to subsequent layers, and process the packets. The first firewall engine compares the packet information to one or more installed filters and returns an action to the layers indicating how to treat the packet. The callouts provide additional functionality such as intrusion detection, logging, and parental control features.

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(71) Applicant: **MICROSOFT CORPORATION**
Redmond, Washington 98052-6399 (US)

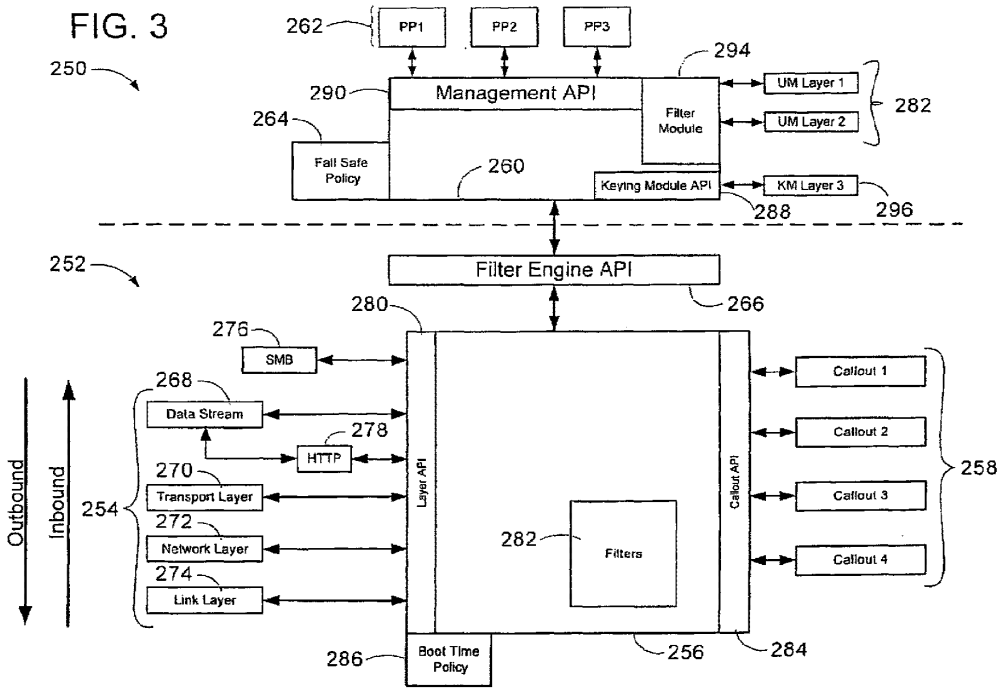
(72) Inventors:
- **Swander, Brian D.**
  Bellevue Washington 98004 (US)
- **Mayfield, Paul G.**
  Sammamish 98075 (US)

(74) Representative: **Grünecker, Kinkeldey,**
Stockmair & Schwanhäusser Anwaltssozietät
Maximilianstrasse 58
80538 München (DE)

(54) Multi-layered firewall architecture

(57) A method and system are provided for implementing a firewall architecture in a network device. The firewall architecture includes a plurality of network layers, a first firewall engine, and one or more callout modules. The layers send packets and packet information to the first firewall engine, maintain and pass packet context to subsequent layers, and process the packets. The first firewall engine compares the packet information to one or more installed filters and returns an action to the layers indicating how to treat the packet. The callouts provide additional functionality such as intrusion detection, logging, and parental control features.

FIG. 3



EP 1 484 884 A2

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Description

RELATED APPLICATIONS

[0001] The present application contains subject matter related to that of patent application "Multi-Layer Based Method for Implementing Network Firewalls," attorney docket number 221039; "A Method and Framework for Integrating a Plurality of Network Policies," attorney docket number 221041; and "Method for Managing Network Filter Based Policy," attorney docket number 221037; filed on the same day as the present application, the disclosures of which are hereby expressly incorporated by reference.

TECHNICAL FIELD

[0002] This invention generally relates to computer systems and to network security. More particularly, this invention relates to a firewall architecture implemented in one or more network devices.

BACKGROUND OF THE INVENTION

[0003] Network protocols are designed to facilitate communication between network devices through an open exchange of data. While the open exchange of data greatly enhances the use of network devices to accomplish tasks, it also creates problems because network protocols are not designed for, and generally do not provide, network security. Computers coupled to both public and private networks, such as Local Area Networks (LANs), Wide Area Networks (WANs), intranets, and the Internet are susceptible to malicious attacks perpetrated by other network devices coupled either directly or indirectly to the network. Such malicious attacks include theft of data, Denial of Service (DOS) attacks, the proliferation of computer viruses, and the like. Other related issues arise when coupling computers to networks such as controlling access to undesirable or inappropriate web sites by children.

[0004] A firewall is a tool used to protect individual users, network devices, and networks in general, from malicious attacks, while also adding the ability to control the exchange of data over the network through implementation of a policy. The firewall implements the policy by examining network packets and determining, based on the examination, whether the packets should be permitted, or conversely blocked, from further traversing the network.

[0005] The policy implemented via the firewall is defined by one or more filters. Each filter includes filter parameters and an associated action. The filter parameters are used to identify network packets that are subject to the firewall policy and include information such as hardware addresses, e.g. Media Access Control (MAC) addresses, network addresses, e.g. Internet Protocol (IP) addresses, protocol type, e.g. Transport Control Protocol (TCP), port numbers, and the like. The action defines how packets with parameters that match the filter parameters should be treated. As a specific example, the filter includes as its parameters a Uniform Resource Locator (URL) address, e.g. "http://www.foo.com." The filter further associates the action of block, i.e. drop the packet, with that URL address. Whenever the firewall examines a packet and through that examination identifies the URL address "http://www.foo.com" as embedded in the packet, the firewall drops the packet thereby preventing it from traversing the network.

[0006] Network devices exchange data by sending and receiving packets through a network stack comprising a layered network architecture. While different network architecture models exist, most include at least an application layer, a transport layer, a network layer, and a link layer. Network packets traverse each layer sequentially and, as each layer is traversed, the packet is subject to processing. For outbound packets, the application layer processes data according to application protocols such as Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP), and Simple Mail Transfer Protocol (SMTP) to name a few. Other layers, such as the network layer and the transport layer packetize the data by embedding it in TCP and IP headers. The layers perform reciprocal processing for inbound packets by, for example, parsing headers, unpacketizing data etc. The layered "stack" architecture and processing function performed by the layers results in a dynamic packet structure whereby packet content including the packet parameters change as the packet traverses the network protocol stack.

[0007] Firewalls examine packets at an inspection point located within the layered network stack. At one extreme, the inspection point is at the application layer. For example, the firewall is deployed as a Layered Service Provider (LSP). Packets at the application layer include the underlying data that will be transmitted to another network device or that has been received from another network device. Examining the packet at the application layer permits the firewall to identify application layer parameters, such as a URL address, and compare the application layer parameters to the filter parameters. However, other packet parameters such as IP addresses, port numbers, MAC addresses, and the like are not available because they have either not been added to outbound packets or have been parsed away from inbound packets.

[0008] At the other extreme, the firewall inspection point is implemented at lower levels of the network stack as an intermediate driver interposed between the link layer and the network layer. Packets at the lower levels of the network

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stack include a maximum number of parameters, e.g. interface numbers, MAC addresses, IP addresses, protocol type, ports, and payload data. Although the packets include such parameters, it does not follow that the parameters are readily identifiable. After the firewall receives the packet, the firewall needs to parse and interpret the relevant packet parameter for comparison with the filter parameters. Thus, both the layers in the network stack and the firewall perform redundant packet parsing and interpretation functions.

SUMMARY OF THE INVENTION

[0009] The present invention is directed towards a firewall architecture that permits application of firewall filters to network packets at all layers within a network stack. The architecture includes a set layer processors capable of processing layer parameters from a network packet. The layer parameters are parameters associated with the layer processor and include parameters that the layer processor parses from, adds to, or otherwise derives from the network packet. The layer processors are further capable of issuing classification requests that include the layer parameters.

[0010] The architecture also includes a first firewall engine comprising a layer interface, a set of installed filters, and a lookup component. The layer interface receives the layer parameters sent as part of the classification request. The first firewall engine lookup component uses the layer parameters to identify one or more matching filters from the set of installed filters. Each matching filter includes an action that instructs the layer processor whether to permit the packet to further traverse the network or whether to block the packet. The first firewall engine returns at least one action to the layer processor via the layer interface.

[0011] In an embodiment of the invention, the layer processors maintain packet context. The layer processor receives the packet context from a previous layer processor and sends the packet context to the first firewall engine. The lookup component in the first firewall engine uses the packet context in combination with the layer parameters to identify the one or more matching filters. The layer processor also modifies the packet context by adding the layer parameters and then sending the modified packet context to a next layer processor.

[0012] In another embodiment of the invention, one or more callouts are included as part of the firewall architecture. Each of the one or more callout modules provide added functionality (beyond permit and block) such as packet logging functions, Internet Protocol Security (IPSec) verification, and execution of parental controls. The callout module is executed on the packet when it is identified as the action in one of the matching filters.

[0013] In another embodiment of the invention, a second firewall engine is provided. The second firewall engine adds new filters into the set of installed filters via a management API. The second firewall engine also includes an instance of the first firewall engine, referred to as a filter module that replicates the services of the first firewall engine within the second firewall engine.

[0014] Additional features and advantages of the invention will be made apparent from the following detailed description of illustrative embodiments, which proceeds with reference to the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] While the appended claims set forth the features of the present invention with particularity, the invention, together with its objects and advantages, may be best understood from the following detailed description taken in conjunction with the accompanying drawings of which:

[0016] Figure 1 is a block diagram generally illustrating an exemplary computer system on which the present invention resides;

[0017] Figure 2 is a block diagram generally illustrating an exemplary network environment whereby the present invention is employed;

[0018] Figure 3 is a block diagram generally illustrating the firewall architecture of the present invention;

[0019] Figure 4 is a block diagram illustrating an exemplary filter used with the present invention;

[0020] Figure 5 is a block diagram illustrating an exemplary data structure for packet context used with the present invention;

[0021] Figure 6 is a block diagram illustrating an exemplary set of application programming interfaces used with the present invention;

[0022] Figure 7 is a block diagram illustrating an exemplary application programming interface used with the present invention;

[0023] Figure 8 is a block diagram illustrating functions performed by network layers according to the present invention; and

[0024] Figure 9 is a block diagram illustrating an exemplary set of callouts used with the present invention.

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DETAILED DESCRIPTION OF THE INVENTION

[0025] A firewall architecture that permits filtering at multiple layer processes, referred to herein as layers, is disclosed. The architecture includes a user mode process and a kernel mode process executing in an operating system. Alternatively, the firewall architecture is executed outside of the operating system in one or more program modules or within a single operating system mode.

[0026] The kernel mode process includes a plurality of layers comprising a protocol stack, a kernel firewall engine, and one or more callouts. The protocol stack includes an application layer, a transport layer, a network layer, and link layer. Additional layers are added or deleted from the architecture as desired. The layers each form a requesting layer capable of receiving a network packet and corresponding packet context data from a previous layer or process. The requesting layer then issues a classification request to the kernel firewall engine via a layer API. The classification request includes the packet received by the requesting layer, the packet context, and a set of layer parameters associated with the requesting layer. The kernel firewall engine processes the request and returns an action. The action, by way of example, instructs the requesting layer how to treat the packet (e.g. permit or block). If the action is permit, the requesting layer processes the packet according to a layer protocol, modifies the packet context to include the layer parameters, and passes the packet and packet context to a next layer. If the action is block, the requesting layer drops the packet and does not pass the packet to the next layer. The requesting layer may perform additional functions as a result of the block action, such as tearing down a TCP connection where a TCP packet is dropped.

[0027] The kernel firewall engine includes the layer API, a set of installed filters, and a callout API. Each of the set of installed filters includes a set of filter conditions and an associated action. The kernel firewall engine processes the classification request sent from the requesting layer by identifying one or more matching filters. The matching filters have filter conditions that match the layer parameters and packet context. Once the matching filters are identified, they are applied in order of filter priority. If the action of the filter being applied is permit or block, the action is returned to the requesting layer. If the action is callout, the classification request issued by the requesting layer, along with matching filter identification, is passed to one of the callout modules. The callout module performs its programmed function, and returns an action to the kernel firewall engine.

[0028] The kernel firewall engine applies matching filters in order of priority to the packet until at least a terminating action is designated. Once the terminating action is designated, it is returned to the requesting layer and no additional matching filters are applied. If no matching filters are identified for a packet, the requesting layer is notified that no matching filters were found and the requesting layer then decides how to treat the packet. Typically, where no matching filter is identified, the requesting layer treats the packet as if a permit action was returned.

[0029] Exemplary user mode processes include a user mode firewall engine and one or more policy providers. The policy providers obtain policy from any suitable source such as volatile or non-volatile memory or is user entered through a graphical user interface or similar tool. The policy is a source of information for rendering a new filter, including the set of filter conditions and associated actions.

[0030] The user mode also includes an instance of the kernel firewall engine within the user firewall engine thereby permitting user mode layers to be created. The user mode layers then use the user mode instance of the kernel firewall engine to install filters, and identify filters that match a set of parameters allowing the application of filtering within the user mode.

[0031] In an embodiment of the invention, a callout interface from the firewall engine to a set of callout modules enables virtually unlimited extension of the firewall capabilities. By way of example, an HTTP context callout provides a parental control feature by identifying acceptable and unacceptable URL addresses. An IPSec callout verifies that packets that are supposed to use IPSec have been properly subject to IPSec processing. A logging callout logs packets meeting established criteria thereby facilitating later examination of packets. An intrusion detection callout identifies suspicious packets based on known algorithms.

[0032] Turning to the drawings, wherein like reference numerals refer to like elements, the invention is illustrated as being implemented in a suitable computing environment. Although not required, the invention will be described in the general context of computer-executable instructions, such as program modules, being executed by a personal computer. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. The invention may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

[0033] Figure 1 illustrates an example of a suitable computing system environment 100 on which the invention may be implemented. The computing system environment 100 is only one example of a suitable computing environment and is not intended to suggest any limitation as to the scope of use or functionality of the invention. Neither should the computing environment 100 be interpreted as having any dependency or requirement relating to any one or combination of components illustrated in the exemplary operating environment 100.

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[0034] The invention is operational with numerous other general purpose or special purpose computing system environments or configurations. Examples of well known computing systems, environments, and/or configurations that may be suitable for use with the invention include, but are not limited to, personal computers, server computers, handheld or laptop devices, multiprocessor systems, microprocessor-based systems, set top boxes, programmable consumer electronics, network PCs, minicomputers, mainframe computers, distributed computing environments that include any of the above systems or devices, and the like.

[0035] The invention may be described in the general context of computer-executable instructions, such as program modules, being executed by a computer. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. The invention may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules may be located in both local and remote computer storage media including memory storage devices.

[0036] With reference to Figure 1, an exemplary system for implementing the invention includes a general purpose computing device in the form of a computer 110. Components of computer 110 may include, but are not limited to, a processing unit 120, a system memory 130, and a system bus 121 that couples various system components including the system memory to the processing unit 120. The system bus 121 may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures. By way of example, and not limitation, such architectures include Industry Standard Architecture (ISA) bus, Micro Channel Architecture (MCA) bus, Enhanced ISA (EISA) bus, Video Electronics Standards Associate (VESA) local bus, and Peripheral Component Interconnect (PCI) bus also known as Mezzanine bus.

[0037] Computer 110 typically includes a variety of computer readable media. Computer readable media can be any available media that can be accessed by computer 110 and includes both volatile and nonvolatile media, removable and non-removable media. By way of example, and not limitation, computer readable media may comprise computer storage media and communication media. Computer storage media includes both volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules or other data. Computer storage media includes, but is not limited to, RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by computer 110. Communication media typically embodies computer readable instructions, data structures, program modules or other data in a modulated data signal such as a carrier wave or other transport mechanism and includes any information delivery media. The term "modulated data signal" means a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal. By way of example, and not limitation, communication media includes wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, RF, infrared and other wireless media. Combinations of the any of the above should also be included within the scope of computer readable media.

[0038] The system memory 130 includes computer storage media in the form of volatile and/or nonvolatile memory such as read only memory (ROM) 131 and random access memory (RAM) 132. A basic input/output system 133 (BIOS), containing the basic routines that help to transfer information between elements within computer 110, such as during start-up, is typically stored in ROM 131. RAM 132 typically contains data and/or program modules that are immediately accessible to and/or presently being operated on by processing unit 120. By way of example, and not limitation, Figure 1 illustrates operating system 134, application programs 135, other program modules 136, and program data 137.

[0039] The computer 110 may also include other removable/non-removable, volatile/nonvolatile computer storage media. By way of example only, Figure 1 illustrates a hard disk drive 141 that reads from or writes to non-removable, nonvolatile magnetic media, a magnetic disk drive 151 that reads from or writes to a removable, nonvolatile magnetic disk 152, and an optical disk drive 155 that reads from or writes to a removable, nonvolatile optical disk 156 such as a CD ROM or other optical media. Other removable/non-removable, volatile/nonvolatile computer storage media that can be used in the exemplary operating environment include, but are not limited to, magnetic tape cassettes, flash memory cards, digital versatile disks, digital video tape, solid state RAM, solid state ROM, and the like. The hard disk drive 141 is typically connected to the system bus 121 through a non-removable memory interface such as interface 140, and magnetic disk drive 151 and optical disk drive 155 are typically connected to the system bus 121 by a removable memory interface, such as interface 150.

[0040] The drives and their associated computer storage media discussed above and illustrated in Figure 1, provide storage of computer readable instructions, data structures, program modules and other data for the computer 110. In Figure 1, for example, hard disk drive 141 is illustrated as storing operating system 144, application programs 145, other program modules 146, and program data 147. Note that these components can either be the same as or different from operating system 134, application programs 135, other program modules 136, and program data 137. Operating

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system 144, application programs 145, other program modules 146, and program data 147 are given different numbers hereto illustrate that, at a minimum, they are different copies. A user may enter commands and information into the computer 110 through input devices such as a keyboard 162 and pointing device 161, commonly referred to as a mouse, trackball or touch pad. Other input devices (not shown) may include a microphone, joystick, game pad, satellite dish, scanner, or the like. These and other input devices are often connected to the processing unit 120 through a user input interface 160 that is coupled to the system bus, but may be connected by other interface and bus structures, such as a parallel port, game port or a universal serial bus (USB). A monitor 191 or other type of display device is also connected to the system bus 121 via an interface, such as a video interface 190. In addition to the monitor, computers may also include other peripheral output devices such as speakers 197 and printer 196, which may be connected through a output peripheral interface 195.

[0041] The computer 110 may operate in a networked environment using logical connections to one or more remote computers, such as a remote computer 180. The remote computer 180 may be another personal computer, a server, a router, a network PC, a peer device or other common network node, and typically includes many or all of the elements described above relative to the personal computer 110, although only a memory storage device 181 has been illustrated in Figure 1. The logical connections depicted in Figure 1 include a local area network (LAN) 171 and a wide area network (WAN) 173, but may also include other networks. Such networking environments are commonplace in offices, enterprise-wide computer networks, intranets and the Internet.

[0042] When used in a LAN networking environment, the personal computer 110 is connected to the LAN 171 through a network interface or adapter 170. When used in a WAN networking environment, the computer 110 typically includes a modem 172 or other means for establishing communications over the WAN 173, such as the Internet. The modem 172, which may be internal or external, may be connected to the system bus 121 via the user input interface 160, or other appropriate mechanism. In a networked environment, program modules depicted relative to the personal computer 110, or portions thereof, may be stored in the remote memory storage device. By way of example, and not limitation, Figure 1 illustrates remote application programs 185 as residing on memory device 181. It will be appreciated that the network connections shown are exemplary and other means of establishing a communications link between the computers may be used.

[0043] In the description that follows, the invention will be described with reference to acts and symbolic representations of operations that are performed by one or more computer, unless indicated otherwise, As such, it will be understood that such acts and operations, which are at times referred to as being computer-executed, include the manipulation by the processing unit of the computer of electrical signals representing data in a structured form. This manipulation transforms the data or maintains it at locations in the memory system of the computer, which reconfigures or otherwise alters the operation of the computer in a manner well understood by those skilled in the art. The data structures where data is maintained are physical locations of the memory that have particular properties defined by the format of the data. However, while the invention is being described in the foregoing context, it is not meant to be limiting as those of skill in the art will appreciate that various of the acts and operation described hereinafter may also be implemented in hardware.

[0044] A network environment wherein the firewall architecture of the present invention is used will now be described with reference to FIG. 2. The network is exemplary in nature as the firewall architecture of the present invention is implemented in any network device that is coupled to any network configuration. The network environment includes a private network 200 and a public network 202. The private network 200 and public network 202 are any suitable type such as Local Area Networks (LANs), Wide Area Networks (WANs), intranets, the Internet, or any combination thereof.

[0045] The network environment includes a plurality of network devices 204, 206, 208, 210 and 212. Network devices 204, 206 are coupled to the private network 200. Network devices 210, 212 are coupled to the public network 202. The network device 208 is coupled to, and provides an interface between, both the private network 200 and the public network 202. The network devices are coupled to the public and private networks using any suitable technology such as Ethernet, 1394, or 802 11 (b). The network devices are further implemented as any suitable computing devices such as personal computers, servers, handheld devices, printers, switches, routers, bridges, repeaters or the like.

[0046] The network device 208 includes a firewall 214 and one or more filters 216. The firewall 214 is a program module or a set of program modules, implemented according to the architecture of the present invention, that examine network packets exchanged between the network devices 204, 206, 208 coupled to the private network 200 and the network devices 210, 212 coupled to the public network 202. In an embodiment of the invention, the firewall 214 also examines locally destined network packets sent from, and destined to, network devices within the private network 200.

[0047] The firewall 214 is implemented in network device 208 to protect and control network traffic exchanged between the private network 200 and the public network 202, referred to as an edge firewall. Alternatively, the firewall 214 is implemented in, and protects, a single network device such as illustrated in the network device 210, referred to as a host firewall. The firewall is also capable of being implemented as a centrally administered set of hosts and/or edge firewalls in a synchronized manner, referred to as a distributed firewall. Placement of the network device or devices implementing the firewall 214 is preferably selected such that the firewall 214 examines all network traffic

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destined for the network devices it is supposed to protect.

[0048] The filters 216 are implemented as part of the firewall 214. Alternatively, the filters 216 are implemented as part of separate data structure accessible by the firewall 214. The firewall 214 and filters 216 execute a firewall policy designed to protect network devices 204, 206, 208 from malicious attacks originating from network devices 210, 212 coupled to the public network. The firewall 214 also provides added functionality such as facilitating parental controls, intrusion detection, logging of network packets, and other added filter based functionality.

[0049] Each filter 216 includes a set of filter conditions and one or more associated actions. The filter conditions include parameters and information that can be parsed or otherwise obtained from network packets such as interface numbers, hardware addresses, network addresses, protocol type, port numbers, and payload data. The one or more associated actions define how the network device implementing the firewall should treat packets that match the filter conditions. Typical actions include permit, i.e. allow the packet to continue network traversal, and block, i.e. preclude further network traversal by dropping packet.

[0050] The firewall 214 examines network packets traversing the network when received at network device 208 and, by comparing the packet parameters to the filter conditions, identifies one or more matching filters. A matching filter results when the filter conditions match the packet parameters. The packet parameters, like filter conditions, include information that is parsed or otherwise obtained from packets. When the firewall identifies a matching filter, the one or more actions associated with the filter conditions are executed.

[0051] FIG. 3 shows an overall view an embodiment of the firewall architecture of the present invention. The architecture provides the ability to subject packets to filters at all layers of a network stack. The firewall provides central management capabilities that allow filters to be added and deleted and for filter conflicts to be identified and resolved. The firewall architecture is extensible in that filter layers are added and deleted as needed and is expanded to include specialized functionality beyond permit and block actions. Although the invention is described with specific reference to firewalls and firewall filters, it is also used to facilitate and manage other filters and policies. As specific examples, the present invention is suitable for facilitating and managing filters used with Quality of Service (QOS), Internet Protocol Security (IPSec) suite, as well as other encrypting, authenticating, and key management protocols.

[0052] The firewall architecture includes a user mode process 250 and a kernel mode process 252. The user mode process 250 and kernel mode process 252 execute as part of an operating system in a network device. Those skilled in the art will appreciate that the user mode process 250 and the kernel mode process 252 of the operating system include additional components that for simplicity are not shown. Alternatively, the firewall architecture is executed in whole or in part outside of the operating system as one or more program modules or application programs or within a single operating system process.

[0053] The kernel mode process 252 includes a network stack 254, a first firewall engine referred to herein as a kernel firewall engine 256, and optional callouts 258. Collectively, the kernel mode process 252 implements an established firewall policy by identifying matching filters for network packets, processing packets according to known protocols, and executing other actions on the packet as designated by matching filters.

[0054] The network stack 254 comprises a plurality of layer processes, referred to herein as layers, including a data stream layer 268, a transport layer 270, a network layer 272, and a link layer 274. The firewall architecture of the present invention is extensible and additional layers are dynamically added and deleted as needed. An example of an added layer includes file access layer 276, implemented according to a Server Master Block (SMB) protocol. The layers may work in cooperation with other program modules such as a Hypertext Transfer Protocol (HTTP) parser module 278.

[0055] The layers in the network stack 254 process inbound and outbound network packets. Outbound network packets are packets being transmitted from the network device implementing the firewall architecture onto the network. Inbound packets are packets received at the network device implementing the firewall architecture. As indicated by the respective arrows shown in Fig. 3, inbound packets traverse the network stack 254 from bottom to top and outbound packets traverse the network stack 254 from top to bottom.

[0056] Network packets traverse, and are processed by, the network layers sequentially. In accordance with known techniques, each layer in the network stack 254 is capable of receiving packets from a previous layer or process, processing the packet according to a specification or protocol, and sending the processed packet to a next layer or process. In accordance with the invention, each layer in the network stack 254 also maintains packet context, passes the packet context to the next layer, issues a classification request to the kernel firewall engine 256, and takes action on the packet according to the firewall policy..

[0057] The packet context is a data structure that follows the packet from layer to layer. Each layer maintains the context by adding into the context data structure a set of parameters that the layer is designed to process, e.g. the information that the layer is designed to parse from inbound packets, add to outbound packets or otherwise derive from contents of packets. An exemplary data structure used for the packet context is described with reference to Fig. 5.

[0058] One of the operations carried out by the layers of the network stack 254 is to invoke the kernel firewall engine by issuing the classification request. The classification request is a call by a layer in the network stack 254 requesting that any filters that match the packet be identified and any associated action, e.g. permit or block, be returned to the

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layer. The layer issuing the classification request is referred to herein as a requesting layer. Each layer also takes the action on the packet that is returned by the kernel firewall engine 256.

[0059] The kernel firewall engine 256 includes a layer API 280, a set of installed filters 282, and a callout API 284. The kernel firewall engine 256 performs various functions including (1) maintaining the set of installed filters 282 defining the firewall policy, (2) receiving classification requests from the layers in the network stack 254, (3) identifying one or more matching filters based on the classification request, and (4) instructing the requesting layer of any action to take on the packet based on the matching filters.

[0060] Each filter of the set of installed filters includes a set of filter conditions and one or more associated actions. As described with reference to FIG. 2, the filter conditions identify the network packets that are subject to the associated filter action. The actions specified in the set of installed filters 282 include permit and block. Additional functionality is added via optional callouts 258. An exemplary form of the filters is described with reference to Fig. 4.

[0061] The layer API 280 provides an interface between the layers in the network stack 254 and the kernel firewall engine 256. Through the layer API 280, the requesting layer issues the classification request to the kernel firewall engine 256. The classification request includes the packet as received by requesting layer, the packet context as received by the requesting layer, and layer parameters. The layer parameters are packet parameters processed by, e.g. added or parsed, by the requesting layer. As a specific example, source and destination Internet Protocol (IP) addresses are layer parameters sent by the network layer 272 when implementing the IP protocol. Layer parameters may also include information beyond the packet parameters that are added to or parsed from the packet. As a specific example, the layer parameters include a local address type. The local address type is determined by the IP layer and sent as part of the classification request. Local address types include unicast, broadcast, multicast, anycast and the like. A specific implementation of the layer API 280 is described with reference to FIG. 6.

[0062] Optionally, the callouts 258 are used to implement added functionality beyond the permit and block filter actions. A callout is executed when the kernel firewall engine 256 identifies a matching filter for the packet that includes, as the associated action, a callout to one of the callout modules. The kernel firewall engine sends the classification request as issued by the requesting layer, i.e. full packet, layer parameters, and packet context, to the callout module, along with an identification of the matching filter, via the callout API 284. In an embodiment of the invention, the firewall architecture includes a base set of callouts 258. Additional callouts, like layers, are added as needed to the extensible firewall architecture. A specific implementation of the callout API 284 is described with reference to Fig. 6.

[0063] The user mode process 250 includes a second firewall engine referred to as a user firewall engine 260 and one or more policy providers 262 identified as "PP1," "PP2," and "PP3." The policy providers 262 are processes that add firewall policy, i.e. installed filters 282, into the firewall architecture. Any process is used to accomplish this task. An example is a legacy IPSec policy service (LIPS). The legacy IPSec policy service adds filters defining network traffic that is supposed to use IPSec protocols such as Encapsulating Security Protocol (ESP) and Authentication Header Protocol (AH). As a specific example, the legacy IPSec policy adds a firewall policy indicating that all unsolicited inbound packets must be encrypted according to the ESP protocol. The policy further provides that any unsolicited inbound packet in clear text, i.e. an unencrypted packet, should be blocked. The policy providers 262 obtain the policy from any suitable source such as data in volatile or nonvolatile memory, or a Graphical User Interface (GUI) that permits an administrator or system users to directly enter policy. The user firewall engine 260 converts the policy into a new filter, i.e. defines the policy in terms of filter conditions and associated actions, and adds the new filter into the set of installed filters 282.

[0064] The user firewall engine 260 also performs filter arbitration and conflict resolution functions. When the policy provider 262 provides new policy to the user mode firewall engine 260, the user firewall engine determines whether the new filter resulting from the new policy conflicts with any of the installed filters 282. An example of a method of identifying and resolving conflicts that is suitable for use in the framework of the present invention is described in United States Patent Application entitled "Method for Managing Network Filter Based Policy," attorney docket number 221037.

[0065] The architecture further includes a filter engine API 266 that forms an interface between the user mode firewall engine 260 and the kernel firewall engine 256. The filter engine API 266 provides a mechanism for the user firewall engine 260 to add new filters to or remove existing filters from the set of installed filters 282, and to examine installed filters 282 so that filter conflicts can be detected and resolved. A management API 290, accessible by policy providers 262, also provides a mechanism to add and remove filters from the architecture.

[0066] The user mode firewall engine 260 also includes a filter module 294. The filter module 294 is an instance of the kernel firewall engine 256 in the user mode 250. The instance of the filter module 294 in the user mode firewall engine 260 permits the user firewall engine 260 to replicate the services of the kernel firewall engine 256 for one or more user mode layer processes referred to herein as user mode layers 282. The user mode layers 282 are added in the same way that kernel mode layers are created. Because the filter module 294 is the user mode instance of the kernel firewall engine 256, it will be understood that any functionality described herein for the kernel firewall engine 256 also applies to the filter module 294.

[0067] A keying module API 288 provides an interface between the user policy engine 260 and keying module 296.

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The keying module API 288 is used to signal the keying module of the need to establish an SA.

[0068] The firewall architecture includes a boot time policy 286 and a failsafe policy 264. The boot time policy 286 and the failsafe policy 264 are implemented to provide a basic set of installed filters 282 while the system is in a transitional state such as when the network device is initialized, e.g. turned on, reset, or restarted. During the transitional state, there is a latent period during which the user mode 250 is not established and it is not possible to install filters via policy providers 262 and the user firewall engine 260. As a result, the network device is vulnerable to malicious attacks from, for example, unsolicited inbound packets. The boot time policy 286 resides in the kernel mode 252 and is loaded into the kernel firewall engine 256 prior to the time the user mode 250 is established. The boot time policy 296 provides the basic installed filter 282 configurable to provide any suitable filter conditions and associated actions for protecting the system during the transitional state. An example of the boot time policy 286 is one that blocks all inbound and outbound network packets.

[0069] Once the user mode 250 is established, the transitional state continues while the policy providers 262 are identifying policy and attempting to add installed filters 282 into the kernel firewall engine 256. When the user mode 250 is established, the user firewall engine 260 first loads the fail-safe policy 264 into the kernel firewall engine 256 before any policy is accepted by the policy providers 262. The boot time policy 286 is then disabled. Like the boot time policy 286, the fail-safe policy 264 is a basic filter designed to protect the system from attacks during the transitional state when the policy providers and user firewall engine are still in the process of installing filters. Once the policy providers 262 successfully install their respective filters into the network device, the fail-safe policy 264 is disabled.

[0070] Referring to FIG. 4, the set of installed filters 282 will now be described. Each filter 310 of the set of installed filters 282 has a plurality of fields including a filter Id 312, a weight 314, one or more actions 316, a policy context 328, and a set of filter conditions 318. The filter Id 312 provides a unique identification to the filter. The filter Id 312 is used, for example, as a means for the kernel firewall engine 256 to return matching filter information to the user firewall engine 260 and the callouts 258. In an embodiment of the invention, the filter is assigned to one of the layers in the network stack 254. The filter Id 312 is used by the kernel firewall engine 256 to track which filter is assigned to which layer.

[0071] The weight field 314 includes a value that identifies priority of the filter 310. The higher the value in the weight field 314, the higher the priority of the filter. The filter priority determines the order whereby matching filters are applied to the packet by the kernel firewall engine 256.

[0072] In an embodiment of the invention, the filter with the highest priority, i.e. highest weight value, is applied first, then the next highest priority filter is applied and so on, until a matching filter with a terminating action is encountered. Terminating actions are described in more detail below. Once the matching filter with the terminating action is applied, the kernel firewall engine 256 stops applying matching filters. Thus, the action 316 specified by lower priority matching filters are not taken on the packet after the terminating action is applied. Alternatively, the firewall engine 256 identifies a single matching filter and returns a set of actions from the single matching filter.

[0073] The set of filter conditions 318 determine whether a packet matches the filter 310. Each filter condition 318 includes a type 320, data 322, and a layer Id:field Id 324. The type 320 defines the length and number of variables included in the corresponding data 322. The architecture provides for predefined known variable types such as Byte, Short, Long, 8 Bytes, String, Internet Protocol version 4 (IPv4) Address, Internet Protocol version 6 (IPv6) Address, IPv4 Address plus Mask, IPv6 Address plus Mask, and Address Range.

[0074] The data field 322 includes data matching the type. For example, if the type is IPv4 Address, an acceptable value for the data field 322 is a 32-bit number in range of 00.00.00.00 to 255.255.255.255 as expressed in dotted decimal notation. In some instances, the type 320 provides for multiple values in the data field 322. The Address Range, IPv4 Address plus Mask, and IPv6 Address plus mask types allow two IP address values, defining a beginning and ending range of IP addresses. For maximum flexibility, the architecture also permits user-defined types. Alternatively, additional types are manually added to the system architecture.

[0075] The layer Id:field Id 324 is used to identify an originating layer and a parameter from the originating layer, respectively. The originating layer and the parameter from the originating layer define packet parameters, i.e. layer parameters and packet context that the data 322 is compared against when identifying matching filters. The originating layer identifies a layer in the network stack. The parameter from the originating layer identifies a specific parameter associated with the originating layer. A specific example is illustrated by filter condition 326. The type is IPv4 thereby indicating the data 322 is a 32-bit IP address. The layer Id is "IP" representing that the 32 bit number is an IP, i.e. network, layer parameter. The field Id is "Src IP Addr" which in the example represents a source IP address. The IP address provided in the data field 322 is "123.3.2.1" indicating that any packet with that source IP address meets the filter condition thereby matching the filter. The filter 310 may include multiple filter conditions 318, in which case a packet matches the filter 310 only if all filter conditions are met.

[0076] The action 316 in the filter 310 is permit, block, or callout. If the action 324 in the filter 310 is permit or block and the packet matches the filter 310, the permit or block action is returned to the requesting layer by the kernel firewall engine 256. If the action 316 is callout, the kernel firewall engine 256 issues its own classification request that includes

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the full packet, layer parameters, context and identification of the matching filter to the designated callout module 258. The callout module 258 performs its programmed function on the packet, e.g. intrusion detection. The callout may return an action (either permit, block) to the kernel firewall engine, which in turn relays the action to the requesting layer. The callout is also capable of maintaining packet context that is likewise returned to the requesting layer via the kernel firewall engine 256. The action may also be a value, such as a null value, indicating that no firewall policy exists.

[0077] Actions are designated terminating or non-terminating. If the action is terminating, once that action is identified for a packet, the action is returned to the requesting layer and no additional filters are applied to the packet. If the action is non-terminating, additional filter lookups continue until a terminating action for the packet is identified. As a default, permit and block are designated terminating actions.

[0078] The policy context 328 is used to store policy other than firewall policy, such as security policy or QOS policy. The policy context is any suitable data structure. For example, the policy context is a 64 bit number that is interpreted by a process that added the policy context. The policy context and/or action may be a null value.

[0079] FIG. 5 illustrates an example of a data structure 330 used for the packet context that is maintained by, and passed to, the layers in the network stack 254 and the callout modules 258. The packet context 330 follows the inbound or outbound network packet as it traverses the layers and includes one or more entries, labeled 336-340. Each entry includes a layer Id:field Id 332 and a corresponding value 334.

[0080] The layer Id:field Id 332 has the same meaning as the layer Id:field Id 324 provided as part of the filter conditions 318 in the filters 310 (FIG. 4). Namely, the layer Id:field Id 322 identifies the originating layer and the layer parameter from the originating layer for the data in the value field 334. The value field 334 includes a specific layer parameter.

[0081] As a specific example, entry 336 includes the layer Id:field Id 332 "NDIS: Src. MAC Addr." "NDIS" represents a Network Driver Interface Specification implementation of the Link layer 274 (Fig. 1). "Src MAC addr." represents a source MAC address. Thus, the layer:field Id 332 indicates that the data in the value field 334 is a source MAC address that was processed by the NDIS (Link) layer. The value field 334 includes the actual source MAC address which in the example is "00.08.74.4F.22.E5" as expressed in hexadecimal notation.

[0082] As a second example, entry 338 has a layer Id:field Id 332 of "NDIS:IF No." This again identifies the layer as NDIS, but in this case identifies the parameter as "IF No" representing an interface number as the specific NDIS parameter. The value field 334 includes the actual interface number, which in this case is 2.

[0083] As a third example, entry 340 has a layer Id:field Id 332 of "IP:Dst IP Addr." The "IP" represents the network layer using the IP protocol and the "Dst IP Addr" represents a destination IP address as the IP layer parameter. The value field 334 includes the actual destination IP address of "123.3.2.1."

[0084] Having described the underlying firewall architecture of the present invention, attention is drawn to the functional interfaces of the system and exemplary methods that are performed using the underlying firewall architecture described herein. The functional interfaces are implemented as a plurality of application programming interfaces (APIs) The APIs include the layer API 280, the callout API 284, the filter engine API 266, and the keying module API 288 as shown in FIG. 6 and FIG. 7.

[0085] The layer API 280 facilitates data exchange between each of the layers in the network stack 254 and the kernel firewall engine 256.. As shown, the layer API 280 includes a Classify method 402, an Add Layer method 404, and a Delete Layer method 406. The layer API 280 may also execute within the filter module 294 to facilitate communication between the user mode layers and the filter module 294.

[0086] The Classify method 402 is used by the requesting layer to send layer parameters, the packet as received by the requesting, and the packet context to the kernel firewall engine 256. The kernel firewall engine 256 compares the (1) layer parameters from the requesting layer and (2) packet context entries to the filter conditions 318 in each filter 310 assigned to the requesting layer to identify matching filters. The following is an exemplary implementation of the Classify method. It will be understood that the following methods are described as receiving or returning data values. According to known programming techniques, the methods may use pointers to data values instead of actual data values.

```
NTSTATUS
WFPClassify
(
```


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```
    IN ULONG                          LayerId,
    IN WFP_INCOMING_VALUES*           pInFixedValues,
    IN WFP_INCOMING_CONTEXT_VALUE*    pInContext,
    PVOID                             pPacket,
    OUT WFP_ACTION_TYPE*              pActionType,
    OUT UINT64*                       pOutContext
);
```

[0087] Where the following characterizes the recited parameters.

[0088] **LayerId** identifies the network layer issuing the classification request, i.e. the requesting layer. Referring to FIG. 3, the Layer Id identifies the layer as the data stream layer 268, the transport layer 270, the network layer 272 or the link layer 274. Other layers are valid if added to the system. For example, if the SMB layer 276 is added, it has its own unique identification. The firewall architecture of the present invention further permits multiple protocol implementations at a layer in the network stack 254. For example the stack has two transport layers 270, a first transport layer uses the TCP protocol and a second transport layer uses the UDP protocol. User mode layers 282 may also be added thereby forming a valid layer.

[0089] **pInFixedValues** includes a subset of the layer parameters processed by the requesting layer. The pInFixedValues, along with the packet context entries, are compared to the filter conditions to determine if the packet matches the filter. An example of default layer parameters included in the pInFixedValues for each layer are identified in Table A below. It will be understood that the following values are exemplary only as an advantage of the architecture is that it allows the layers to use any values accessible to that layer.

Table A

Layer	Default Layer Parameters
Link Layer	Source and Destination MAC Addresses; Interface Number
Network Layer	Source and Destination IP Addresses; Protocol Type; Local Address Type
Transport Layer	Source and Destination Port Numbers;
Application	Deciphered application layer protocol payload

[0090] **pInContext** includes the context data structure 330 (FIG. 5) as received by the requesting layer. The packet context is used by the kernel firewall engine 256 in conjunction with the layer parameters to identify matching packets.

[0091] **pPacket** includes the entire packet as received by the requesting layer. The pPacket is not used by the kernel firewall engine 256 to identify matching filters. As previously described, the kernel firewall engine 256 uses the pInFixedValues and pInContext to identify matching filters. The pPacket is included in the Classify method so that the kernel firewall engine 256 can send it to one or more callout modules 258 identified as the action 316 in matching filters.

[0092] **pActionType** includes the action 316 that is returned to the requesting layer. The action 316 returned is permit or block as identified in the matching filter, or callout modules executed by the matching filter.

[0093] **pOutContext** includes the policy context data. As previously described, the policy context is used to facilitate network policies associated with IPSec, QOS and any other non-firewall filter based policy.

[0094] The Add Layer 404 and Delete Layer 406 methods are used to add and remove a layer from the firewall architecture, respectively. The following is an exemplary form of the Add Layer 404 method.

```
NTSTATUS
AddExtensionLayer(OUT PULONG pLayerId);
```

[0095] Where the following characterizes the recited parameters.

[0096] **pLayerId** is a unique layer identification value returned to the layer being added, i.e. the layer executing the Add Layer method.

[0097] The following is an exemplary form of the Delete Layer 406 method.

```
NTSTATUS
RemoveExtensionLayer(ULONG LayerId);
```

[0098] Where the following characterizes the recited parameters.

[0099] **LayerId** identifies the layer being removed; i.e. the layer executing the Delete Layer method.

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[0100] The Callout API 284 facilitates data exchange between the kernel firewall engine 256 and the callouts 258. The Callout API 284 includes a Classify method 410, a Notify method 412, a Register Callout method 414, and a Deregister Callout method 416. The Classify method 410 of the Callout API 284 is similar to the Classify method 402 of the Layer API 280 except that it also includes matching filter data. The following is an exemplary form of the Classify method 410 used to execute a callout.

```
typedef NTSTATUS (*WFP_CALLOUT_CLASSIFY_FN)
(
    IN const WFP_INCOMING_VALUES*          fixedValues,
    IN WFP_INCOMING_CONTEXT_VALUE*         wfpContext,
    IN VOID*                               packet,
    IN WFP_FILTER*                         matchedFilter,
    OUT WFP_ACTION_TYPE*                   action,
    OUT UINT64*                            outContext
);
```

[0101] Where the following characterizes the recited parameters.

[0102] **fixedValues** includes the layer parameters sent from the requesting layer. The fixedValues is the same data provided by the requesting layer in pInFixedValues data sent as part of the Classify method 402 in the layer API 280.

[0103] wfpContext includes the context data structure 330 (FIG. 5). This data is the same as sent by the requesting layer in the pInContext sent as part of the Classify method 402 in the layer API 280.

[0104] **packet** includes the entire packet as received by the requesting layer. This data is the same as sent by the requesting layer in the pPacket sent as part of the Classify method 402 in the layer API 280.

[0105] **matchedFilter** identifies the filter requesting the callout. Typically, the matching filter is identified by the filter Id 312 of the matching filter 310 initiating the Classify method 410 of the callout API 284.

[0106] **pActionType** includes the action that is returned to the kernel firewall engine 256 from the callout 258. If the pActionType is permit or block, it is returned to the requesting layer as the pActionType returned by the Layer API 280. The callout can also return a continue action that instructs the kernel firewall engine 256 to continue applying matching filters to the packet.

[0107] **pOutContext** includes the policy context data, such as security or QOS policy data.

[0108] The Notify method 412 is used to notify a callout when a filter 310 is added or deleted to the set of installed filters 282 that identifies as one of its actions 316, the callout module 258. The notify provides the callout with an opportunity to take any required action such as allocating or de-allocating buffers that will be used by the callout 258 when it is executed by the kernel firewall engine 256. The following is an exemplary form of the Notify method.

```
typedef NTSTATUS (*WFP_CALLOUT_NOTIFY_FN)
(
    IN WFP_NOTIFY_ENUM    notify,
    IN WFP_FILTER*        filter
);
```

[0109] Where the following characterizes the recited parameters.

[0110] **notify** includes a numerical value that indicates whether the filter is being added or deleted. For example, a value of 1 indicates the filter is being added and a value of 2 indicates that the filter is being deleted.

[0111] **filter** identifies the filter being added or deleted by unique value. This may be accomplished by providing the filter Id 312 included as part of the filter 310.

[0112] The callout Registration method 414 and callout Deregistration 416 method are used to add and remove callout modules, respectively. An exemplary form the registration method 414 is as follows:

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```
NTSTATUS WfpRegisterCallout
(
        IN const GUID*                  calloutId,
        IN const WFP_CALLOUT*           callout,
        IN const SECURITY_DESCRIPTOR*   sd
);
```

[0113] Where the following characterizes the recited parameters.

[0114] **callout Id** provides a unique identification for the registering callout module.

[0115] **callout** provides any callout specific information such as a driver service name, device name, and pointers to the callout classify and notify functions.

[0116] **sd** provides a security descriptor for the callout. The security descriptor provides an access control list (ACL) that specifies which processes can modify and delete the callout.

[0117] An exemplary form of the callout deregistration method 416 is as follows:

```
NTSTATUS WfpDeregisterCallout
(
        IN const GUID*      calloutId
);
```

[0118] Where the following characterizes the recited parameters.

[0119] **callout Id** is the unique Id of the callout to be removed.

[0120] The filter engine API 266 facilitates data exchange between the user mode firewall engine 260 and the kernel mode firewall 256 engine. As shown, the management API 266 includes an Add Filter method 418, a Delete Filter method 420, and an Enum Layer method 422. The methods of the filter engine API 266 are also provided as part of the management API 290.

[0121] The Add Filter 418 and Delete Filter 418 methods are used to add a new filter to the set of installed filters 282 and to delete an existing filter from the set of installed filters 282, respectively. The following is an exemplary form of the Add Filter method 418.

```
NTSTATUS
AddFilterToLayer
(
        ULONG               LayerId,
        WFP_FILTER*         pFilter
);
```

[0122] Where the following characterizes the recited parameters.

[0123] **LayerId** identifies the layer that the filter is assigned to.

[0124] **pFilter** is the filter 310 being added to the set of installed filters 282.

[0125] The following is an exemplary form of the Delete Filter method 420.

```
NTSTATUS
DeleteFilterFromLayer
(
        ULONG       LayerId,
        ULONG       FilterId
);
```


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[0126] Where the following characterizes the recited parameters.

[0127] **LayerId** identifies the layer that the filter is assigned to.

[0128] **pFilter** is the filter being deleted from the set of installed filters.

[0129] The Enum Layer method 422 provides a mechanism for the user firewall engine 260 to identify all filters matching a set of criteria. This allows the filter engine API to identify conflicting filters for filter arbitration and conflict resolution. The following is an exemplary form of the Enum Layer method 422.

```
LayerStartEnum
(
        PWFP_ENUM_TEMPLATE      pEnumTemplate,
        OUT PULONG              pMatchCount,
        OUT PWFP_ENUM_HANDLE    pEnumHandle
)
```

[0130] Wherein the following characterizes the recited parameters.

[0131] **pEnumTemplate** includes a data structure defining the filters that should be returned. Fore example, it include parameters that the filter conditions must match for the filter to be returned.

[0132] **pMatchCount** includes the number of filter matches based on the specified pEnumTemplate.

[0133] **pEnumHanlde** includes a reference to the matched filter entries.

[0134] The keying module API 288 provides an interface between keying modules and the user firewall engine 260. The keying module API 288 includes an IPSec SA Acquire method 430, an Expire Notify method 432, and an IPSec SA Acquire Complete method 434, a Keying Module Register method 436, a Keying Module Deregister method 438, an IPSec Inbound Get SPI method 440, an Add Inbound SA method 444, an Add Outbound SA method 446, an Inbound SA Expire 448 method, and a Keying Module Initiate method 350. The keying module API 288 may also include the methods previously described for the layer API, such as a Classify method 402, an Add Layer method 404 and a Delete Layer method 406.

[0135] The keying module API is used to facilitate use of known security protocols, such as defined by IPSec, used by an initiating computer and a responding computer. IPSec includes protocols such as AH and ESP. The ESP protocol is an authenticating and encrypting protocol that uses cryptographic mechanisms to provide integrity, source authentication, and confidentiality of data. The AH protocol is an authentication protocol that uses a hash signature in the packet header to validate the integrity of the packet data and authenticity of the sender.

[0136] An IKE protocol provides a method for an initiating computer and a responding computer to negotiate security settings used with the AH and ESP protocols. The negotiated security settings form a data structure called a security association (SA). The SA defines parameters such as an authentication algorithm, encryption algorithm, keys, and the lifetime of keys, used by ESP or AH to protect the contents of an IP packet. Because ESP and AH require an established SA, an IKE negotiation is executed before the ESP or AH protocols are used by the initiating and responding computer. A given SA is identified by a value known as a Security Parameter Index (SPI).

[0137] Each of the initiating and responding computers include an IPSec driver that determines, based on an IPSec policy, whether data sent between the initiating and responding computers requires encryption or authentication. The IPSec policy is a set of filters that defines how the network device uses IPSec and includes filter lists, authentication methods, and other information In an embodiment of the invention, the IPSec policy is defined by filters included in the set of installed filters in the kernel firewall engine or the filter module 294. The policy that applies to a packet is identified by invoking the keying module layer which uses the Classify method to identify matching filters.

[0138] The IPSec SA Acquire method 430 is called by the user firewall engine 260 (via a client proxy) to pass a driver acquire or an external initiate request a user mode layer 282 implemented as a keying module layer. The keying module layer returns this call and does the negotiation asynchronously. Once the keying module layer has completed the negotiation, the keying module layer calls the IPSec SA Acquire Complete method 343 to notify the user policy engine 260 that the negotiation is complete. The following is an exemplary form of the IPSec SA Acquire method.

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```
typedef WIN32_ERR (*PROCESS_IPSEC_SA_ACQUIRE0)
(
        IN FWP_IPSEC_ACQUIRE_CONTEXT0   ipsecContext,
        IN const FWP_IPSEC_SA_ACQUIRE0* acquire,
        IN FWP_IPSEC_SPI                inboundSAspi
);
```

[0139] Wherein the following characterizes the recited parameters.

[0140] **ipsecContext** is a handle to link the acquire with the SA being added.

[0141] **acquire** includes the necessary information for negotiating the SA according to known protocols such as IKE.

[0142] **inboundSAspi** includes a SPI that is used for an inbound SA.

[0143] The Expire Notify method 432 is called to pass an expire-notify to the keying module layer that added the inbound SA. The following is an exemplary form the Expire Notify method.

```
typedef VOID (*PROCESS_IPSEC_SA_EXPIRE0)
(
        IN const FWP_IPSEC_SA_EXPIRE_NOTIFY0* expireNotify
);
```

[0144] Wherein the following characterizes the recited parameters.

[0145] **expireNotify** contains information identifying the expiring SA. For example, in the case of an outbound SA, the SPI is provided.

[0146] The IPSec SA Acquire Complete 434 method is called by a keying module layer to close the user firewall engine's context after it has finished negotiation and added all the SAs, or after it has come across an error. After this method is executed, the keying module layer does not reuse the ipsecContext for any other API method. The following is an exemplary form the IPSec SA Acquire Complete method.

```
WIN32_ERR
FwpIPSecSAAcquireComplete0
(
        IN FWPM_ENGINE_HANDLE                   engineHandle,
        IN FWP_IPSEC_ACQUIRE_CONTEXT0           ipsecContext,
        IN const FWP_IPSEC_NEGOTIATION_STATUS0* status
);
```

[0147] Wherein the following characterizes the recited parameters.

[0148] **engincHandle** provides a handle to the user firewall engine 260.

[0149] **ipsecContext** is the context passed by user firewall engine with the IPSec Acquire method.

[0150] **status** provides status and other details of the SA negotiation. The status is returned by the user firewall engine 260 if the acquire was externally initiated via FwpKeyingModuleInitiate0.

[0151] The Keying Module Register method 436 is called by a keying module layer to register with the user firewall engine 260 and pass its function pointers. The following is an exemplary form of the Keying Module Register method.

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```
WIN32_ERR
FwpKeyingModuleRegister0
(
        IN FWPM_ENGINE_HANDLE                   engineHandle,
        IN const GUID*                          keyingModuleID,
        IN const FWP_KEYING_MODULE_INFO0*       keymodInfo
);
```

[0152] Wherein the following characterizes the recited parameters.

[0153] **engineHandle** provides the handle to the user firewall engine 260.

[0154] **keyingModuleID** is a unique ID for the keying module layer.

[0155] **keymodInfo** includes registration information about the keying module layer such as pointers to process IPSec SA Acquire and process IPSec SA Expire functions.

[0156] The Keying Module Deregister method 438 is called by the keying module layer to deregister the keying module from the user firewall engine 260. The following is an exemplary form of the Keying Module Deregister method.

```
WIN32_ERR
FwpKeyingModuleDeregister0
(
        IN FWPM_ENGINE_HANDLE       engineHandle,
        IN const GUID*              keyingModuleID
);
```

[0157] Wherein the following characterizes the recited parameters.

[0158] **engineHandle** is the handle to the user firewall engine 260.

[0159] **keyingModuleID** is the unique ID of the keying module layer.

[0160] The IPSec Inbound Get SPI method 440 is called by the keying module layer to obtain the SPI for a new inbound SA. The IPSec Inbound Get SPI method 440 is usually used when the keying module layer executes in a responding network device. The following is an exemplary form the IPSec Inbound Get SPI method.

```
WIN32_ERR
FwpIPSecSAInboundGetSpi0
(
        IN FWPM_ENGINE_HANDLE               engineHandle,
        IN const FWP_IPSEC_TRAFFIC0*        ipsecTrafficDescription,
        IN const FWP_IPSEC_UDP_ENCAP0*      udpEncapInfo,
        OUT FWP_IPSEC_SPI*                  inboundSpi
);
```

[0161] Wherein the following characterizes the recited parameters.

[0162] **engineHandle** is the handle to the user firewall engine 260.

[0163] **ipsecTrafficDescription** is a 5-tuple description for creating an inbound larval SA. The 5-tuple includes source and destination IP addresses, source and destination ports, and transport layer protocol type.

[0164] **udpEncapInfo** is UDP encapsulation data for creating the larval SA. UDP encapsulation is a known method of embedding a packet formatted according to a security protocol into an unencrypted UDP packet.

[0165] **inboundSpi** is the SPI for the inbound SA.

[0166] The Add Inbound SA method 444 is called by the keying module layer to add an inbound SA, i.e. update the larval SA. The user firewall engine 260 uses the SPI in the SA to map this call to its internal state, and ioctl the SA down to the IPSec driver. The following is an exemplary form of the Add Inbound SA method.

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```
WIN32_ERR
FwpIPSecSAInboundAdd0
(
        IN FWPM_ENGINE_HANDLE              engineHandle,
        IN const FWP_IPSEC_SA_STRUCT0*     inboundSA
);
```

[0167] Wherein the following characterizes the recited parameters.

[0168] **engineHandle** in the handle to the user firewall engine 260.

[0169] **inboundSA** includes the inbound SA.

[0170] The Add Outbound SA 446 method is called by a keying module layer to add an outbound SA. The user firewall engine uses an inbound SPI parameter to map this call to its internal state, and ioctl the SA down to the IPSec driver.. The following is an exemplary form the Add Outbound SA method.

```
WIN32_ERR
FwpIPSecSAOutboundAdd0
(
        IN FWPM_ENGINE_HANDLE              engineHandle,

        IN FWP_IPSEC_SPI                   inboundSpi,
        IN const FWP_IPSEC_SA_STRUCT0*     outboundSA
);
```

[0171] Wherein the following characterizes the recited parameters.

[0172] **engineHandle** is the handle to the user firewall engine 260.

[0173] **inboundSpi** is the SPI for the inbound SA, with which an outbound SA is paired.

[0174] **outboundSA** includes the outbound SA.

[0175] The Inbound SA Expire method 448 is called by the keying module layer to expire the inbound SA that was previously added. The following is an exemplary form the Inbound SA Expire method 448.

```
WIN32_ERR
FwpIPSecSAInboundExpire0
(
        IN FWPM_ENGINE_HANDLE              engineHandle,
        IN const FWP_IPSEC_SA_EXPIRE0*     expire
);
```

[0176] Wherein the following characterizes the recited parameters.

[0177] **engineHandle** is the handle to the user firewall engine 260.

[0178] **expire** includes data for the SA to be expired.

[0179] The Keying Module Initiate method 450 is called by known external application like RAS, Winsock API, and the like to initiate the keying module layer and setup SAs before an application starts sending its network traffic. The user firewall engine 260 asynchronously pends the RPC call, gets the SPI from an IPSec driver, and passes the acquire to the appropriate keying module. Once the keying module layer calls FwpIPSecSAAcquireComplete0, the user firewall engine completes the asynchronous RPC with the negotiation status. The following is an exemplary form of the Keying Module Initiate method.

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```
WIN32_ERR
FwpKeyingModuleInitiate0
(
        IN FWPM_ENGINE_HANDLE                   engineHandle,
        IN const FWP_IPSEC_SA_ACQUIRE0*         acquire,
        IN HANDLE                               waitEvent,
        OUT FWP_IPSEC_NEGOTIATION_STATUS0*      negotiationStatus
);
```

[0180] Wherein the following characterizes the recited parameters.

[0181] **engineHandle** is the handle to the user firewall engine 260.

[0182] **acquire** includes data necessary for negotiating an SA.

[0183] **waitEvent** is a handle to an event that is triggered when negotiation status is available. If a client, i.e. calling external application, is not interested in waiting for the negotiation to complete, it can set this parameter to NULL. Internally the client proxy optionally passes this event to RPC and request it to set the event once the asynchronous RPC call completes.

[0184] **negotiationStatus** includes an outcome of the negotiation. The negotiationStatus is NULL if waitEvent is NULL. Otherwise negotiationStatus remains valid until the waitEvent is triggered.

[0185] FIG. 8 illustrates the methods used by the layers in the network stack 254 according to the present invention. The method illustrated in FIG. 8 may also be used by one or more user mode layers 282 in concert with the filter module 294 and the user firewall engine 260.

[0186] Each layer is capable of a plurality of functions including processing network packets, issuing classification requests to the kernel firewall engine 256, and managing packet context. In an embodiment of the invention, the functions are executed at each of the layers in a shim 460, 462, 464, 466 installed in the network stack 254. Alternatively, the functionality is directly built into the individual layers without the need for the shims.

[0187] The network stack 254 includes the data stream layer 268, the transport layer 270, the network layer 272, and the link layer 274. For the purposes of illustrating the present invention, the link layer 274 is implemented as a NDIS driver, the network layer 272 is implemented as an IP layer, the transport layer 270 is implemented as a TCP layer, and the data stream layer 268 is implemented as a HTTP layer. It will be understood that layers may be implemented according to any protocol. For example the transport layer also accommodates a User Datagram Protocol (UDP). The application layer supports File Transfer Protocol (FTP), Remote Procedure Call (RPC), Simple Mail Transfer Protocol (SMTP), Server Master Block (SMB) etc. As previously described, additional layers can be added to the architecture and layers may be deleted. For example, layers are added and deleted using the Add Layer and Delete Layer methods described with reference to FIG 6.

[0188] A network packet, labeled 468(a)-(d), illustrates the network packet as it traverses and is processed by the layers in the network stack 254. If the packet 468(a)-(d) is an inbound packet, it traverses the network stack from bottom to top. If the packet 468(a)-(d) is an outbound packet, it traverses the network stack from top to bottom. While such processing is well known, it is briefly described for the purpose of illustrating the present invention.

[0189] Assuming an application executing in a network device, such as a web browser, initiates a request for contents of a web page located on another network device, the application issues the request to the data stream layer 268. In the example, the data stream 264 formats the request according to the HTTP protocol and sends the request to the transport layer in packet 468(a). The transport layer 270 receives packet 468(a). The transport layer 270, which implements the TCP protocol, places the data in one or more packets, and each packet is provided with a TCP header. The TCP header includes information such as the source and destination ports, protocol type, i.e. TCP, sequence numbers, flags, and checksums. The transport layer then sends the packet, labeled 468(b) to the network layer.

[0190] The network layer implements the IP protocol and encapsulates the data within an IP header that includes the source and destination IP addresses, flags, checksums and other known information. The IP header also indicates whether the packet is fragmented. A packet is fragmented when the size of the IP packet exceeds a Maximum Transmission Unit (MTU) size for the network technology used to transmit the packet. For example, Ethernet technology specifies that the MTU is 1500 bytes. If the IP packet length exceeds the MTU, it is fragmented into two or more IP packets, each with its own IP header, all of equal or smaller length as compared to the MTU.

[0191] In an embodiment of the invention, the network layer is divided into first and second layers. The first layer, referred to as a fragment layer, processes IP packet fragments. The second layer, referred to as a fully assembled layer, processes full IP packets, e.g. before outbound IP packets are fragmented and after inbound IP packets are reassembled into a single IP packet. Following network layer processing and possible fragmentation, the packet 468

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(c) is sent to the link layer 274. The link layer 274 further packetizes the data by providing a MAC header, with the source and destination MAC addresses, as well as other information. The packet is then sent to a network interface card (NIC) where it is physically transmitted onto the network.

[0192] Inbound packets are processed in a reciprocal fashion. Packet 468(d) is received by the NIC and sent to the link layer 274. The MAC header is removed and the packet 468(c) is sent to the network layer where the IP packet fragments are reassembled, if necessary, and the IP header is parsed. The network layer then sends the packet 468 (b) to the transport layer where the TCP header is removed and if the data stream was sent in a plurality of TCP packets, the data stream is reassembled. Finally, the data stream 468(a) is sent to the data stream layer 268 where the data is deciphered by the application protocol, in this case the HTTP protocol.

[0193] For each outbound packet, the layers of the network stack maintain packet context 470(a)-(c). For each inbound packet, the layers of the network stack maintain packet context 472(a)-(c). The packet context follows each packet as it traverses the network layers. Packet context is also passed to, and may be modified by, the callouts 258 (FIG. 1).

[0194] The packet context is updated as the packets are processed at each layer. Each layer adds its layer parameters to the packet context thereby providing this information to subsequent layers or processes. As shown, the link layer 274 adds source and destination MAC addresses and an interface number for an inbound packet as illustrated by context 472(a) That context is received by the network layer 272, which adds source and destination IP addresses as illustrated by context 472(b). The transport layer 266 receives the context and adds the port numbers as illustrated by context 472(a).

[0195] A similar process occurs for the context 470(a)-(c) associated with outbound packets. The data stream layer 268 adds information such as a URL address from the packet payload as illustrated by context 470(a), the transport layer 270 further adds source and destination port numbers as illustrated by context 470(b) and the network layer adds source and destination IP addresses as illustrated by context 470(c).

[0196] It will be understand that each layer can add any context information available to that layer. Typically, this includes any information that the layer is designed to process, i.e. add or parse or otherwise derive from packets.

[0197] When the packet and its corresponding context are received at each layer, the layer functions as a requesting layer by identifying the layer parameters and sending a classification request, labeled 474. The classification request 474 includes, the layer parameters 476, the packet context 478 received from the prior layer, and the full packet 480. An exemplary method used to issue the classification request is the Classify method 402 described with reference to the layer API 280 (Fig.7).

[0198] In response to each classify request, the kernel mode firewall engine 256 compares the layer parameters 476 and packet context 478 to the filter conditions 318 (FIG. 4) of the filters assigned to the requesting layer. The kernel firewall engine 256 sends a response, labeled 482, with the action 484 from the matching filters 310 with the highest weight 314 to the requesting layer. The kernel firewall engine 256 also returns the policy context 482. If no matching filters are identified by the kernel firewall engine 256, the kernel firewall engine notifies the requesting layer that no matching filters exist. The kernel firewall engine 256 continues to identify matching filters until a matching filter designates a terminating action, i.e. permit or block, or until all filters assigned to the requesting layer are checked, whichever comes first. Alternatively, the kernel firewall engine 256 identifies all matches and returns the actions to the requesting layer in a single response.

[0199] As generally illustrated, identifying layer parameters is done as part of the normal layer processing performed by the layers of the network stack 254. Additional packet parsing is not required thereby minimizing impact on system performance. Moreover, because the layers cooperate in maintaining packet context, it is possible to for the firewall engine 256 to compare filter conditions with packet parameters at layers that normally do not have access to those packet parameters. For example, the network layer 268 receives context for inbound packets from the link layer 274 that includes source and destination MAC addresses. Because the network layer 272 issues classification requests with network layer parameters, e.g. source and destination IP addresses, as well as the packet context, the kernel firewall engine 256 can filter on both IP and MAC addresses at the network layer 272 even though the MAC addresses are usually not available.

[0200] Referring to Fig. 9 and exemplary set of callout modules 258 included with the firewall architecture of the present invention will now be described. The callout modules 258 include HTTP context callout 500, intrusion detection callout 502, IPSec callout 504, and logging callout 506. The callout API 284 forms the interface between the kernel firewall engine 256 and the callouts 258.

[0201] The HTTP context callout 500 maintains a cache 508 of acceptable, or alternatively, unacceptable URL addresses. The HTTP context callout 508 periodically accesses a server 510 interfaced to the public network that maintains URL addresses and classifies them as acceptable or unacceptable. When the kernel firewall engine 256 executes the HTTP context callout, the callout examines the packet, deciphers the URL address if necessary, and determines if it is acceptable based on information in the cache 508. The HTTP callout then returns permit as the action 316 if the URL address is acceptable and block if the URL address is unacceptable to the kernel mode firewall engine 256, which

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in turn returns the action 316 to the requesting layer via layer API 280. The HTTP context callout is useful in implementing a parental control function.

[0202] The intrusion detection callout 502 uses available algorithms and techniques to examine the packet to identify indicia of viruses or otherwise suspicious packets. If a suspicious packet is detected, an action 316 of block is returned. An example of a suspicious packet is a packet where all flags in IP and TCP headers are set to a value of one. The packet is suspicious because it is never valid and could indicate an attack signature. Alternatively, the intrusion detection callout 502 modifies packet context to flag the suspicious nature of the packet thereby deferring a decision on whether to block the packet to subsequent layers in the network stack.

[0203] The IPSec callout 504 is designed to determine to whether a proper security protocol was applied to the packet. The IPSec callout 504 communicates with an IPSec process and determines based on IPSec policy whether the packet was supposed to be subject to IPSec processing. If so, the IPSec callout 504 verifies, based on packet context, whether the packet was in fact subject to the IPSec processing. If the packet was supposed to be processed according to IPSec, but was not, e.g. the packet was in clear text, an action of block is returned. If the packet was subject to IPSec processing, the IPSec callout verifies that a proper Security Association (SA) was applied. If the proper SA was not applied, the callout returns an action 316 of block, otherwise an action 316 of permit is returned. Alternatively, the IPSec callout modifies the packet context deferring a decision on whether to block or permit the permit to a subsequent layer.

[0204] The logging callout 506 is used to save information pertaining to the packet, such as the full packet for later use. Such later use might be, for example, diagnostics for certain network traffic that is unexpectedly not traversing the network because it is being blocked or for tracking malicious attacks on the system.

[0205] All of the references cited herein, including are hereby incorporated in their entireties by reference.

[0206] In view of the many possible embodiments to which the principles of this invention may be applied, it should be recognized that the embodiment described herein with respect to the drawing figures is meant to be illustrative only and should not be taken as limiting the scope of invention. For example, those of skill in the art will recognize that the elements of the illustrated embodiment shown in software may be implemented in hardware and vice versa or that the illustrated embodiment can be modified in arrangement and detail without departing from the spirit of the invention. Therefore, the invention as described herein contemplates all such embodiments as may come within the scope of the following claims and equivalents thereof.

Claims

1. A firewall framework implemented within a computer system for providing multi-layering filtering of packet, comprising:

   a set of layer processors, each layer processor being capable of processing layer parameters for the packet associated with the layer processor and each layer processor being further capable of issuing a classification request that includes the layer parameters; and
   a first firewall engine including:

   a layer interface for receiving first layer parameters from a requesting layer processor and for returning an action to the requesting layer, the requesting layer processor being one of the set of layer processors;
   a set of installed filters; and
   a lookup component for identifying at least one matching filter from the set of installed filters and identifying from the matching filter the action to be returned by the layer interface.

2. The firewall framework of claim 1, wherein the requesting layer receives packet context including second layer parameters from a previous layer processor and the classification request includes the packet context, wherein the lookup component further uses the packet context for identifying the at least one matching filter.

3. The firewall framework of claim 2, wherein the firewall engine further comprises:

   a callout interface for sending the first layer parameters, the packet context, and the packet to a callout, wherein the callout analyzes the packet and returns the action to the firewall engine.

4. The firewall framework of claim 2, wherein the requesting layer passes the packet context to a next layer.

5. The firewall framework of claim 1, further comprising:

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a policy provider for establishing a new filter; and
a second firewall engine for adding the new filter to the set of installed filers.

6. The firewall framework of claim 1, wherein each of the installed filters comprises:

a filter condition including a type-data pair, the type defining the size of the data and the data including a filter parameter, and
the action.

7. The firewall framework of claim 6, wherein the filter parameter includes a range of values.

8. The firewall framework of claim 6, wherein the filter comprises a weight factor defining a priority of the filter.

9. The firewall framework of claim 1, wherein the set of layer processors further comprises:

a link layer having layer parameters including an interface number and source and destination MAC addresses;
an network layer having layer parameters including a source and destination IP address;
a transport layer having layer parameters including source and destination ports; and
an application layer having layer parameters including a stream of data.

10. The firewall framework of claim 9, wherein the network layer is further divided into a fragment layer and a fully assembled layer, the fragment layer processing IP packet fragments and the fully assembled layer processing complete IP packets, each of the fragment layer and the fully assembled layer issuing the classify request.

11. The firewall framework of claim 1, wherein the first firewall engine executes in an operating system kernel mode.

12. The firewall framework of claim 1, wherein the first firewall engine executes in an operating system user mode.

13. A method of communicating between a first layer process and a firewall process in an operating system, comprising the steps of:

issuing, by the first layer process, a classify call having a plurality of parameters comprising, a protocol packet, at least one layer parameter. and a packet context from a second layer process;
receiving, by the firewall process, the classify call; and
issuing, by the firewall process, an action identified from a filter matching the at least one layer parameter.

14. The method of claim 13, wherein the first layer process is a new process, further comprising:

issuing by the first layer process, an add layer call.

15. The method of claim 13, wherein the first layer process is an existing process, further comprising:

issuing by the first layer process, a delete layer call.

16. A method of communicating between a firewall process and a callout process in an operating system, comprising the steps of:

issuing, by the firewall process, a classify call having a plurality of parameters comprising, a protocol packet, at least one layer parameter, a packet context, and a matching filter identification;
receiving, by the callout process, the classify call; and
issuing, by the callout process, an action identified from the plurality of parameters in the classify call.

17. The method of claim 16, wherein the callout process is a parental control module maintaining a cache of acceptable resource location, further comprising:

examining the packet to identify a resource location and comparing the resource location to the acceptable locations.

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18. The method of claim 17, wherein the action issued by the callout process is block and the protocol packet is prevented from network traversal.

19. The method of claim 17, wherein the action issued by the callout process is permit and the protocol packet is permitted to further traverse the network.

20. The method of claim 16, wherein the callout process is a logging module, further comprising storing in a memory the protocol packet.

21. The method of claim 16, wherein the callout process is a security module, further comprising:

determining, by the security module, that the protocol packet is required to conform to a security protocol;
verifying that the protocol packet conforms to the security protocol.

22. The method of claim 21, wherein the security protocol is an IPSec security protocol.

23. A computer-readable medium for executing computer-readable instructions for facilitating a firewall framework implemented within a computer system for providing multi-layering filtering of a packet, comprising:

a set of layer processors, each layer processor being capable of processing layer parameters for the packet associated with the layer processor and each layer processor being further capable of issuing a classification request that includes the layer parameters; and
a first firewall engine including:

a layer interface for receiving first layer parameters from a requesting layer processor and for returning an action to the requesting layer, the requesting layer processor being one of the set of layer processors;
a set of installed filters; and
a lookup component for identifying at least one matching filter from the set of installed filters and identifying from the matching filter the action to be returned by the layer interface.

24. The computer-readable medium of claim 23, wherein the requesting layer receives packet context including second layer parameters from a previous layer processor and the classification request includes the packet context, wherein the lookup component further uses the packet context for identifying the at least one matching filter.

25. The computer-readable medium of claim 24, wherein the firewall engine further comprises:

a callout interface for sending the first layer parameters, the packet context, and the packet to a callout, wherein the callout analyzes the packet and returns the action to the firewall engine.

26. The computer-readable medium of claim 24, wherein the requesting layer passes the packet context to a next layer.

27. The computer-readable medium of claim 23, further comprising:

a policy provider for establishing a new filter; and
a second firewall engine for adding the new filter to the set of installed filers.

28. A computer-readable medium for executing computer-readable instructions for communicating between a first layer process and a firewall process in an operating system, comprising the steps of:

issuing, by the first layer process, a classify call having a plurality of parameters comprising, a protocol packet, at least one layer parameter, and a packet context from a second layer process;
receiving, by the firewall process, the classify call; and
issuing, by the firewall process, an action identified from a filter matching the at least one layer parameter.

29. The computer-readable medium of claim 28, wherein the first layer process is a new process, further comprising:

issuing by the first layer process, an add layer call.

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30. The computer-readable medium of claim 28, wherein the first layer process is an existing process, further comprising:

issuing by the first layer process, a delete layer call.

31. A computer-readable medium for executing computer-executable instructions for communicating between a firewall process and a callout process in an operating system, comprising the steps of:

issuing, by the firewall process, a classify call having a plurality of parameters comprising, a protocol packet, at least one layer parameter, a packet context, and a matching filter identification;
receiving, by the callout process, the classify call; and
issuing, by the callout process, an action identified from the plurality of parameters in the classify call.

32. The computer-readable medium of claim 31, wherein the callout process is a logging module, further comprising storing in a memory the protocol packet.

33. The computer-readable medium of claim 31, wherein the callout process is an security module, further comprising:

determining, by the security module, that the protocol packet is required to conform to a security protocol;
verifying that the protocol packet conforms to the security protocol.

34. A functional interface for allowing a requesting layer to obtain policy for a packet, the requesting layer being one of a plurality layers, comprising:

a classify method comprising:

the packet received by the requesting layer;
a set of parameters associated with the packet, the set of parameters including data processed by the requesting layer,
a packet context received by the requesting layer from another layer of the plurality of layers; and
an action to be returned to the requesting layer identifying a first policy to be applied to the packet.

35. The functional interface of claim 34, further comprising:

an add layer method for allowing a new layer to be added to the plurality of layers.

36. The functional interface of claim 34, further comprising:

a delete layer method for removing an existing layer from the plurality of layers.

37. The functional interface of claim 34, further comprising:

a policy context defining a second policy to be applied to the packet.

38. The functional interface of claim 37, wherein the first policy is a firewall policy and the second policy is a non-firewall policy.

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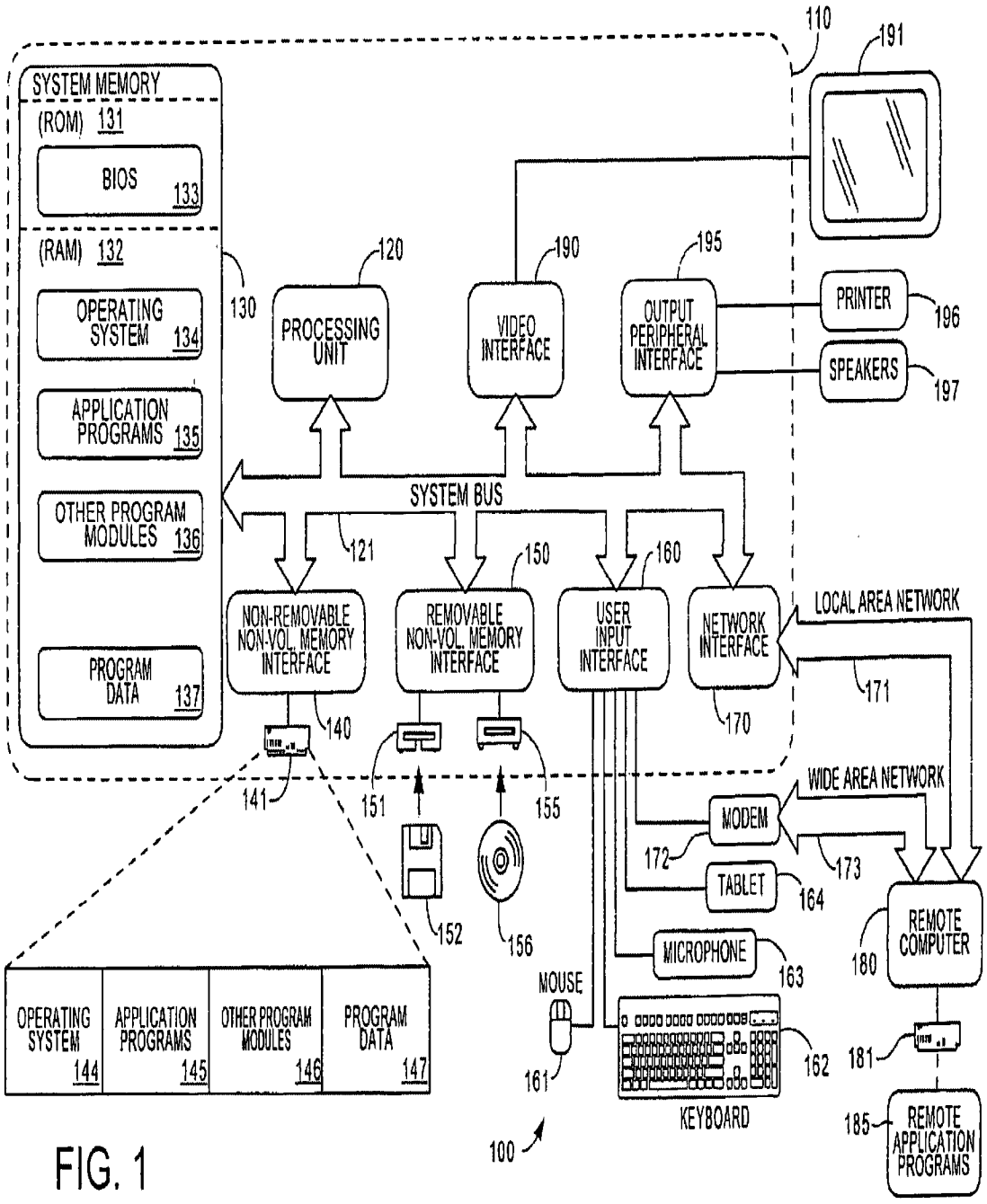
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BIOS 133
(RAM) 132
OPERATING SYSTEM 134
APPLICATION PROGRAMS 135
OTHER PROGRAM MODULES 136
PROGRAM DATA 137
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PROCESSING UNIT
190
VIDEO INTERFACE
195
OUTPUT PERIPHERAL INTERFACE
PRINTER
196
SPEAKERS
197
SYSTEM BUS
121
150
160
NON-REMOVABLE NON-VOL. MEMORY INTERFACE
REMOVABLE NON-VOL. MEMORY INTERFACE
USER INPUT INTERFACE
NETWORK INTERFACE
LOCAL AREA NETWORK
171
170
140
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151
155
WIDE AREA NETWORK
MODEM
172
173
TABLET
164
152
156
MICROPHONE
163
180
REMOTE COMPUTER
MOUSE
161
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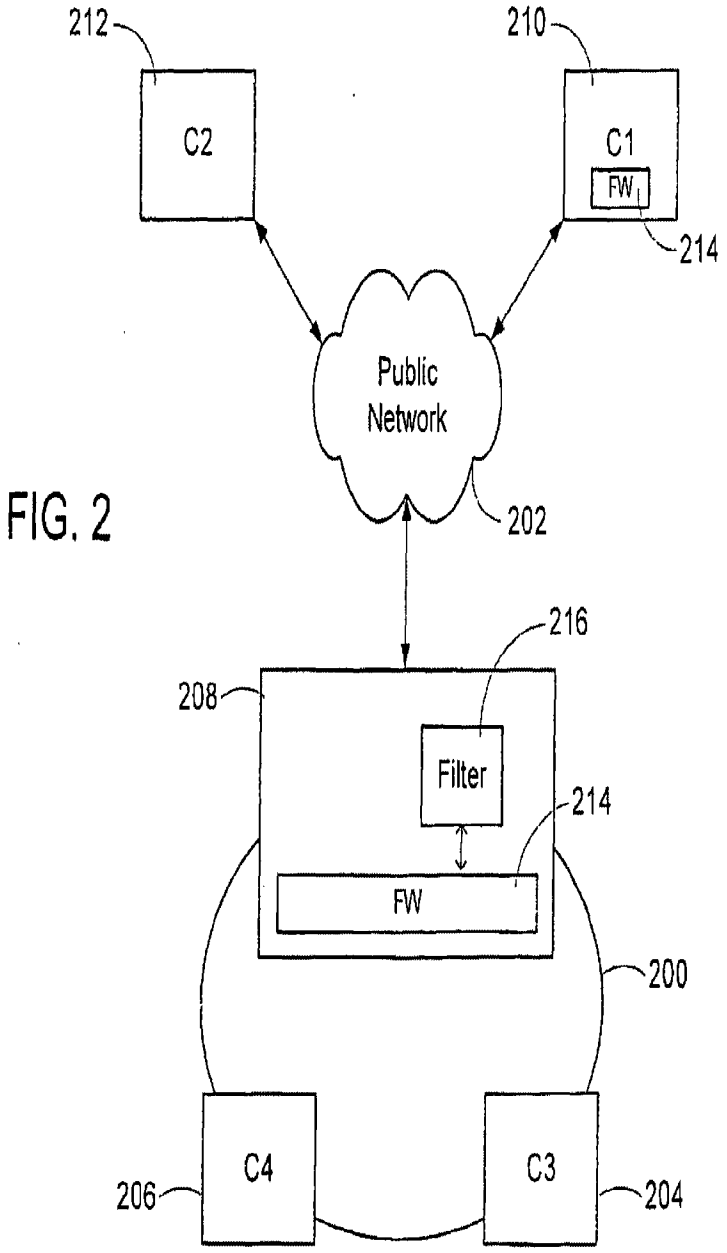
APPLICATION PROGRAMS 145
OTHER PROGRAM MODULES 146
PROGRAM DATA 147

FIG. 1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210
C2
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FW1
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C3
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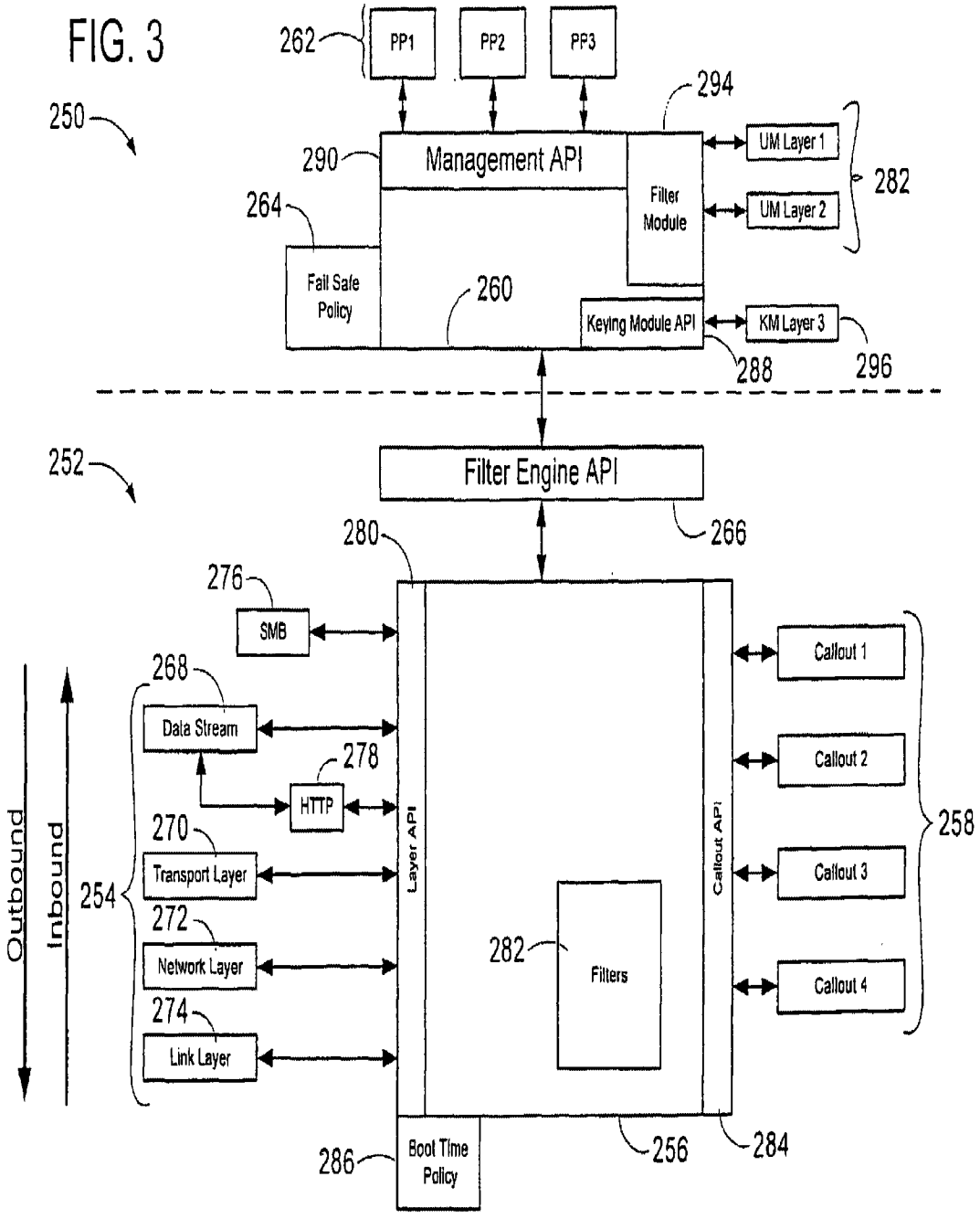
FIG. 2

FIG. 3


262
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PP2
PP3
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250
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Management API
Filter Module
UM Layer 1
UM Layer 2
282
264
Fail Safe Policy
260
Keying Module API
KM Layer 3
288
296
252
Filter Engine API
266
280
276
SMB
268
Data Stream
278
HTTP
270
Transport Layer
272
Network Layer
274
Link Layer
254
Outbound
Inbound
Layer API
Callout API
Callout 1
Callout 2
Callout 3
Callout 4
258
282
Filters
286
Boot Time Policy
256
284

FIG. 4

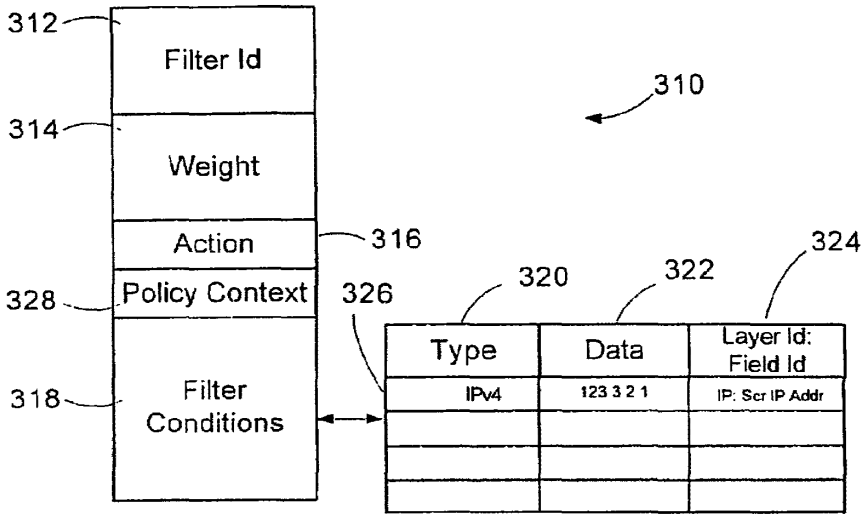
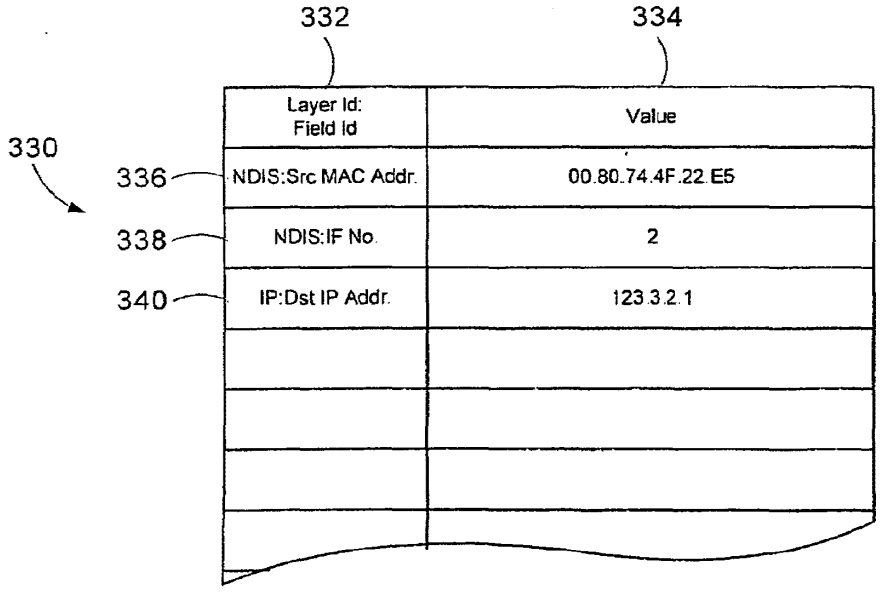


FIG. 5



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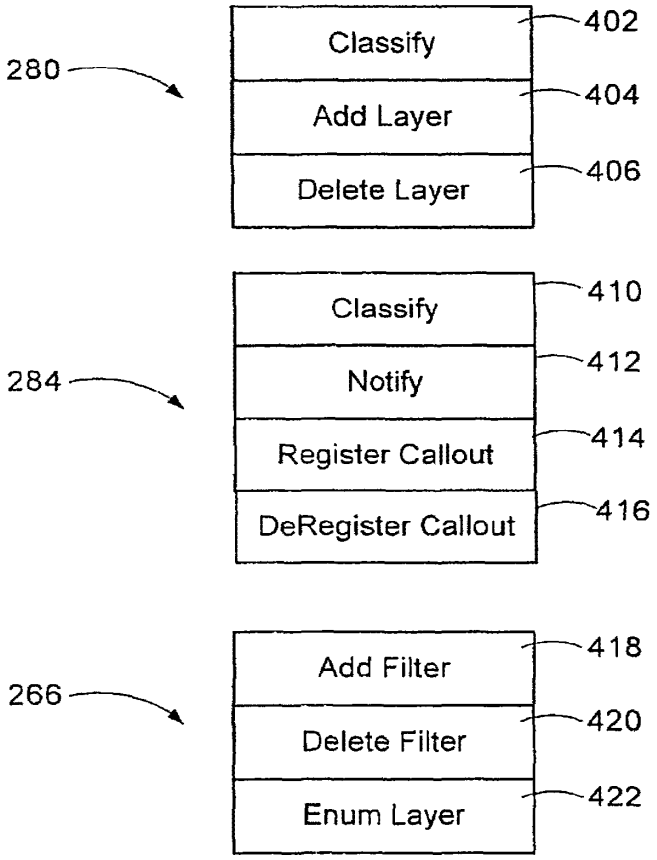

FIG. 6

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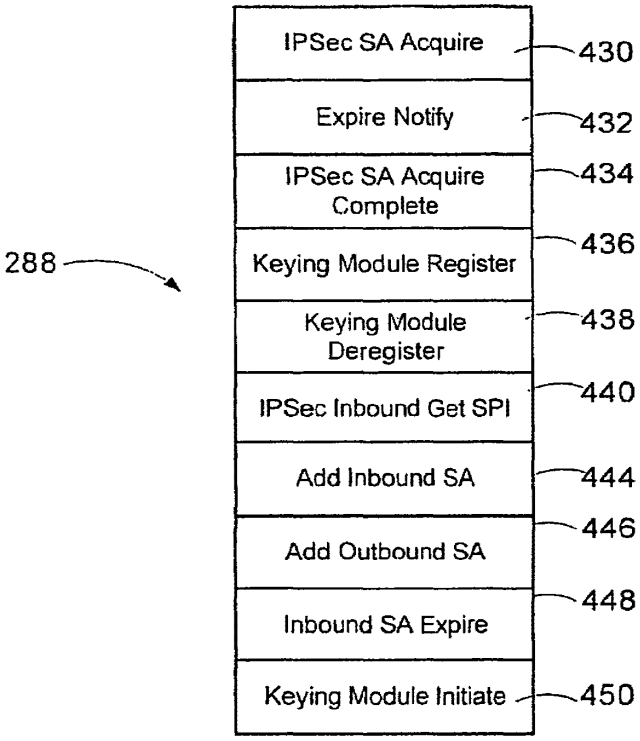

FIG. 7

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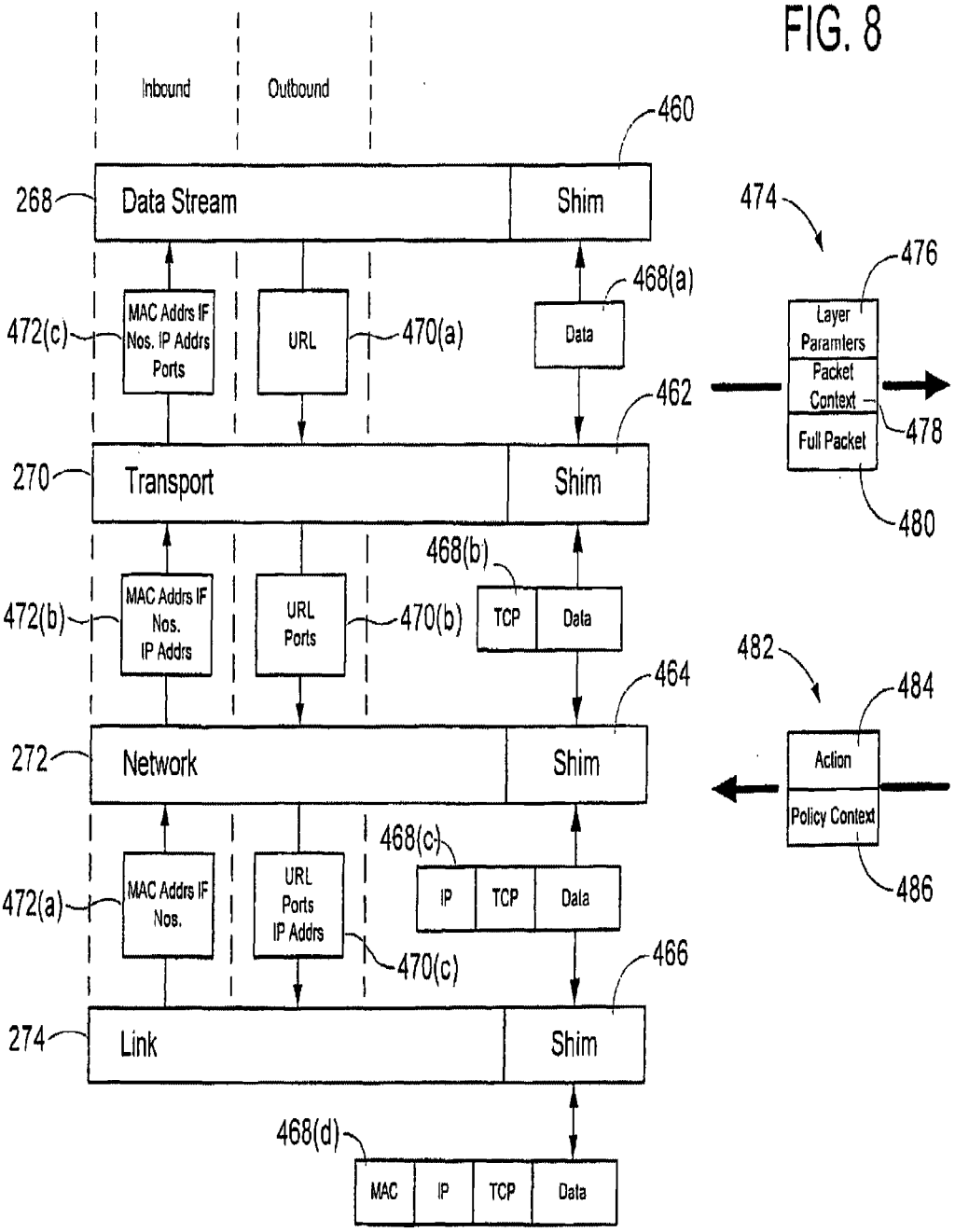
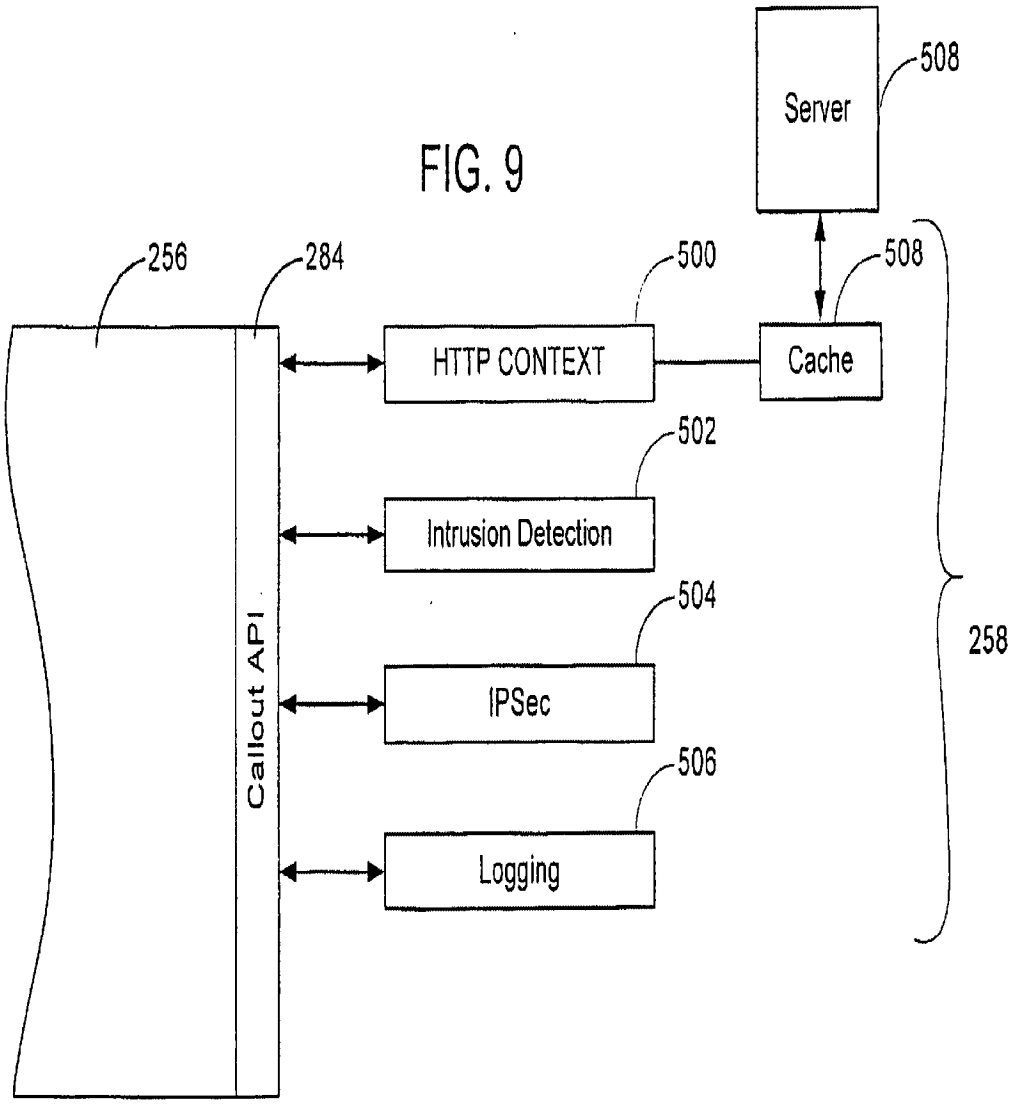
FIG. 8



EP 1 484 884 A2

FIG. 9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256
284
500
508
HTTP CONTEXT
Cache
502
Intrusion Detection
504
IPSec
506
Logging
Callout API
258

Australian Government
IP Australia

LETTERS PATENT

STANDARD PATENT

2006230171

I, Robyn Foster, the Commissioner of Patents, grant a Standard Patent with the following particulars:

Name and Address of Patentee(s):

Wake Forest University
Office of Tachnology Asset Management, Wake Forest University Health Sciences, 200 East First Street, Suite 101, Winston Salem, North Carolina, 27101, United States of America

Name of Actual Inventor(s):

Fulp, Errin W. and Tarsa, Stephen J..

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Term of Letters Patent:

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Priority Details :

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COMMONWEALTH OF AUSTRALIA
AUSTRALIA
PATENT OFFICE

Dated this 4th day of October 2012

R E Foster

Robyn Foster
Commissioner of Patents

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(71) Applicant(s)
Wake Forest University

(72) Inventor(s)
Tarsa, Stephen J.;Fulp, Errin W.

(74) Agent / Attorney
Griffith Hack, GPO Box 3125, Brisbane, QLD, 4001

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(71) Applicant *(for all designated States except US)*: **WAKE FOREST UNIVERSITY** [US/US]; OFFICE OF TECHNOLOGY ASSET MANAGEMENT, WAKE FOREST UNIVERSITY HEALTH SCIECNES, 200 East First Street, Suite 101, Winston Salem, North Carolina 27101 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **FULP, Errin, W.** [US/US]; 308 N. Hawthorne Road, Winston-Salem, North Carolina 27104 (US). **TARSA, Stephen, J.** [US/US]; 135 King Phillips Path, Duxbury, Massachusetts 02332-3503 (US).

(74) Agent: **HUNT, Gregory, A.**; JENKINS, WILSON, TAYLOR & HUNT, P.A., Suite 1200 University Tower, 3100 Tower Boulevard, Durham, North Carolina 27707 (US).

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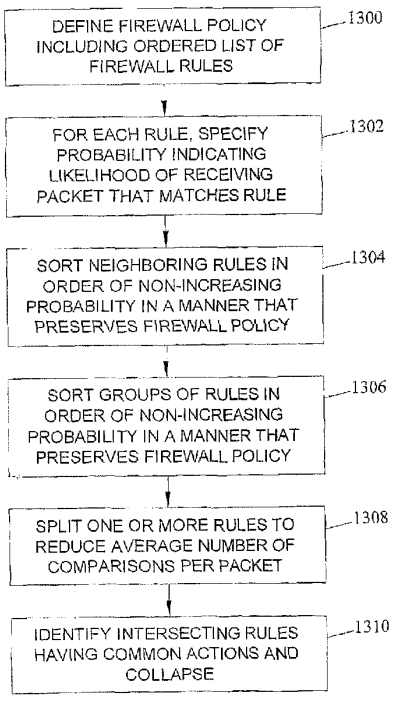
[Continued on next page]

(54) Title: METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION



(57) Abstract: Methods, systems, and computer program products for firewall policy optimization are disclosed. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is determined. The rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.

WO 2006/105093 A2

European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

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TITLE

METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/665,664, filed March 28, 2005; the disclosure of which is incorporated herein by reference in its entirety.

GOVERNMENT INTEREST

This invention was made with Government support under Grant No. DE-FG02-03ER25581 awarded by U.S. Department of Energy, Mathematical and Computational Information Sciences Division. The U.S. Government has certain rights in the invention.

TECHNICAL FIELD

The subject matter described herein relates to optimizing polices for network firewalls. More particularly, the subject matter described herein relates to methods, systems, and computer program products for optimizing performance of network firewalls.

BACKGROUND ART

Network firewalls remain the forefront defense for most computer systems. Guided by a security policy, these devices provide access control, auditing, and traffic control [3, 30, 31]. A security policy is a list of ordered rules, as seen in Table 1, that defines the action to perform on matching packets. For example, an accept action passes the packet into or from the secure network, while deny causes the packet to be discarded. In many implementations, the rule set is stored internally as a linked list. A packet is sequentially compared to the rules, starting with the first, until a match is found; otherwise, a default action is performed [30, 31]. This is referred to as a first-match policy and is used in many firewall systems including the Linux firewall implementation iptables [25].

COMS ID No: ARCS-372276 Received by IP Australia: Time (H:m) 11:49 Date (Y-M-d) 2012-06-06

No.	Proto.	Source IP	Source Port	Destination IP	Destination Port	Action	Prob.
1	UDP	1.1.*	*	*	80	deny	0.01
2	TCP	2.*	*	1.*	90	accept	0.02
3	UDP	*	*	1.*	*	accept	0.10
4	TCP	2.*	*	1.*	20	accept	0.17
5	UDP	1.*	*	*	*	accept	0.20
6	*	*	*	*	*	deny	0.50

Table 1: Example Security Policy Consisting of Multiple Ordered Rules

Traditional firewall implementations consist of a single, dedicated machine, similar to a router, that sequentially applies rules to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [24, 29, 31]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [30]. Successfully handling these traffic loads becomes more difficult as rule sets become more complex [4, 22, 31]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 9, 13, 14]. An attacker could simply inundate the firewall with traffic, delaying or preventing legitimate packets from being processed.

One approach to increase firewall performance focuses on improving hardware design. Current research is investigating different distributed firewall designs to reduce processing delay [4, 9, 22], and possibly provide service differentiation [11]. Another approach focuses on improving performance via better firewall software [6, 7, 12, 16, 17, 24]. Similar to approaches that address the longest matching prefix problem for packet classification [8, 10, 25, 28], solutions typically represent the firewall rule set in different fashions (e.g. tree structures) to improve performance. While both approaches, together or separate, show great promise, each requires radical changes to the firewall system, and therefore are not amenable to current or legacy systems.

Accordingly, there exists a need for improved methods, systems, and computer program products for network firewall policy optimization.

SUMMARY

The subject matter described herein includes methods, systems, and computer program products for network firewall policy optimization. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is defined. Neighboring rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.

As used herein, the term "firewall" refers to a logical entity that is adapted to filter packets at the ingress and/or egress portions of a network based on a policy. The term "firewall" is intended to include systems that block packets from entering or leaving a network and systems that perform intrusion detection and intrusion protection functions for packets entering or leaving a network. Thus, the methods and systems described herein for firewall policy optimization can be used to optimize policies for intrusion detection and intrusion protection firewalls.

The subject matter described herein includes a method to improve firewall performance and lower packet delay that can be applied to both legacy and current systems. In one implementation, a firewall rule set may be re-ordered to minimize the average number of rule comparisons to determine the action, while maintaining the integrity of the original policy. Integrity is preserved if the reordered and original rules always arrive at the same result. To maintain integrity, a firewall rule set may be modeled as a Directed Acyclical Graph (DAG), where vertices are firewall rules and edges indicate precedence relationships. Given this representation, any linear arrangement of the DAG is proven to maintain the original policy integrity. Unfortunately, determining the optimal rule order from all the possible linear arrangements is proven to be *NP*-complete, since it is equivalent to sequencing jobs with precedence constraints for a single machine [15]. Although determining the optimal order is *NP*-complete, a heuristic will be described below to order firewall rules that reduces the average number of comparisons while maintaining integrity. Simulation

results show the proposed reordering method yields rule orders that are comparable to optimal; thus, provides a simple means to significantly improve firewall performance and lower packet delay.

The subject matter described herein for network firewall policy optimization may be implemented using any combination of hardware, software, or firmware. For example, the subject matter described herein may be implemented using a computer program product comprising computer executable instructions embodied in a computer readable medium. Exemplary computer readable media suitable for implementing the subject matter described herein include disk memory devices, chip memory devices, programmable logic devices, application specific integrated circuits, and downloadable electrical signals. In addition, a computer program product that implements the subject matter described herein may be implemented using a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings of which:

Figure 1A is a block diagram of a rule list Directed Acyclical Graph (DAG) for the firewall rules in Table 1;

Figure 1B is a linear arrangement of firewall rules corresponding to the original rule order;

Figure 2A is a policy DAG representing a reordered version of the firewall rule set in Figure 1 after sorting;

Figure 2B is a policy DAG for the rule set illustrated in Table 1 illustrating an optimal rule order;

Figure 3A is a graph illustrating average numbers of packet comparisons versus intersection percentage for different orderings of a firewall policy;

Figure 3B is a graph illustrating the percent difference in average numbers of packet comparisons between sorted and optimal sortings of a firewall policy;

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Figure 4A is a graph of percent difference comparisons between original and sorted versions of a firewall policy;

Figure 4B is a graph illustrating the performance impact of considering rule intersection and actions in performing firewall rule sorting;

Figure 5A is a table illustrating a firewall policy before sorting;

Figure 5B is a table illustrating a sorted version of the firewall policy of Figure 5A;

Figure 6A is a policy trie representation of the firewall policy of Figure 5B;

Figure 6B is a table representing the firewall policy of Figure 5A after TCP and UDP sub-trie rotation;

Figure 7A is a policy trie illustrating the splitting of rule r_5 into rules r_{5a} and r_{5b};

Figure 7B is a table illustrating the firewall policy of Figure 5A after splitting rule r_5 into rules r_{5a} and r_{5b};

Figure 8A is a graph illustrating firewall performance with and without rule splitting;

Figure 8B is a graph illustrating locations and probabilities where splitting is better;

Figure 9A is a policy DAG of a firewall rule set;

Figure 9B is a policy DAG illustrating compression of rules r_1 and r_5;

Figure 10A is a policy DAG of a firewall rule list;

Figure 10B is an original policy trie before sorting;

Figure 10C is a policy trie illustrating the firewall rules after rotating sub-tries T_1 and T_2;

Figure 11A is a policy DAG illustrating a firewall policy;

Figure 11B is a policy trie illustrating firewall rules of the policy before sorting;

Figure 11C is a policy trie illustrating the firewall policy after exchanging nodes r_1 and r_2 and nodes r_7 and r_8;

Figure 11D is a policy trie illustrating the firewall policy after exchanging sub-tries T_3 and T_4;

Figure 11E is a policy trie illustrating the firewall policy after exchanging sub-tries T_1 and T_2;

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Figure 12A is a policy DAG illustrating an original order for a firewall policy;

Figure 12B is a policy DAG illustrating a sorted version of the firewall policy of Figure 12A after exchanging neighbors;

Figure 12C is a policy DAG illustrating a sorted version of the firewall policy after exchanging lists L_1 including rules r_1 and r_3 and lists L_2 including rules r_2 and r_4;

Figure 13 is a flow chart illustrating exemplary steps for network firewall policy optimization according to an embodiment of the subject matter described herein;

Figure 14 is a block diagram illustrating exemplary components of a system for firewall policy optimization according to an embodiment of the subject matter described herein; and

Figure 15 is a block diagram illustrating a plurality of firewall nodes for implementing a firewall policy according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION OF THE INVENTION

Modeling Firewall Security Policies

As described above, a firewall rule set, also known as a firewall policy, is traditionally an ordered list of firewall rules. Firewall policy models have been the subject of recent research [1, 2, 16]; however, the primary purpose is anomaly detection and policy verification. In contrast, the policy model described in this herein is designed for firewall performance optimization and integrity. Firewall performance refers to reducing the average number of comparisons required to determine an action, while integrity refers to maintaining the original policy intent. Although improving the worst-case performance is important, it is not possible without changing the list-based representation [16, 24].

Firewall Rule and Policy Models

In the examples described herein, a rule r is modeled as an ordered tuple of sets, $r = (r[1], r[2], ..., r[k])$. Order is necessary among the tuples since

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comparing rules and packets requires the comparison of corresponding tuples. Each tuple $r[l]$ is a set that can be fully specified, specify a range, or contain wildcards '*' in standard prefix format. For the Internet, security rules are commonly represented as a 5-tuple consisting of: protocol type, IP source address, source port number, IP destination address, and destination port number [30, 31]. Given this model, the ordered tuples can be supersets and subsets of each other, which forms the basis of precedence relationships. In addition to the prefixes, each filter rule has an action, which is to accept or deny. However, the action will not be considered when comparing packets and rules. Similar to a rule, a packet (IP datagram) d can be viewed as an ordered k-tuple $d = (d[1], d[2], ..., d[k])$; however, ranges and wildcards are not possible for any packet tuple.

Using the previous rule definition, a standard security policy can be modeled as an ordered set (list) of n rules, denoted as $R = \{r_1, r_2, ..., r_n\}$. A packet d is sequentially compared against each rule r_i starting with the first, until a match is found ($d \Rightarrow r_i$) then the associated action is performed. A match is found between a packet and rule when every tuple of the packet is a subset of the corresponding tuple in the rule.

Definition Packet d matches r_i if

$$d \Rightarrow r_i \quad \text{iff} \quad d[l] \subseteq r_i[l], \quad l = 1, ..., k$$

The rule list R is comprehensive if for every possible legal packet d a match is found using R. Furthermore, two rule lists R and R' are equivalent if for every possible legal packet d the same action is performed by the two rule lists. If R and R' are different (e.g. a reorder) and the lists are equivalent, then the policy integrity is maintained.

As previously mentioned, a rule list has an implied precedence relationship where certain rules must appear before others if the integrity of the policy is to be maintained. For example consider the rule list in Table 1. Rule r_1 must appear before rules r_3 and r_5, likewise rule r_6 must be the last rule in the policy. If for example, rule r_3 was moved to the beginning of the policy, then it will shadow [2] the original rule r_1. However, there is no precedence relationship between rules r_2 and r_4 given in Table 1. Therefore, the relative ordering of these two rules will not impact the policy integrity and can be

changed to improve performance. The present example assumes that the original policy is free from any anomalies. Likewise, when a policy is reordered to improve performance it should not introduce any anomalies, which will occur if precedence relationships are not maintained. As a result, a model is needed to effectively represent precedence relationships.

Modeling Rule List Precedence Relationships

The precedence relationship between rules in a policy will be modeled as a Directed Acyclical Graph (DAG) [23, 18]. Such graphs have been successfully used to represent the relative order of individual tasks that must take place to complete a job (referred to as a task graph model). Since certain rules must appear before others to maintain policy integrity, this structure is well suited for modeling the precedence of firewall rules. Let $G = (R, E)$ be a rule list DAG for a rule list R, where vertices are rules and edges E are the precedence relationships (constraint). A precedence relationship, or edge, exists between rules r_i and r_j, if $i < j$, the actions for each rule are different, and the rules intersect.

Definition The intersection of rule r_i and r_j, denoted as $r_i \cap r_j$ is

$$r_i \cap r_j = (r_i[l] \cap r_j[l]), \qquad l = 1, \ldots, k$$

Therefore, the intersection of two rules results in an ordered set of tuples that collectively describes the packets that match both rules. The rules r_i and r_j intersect if every tuple of the resulting operation is non-empty. In contrast, the rules r_i and r_j do not intersect, denoted as $r_i \not\cap r_j$, if at least one tuple is the empty set. Note the intersection operation is symmetric; therefore, if r_i intersects r_j, then r_j will intersect r_i. The same is true for rules that do not intersect.

For example consider the rules given in Table 1, the intersection of r_1 and r_3 yields (UDP, 1.1.*, *, 1.*, 80). Again, the rule actions are not considered in the intersection or match operation. Since these two rules intersect, a packet can match both rules for example d = (UDP, 1.1.1.1, 80, 1.1.1.1, 80). Furthermore, the actions of the two rules are different. Therefore, the relative order must be maintained between these two rules and an edge drawn from r_1 to r_3 must be present in the rule list DAG, as seen in Figures 1A and 1B. More

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particularly, Figure 1A illustrates a rule list DAG for the rules in Table 1. Figure 1B illustrates a linear arrangement of the rules in Figure 1A. In Figures 1A and 1B, the vertices represent rules, the circles represents an accept rules, and the squares represents deny rules. Edges that connect the vertices represent precedence requirements. As can be seen from Figure 1B, because of the edge between rules r_1 and r_3, precedence between rules r_1 and r_3 must be maintained. In contrast consider the intersection of rules r_3 and r_5. These two rules intersect, indicating packets belonging to the set (UDP, 1.*, *, 1.*, *) would match both rules. However, it does not matter which of the two rules a packet matches first, since the action is the same for both rules. Therefore, an edge does not exist between rules r_3 and r_5 in the diagram. Similarly, rules r_2 and r_4 do not intersect due to the fifth tuple (destination port). A packet cannot match both rules indicating the relative order can change; therefore, an edge will not exist between them.

The match operation can be used to identify precedence relationships, but it cannot do so in every case. Consider a partial-match example [1], where r_a = (UDP, *, 80, 10.*, 90, accept) and r_b = (UDP, 10.*, 80, *, 90, deny). The intersection of r_a and r_b is (UDP, 10.*, 80, 10.*, 90); therefore a packet, such as d = (UDP, 10.10.10.10, 80, 10.10.10.10, 90), can match both rules. If r_a appears before r_b then the packet d is accepted, but if r_b occurs before r_a then d is rejected. As a result, the order of r_a and r_b in the original policy must be maintained. However, the match operation is unable to identify the precedence in this example. A partial match exists in between rules r_3 and r_5 in Table 1, but as previously discussed an edge does not exist between the rules since the actions are the same.

Using the rule list DAG representation a linear arrangement is sought that improves the firewall performance. As depicted in Figure 1B, a linear arrangement (permutation or topological sort) is a list of DAG vertices where all the successors of a vertex appear in sequence after that vertex [23]. Therefore it follows that a linear arrangement of a rule list DAG represents a rule order, if the vertices are read from left to right. Furthermore, it is proven in the following theorem that any linear arrangement of a rule list DAG maintains integrity.

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Theorem Any linear arrangement of a rule list DAG maintains integrity.

Proof Assume a rule list DAG *G* is constructed from the security policy *R* that is free of anomalies. Consider any two rules r_i and r_j in the policy, where $i < j$. If an edge between r_i and r_j in *G* does not exist, then a linear arrangement of *G* can interchange the order of the two rules. An edge will not exist if the rules do not intersect; however, a reorder will not affect integrity since a packet cannot match both rules. Shadowing is not introduced due to the reorder since the intersection operation is symmetric. An edge will not exist if the two rules intersect but have the same action; however, a reorder will not affect integrity since the same action will occur regardless of which rule is matched first. If an edge does exist between the rules, then their relative order will be maintained in every linear arrangement of *G*; thus maintaining precedence and integrity.

Rule List Optimization

As described above, it is important to inspect packets as quickly as possible given increasing network speeds and QoS requirements. Using the rule list DAG to maintain policy integrity, a linear arrangement is sought that minimizes the average number of comparisons required. However, this will require information not present in the firewall rule list. Certain firewall rules have a higher probability of matching a packet than others. As a result, it is possible to develop a policy profile over time that indicates frequency of rule matches (similar to cache hit ratio). Let $P = \{p_1, p_2, ..., p_n\}$ be the policy profile, where p_i is the probability that a packet will match rule *i* (first match in the policy). Furthermore, assume a packet will always find a match, $\sum_{i=1}^{n} p_i = 1$; therefore *R* is comprehensive. Using this information, the average number of rule comparisons required is

$$E[n] = \sum_{i=1}^{n} i \cdot p_i \qquad (1)$$

For example, the average number of comparisons required for the rule set in Table 1 is 5.03.

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Given a rule list DAG $G = (R, E)$ and policy profile $P = \{p_1, p_2, ..., p_n\}$ a linear arrangement π of G is sought that minimizes Equation 1. In the absence of precedence relationships, the average number of comparisons is minimized if the rules are sorted in non-increasing order according to the probabilities [26], which is also referred to as Smith's algorithm [27]. Precedence constraints cause the problem to be more realistic; however, such constraints also make determining the optimal permutation more problematic.

Determining the optimal rule list permutation can be viewed as job scheduling for a single machine with precedence constraints [15, 21]. The notation for such scheduling problems is $\alpha|\beta|\gamma|\delta$, where α is the number of machines, β is the precedence (or absence of) which can be represented as a DAG, γ is a restriction on processing time, and δ is the optimality criterion [15]. Determining the optimal rule order is similar to the $1|\beta|1|\sum \omega C_i$ scheduling problem, or optimality criterion, where ω is a weight associated with a job (for example, importance) and C_i is the completion time. As previously noted, the $1|||\sum \omega C_i$ problem can be solved in linear time the using Smith's algorithm [27], which orders jobs according to non-decreasing $\frac{t_i}{\omega}$ ratio, where t_i is the processing time of job i. In this case set $t_i = 1$ and $\omega = p_i \; \forall i$. However, Lawler [19] and Lenstra et al. [21] proved $1|\beta|1|\sum \omega C_i$ to be *NP*-complete via the linear arrangement problem, which implies determining the optimal firewall rule order is also *NP*-complete. Note, determining the number of possible permutations has been proven to be *NP*-hard [5].

Theorem $1|\beta|1|\sum \omega C_i \; \alpha$ *Determining the optimal order of a firewall rule list*

Proof Consider the $1|\beta|1|\sum \omega C_i$ problem. Each of n jobs J_i, $i \in I$, has to be processed without preemption on a single machine that can handle at most one job at a time. For each $i \in I$, let ω be the associated weight. Furthermore, let $G = (V, E)$ be a DAG that represents the precedence order of the jobs J_i. Assume the processing time of each job equals 1 time unit, the weights to be $0 \leq \omega \leq 1$ such that $\sum \omega = 1$, and β, which is G, to be a rule list DAG. In this case, the

optimization criterion $\sum \omega \cdot C_i$ is the same as $\sum p_i \cdot i$, which is given in equation 1. Clearly, the optimal firewall rule ordering problem has a solution if and only if $1|\beta|1|\sum \omega C_i$ has a solution. Therefore, determining the optimal permutation of firewall rules is *NP*-complete.

Exemplary Rule Sorting Algorithm

Although determining the optimal rule permutation was proven to be *NP*-complete, reducing the average number of comparisons required to process a packet remains an important objective. As previously discussed, a sorting algorithm must maintain the precedence relationships among rules. Of course an exhaustive search is possible if the number of rules is small (generate and test all possible topological orders); however as proven in the previous section, this is not feasible with a realistic rule list.

One exemplary algorithm starts with the original the rule set, then sorts neighboring rules based on nonincreasing probabilities. However, an exchange of neighbors should never occur if the rules intersect and have different actions. This test preserves any precedence relationships in the policy. For example, the following sorting algorithm uses such a comparison to determine if neighboring rules should be exchanged. Note a_i denotes the action associated with the ith rule.

```
done = false
while(!done)
    done = true
    for(i = 1; i <n; i++)
        if(p_i < p_i+1 AND (r_i ∩ r_i+1 OR a_i == a_i+1))then
            exchange rules, actions, and probabilities
            done = false
        endif
    endfor
endwhile
```

Other sorting algorithms are possible if the completion time of the sort is an issue; however, the method presented is easy to implement and only requires a simple neighbor comparison. Assume the match probabilities for the rule list given in Table 1. Applying the sorting algorithm to this rule list results in the ordering depicted in Figure 2A, which has 10% fewer comparisons on

average. However when using the algorithm, it is possible that one rule can prevent another rule from being reordered. For example, rule r_1 prevents rule r_5 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_5 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be further reduced, 15% fewer. This is the optimal order for the 6 rule set, which is depicted in Figure 2B. Although this simple sorting algorithm is unable to move groups of rules, it can still improve the performance of the firewall system. Its effectiveness is measured experimentally in the next section.

Experimental Results

In this section, the average number of rule comparisons required after sorting the rules is compared with average number of comparisons required using the original order and the optimal order. Note the optimal rule ordering was determined via an exhaustive search. As a result, it was not feasible to determine the optimal ordering once the number of rules equaled 15 given the number of permutations to consider. Two different variations of the rule sorting method described in the preceding section were implemented. The difference between the methods was the comparison used to determine if neighboring rules should be exchanged. The first sorting algorithm exchanged neighboring rules if they were out of order and did not intersect. The if-condition was as follows.

if ($p_i < p_{i+1}$ **AND** $r_i \not\cap r_{i+1}$) **then**

Therefore, rule actions were not considered and the method will be referred to as *non-action sort*. The second sorting method did consider the rule action (as described in the preceding section) and will be referred to as *action sort*. The comparison between the two sorting algorithms will indicate the importance of considering rule actions when ordering rules.

In the first experiment, lists of 10 firewall rules were generated with random precedence relationships. The match probability of each rule was given by a Zipf distribution [20], which assigns probabilities according to the rank of an item. For this simulation, the last rule had the highest probability

which is consistent with most policies (last rules are more general). As a result, the original order yields the worst average number of comparisons. The intersection percentage measured the percentage of rules that intersect in the policy. This metric gives a value for the dependency level in the policy; however note, rule action is not considered when calculating this metric. Rules were equally likely to have an accept or deny action and the results (average number of rule comparisons) for a particular intersection percentage were averaged over 1000 simulations.

Results of the first experiment are given in Figures 3A and 3B. More particularly, Figure 3A is a graph illustrating the average number of packet comparisons versus intersection percentage for the original rule sorting, the non-action sort, the action sort, and the optimal sort. Figure 3B is a graph illustrating the percent difference in the average number of comparisons required between the sorted and optimal firewall policy configurations. The average number of comparisons required was lower for the sorted and the optimal lists when the intersection percentage was low, as seen in Figure 3A. This was expected since there is a large number of possible rule permutations (few edges in the DAG). When the intersection percentage approached 100%, the values converged to the number required for the original list. This is due to the limited number of possible rule orders, only one order in the extreme case. The percent difference between the sorted and optimal order is shown in Figure 3B. At zero intersection percentage the sorted and optimal orders are equal, since any ordering is possible. Similarly at an intersection percentage of 100, the sorted and optimal orders are equal since only one order is possible. Between these two extremes, the action sorting algorithm remains close to the optimal value. In contrast, the non-action sort had a maximum difference of 33%.

The benefit of rule sorting on larger policies is also of interest; however as previously described, it was not possible to determine the optimal ordering once the number of rules approaches 15. Therefore, the second experiment used larger rule sets, but only compared the original order and the sorted orders. The number of rules ranged from 10 to 1000, while the matching probabilities and intersection percentages were the same as the previous

experiment. The results of this experiment are depicted in Figure 4A. The sorted rule sets always performed equal to or better than the original order, while the action sort consistently performed better than the non-action sort. As noted in the previous experiment, the percent difference is very large given few intersections (e.g. 80% decrease for 1000 rules with 0% dependency), but approaches zero as all the rules intersect. As the number of rules increases, sorting is increasingly beneficial, although only at low intersection percentages. The benefit of sorting drops more significantly as the intersection percentage increases with larger rule sets. This is primarily due to the low matching probabilities of each rule, which requires a complete reordering to have a significant impact on the average number of comparisons. As a result, large rule sets can benefit from sorting if the intersection percentage is low.

The impact of considering rule actions when sorting is illustrated in Figure 4B. In this experiment lists of 1000 rules were generated, where the intersection percentages ranged from 0% to 100% and the percentage of rules with the same action varied from 50% to 100%. The performance of the action sort to the original list was then compared. As the percentage of rules with the same action increased, the percent difference (reduction) in the average number of comparisons also increased. This is due to the increased number of permutations possible when the rule actions are increasingly the same (fewer edges in the rule list DAG to consider). This is depicted in Figure 4B where a policy with a 100% intersection percentage can significantly reduce the number of comparisons (80% reduction) if all the rules have the same action. This performance increase is not possible with the non-action sort. Therefore, considering the rule action increases the number of possible rule orders, thereby providing more possibilities to improve firewall performance.

Conclusions

Network firewalls enforce a security policy by comparing arriving packets to a list of rules. An action, such as accept or deny, is then performed on the packet based on the matching rule. Unfortunately packet filtering can impose significant delays on traffic due to the complexity and size of rule sets.

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Therefore, improving firewall performance is important, given network Quality of Service (QoS) requirements and increasing network traffic loads.

The sections above describe rule ordering methods to improve the performance of network firewalls. Assuming each rule has a probability of a packet matching, firewall rules should be sorted such that the matching probabilities are non-increasing. This reduces the average number of comparisons and the delay across the firewall. However, a simple sort is not possible given precedence relations across rules. It is common in a security policy that two rules may match the same packet yet have different actions. It is this precedence relationship between rules that must be maintained to preserve integrity. The method described above uses Directed Acyclical Graphs (DAG) to represent the precedence order rules must maintain. Given this representation, a topological sort can be used to determine the optimal order (minimum average number of comparisons); however, the examples above prove this problem to be *NP*-complete (similar to job scheduling for a single nonpreemptive machine with precedence constraints). As an alternative, a simple sorting method was introduced that maintained the precedence order of the rules. Simulation results indicate this method can significantly reduce the average number of comparisons required and is comparable to optimal ordering.

Several areas exist for future research in optimizing firewall rule lists. The sorting method proposed above is based on a simple algorithm. Although it can offer an improvement over the original rule order, algorithms that can move groups of rules could provide a larger reduction in the average number of comparisons. The effect of stateful firewalls should also be addressed in future research. Security can be enhanced with connection state and packet audit information. For example, a table can be used to record the state of each connection, which is useful for preventing certain types of attacks (e.g., TCP SYN flood) [30, 31]. The impact of such rules on the firewall needs to be investigated and whether sorting can be done on-line to reflect temporal changes. In addition, more research is needed to determine more accurate probability distributions for packet matching and dependency percentages.

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Given this information, better algorithms can be designed and more realistic simulations can be performed.

Trie-Based Network Firewall Optimization Methods and Rule Splitting

Overview

As described above, while assuring firewall policy integrity is critical, performance is equally important given increasing network speeds and traffic volumes. Firewall processing delay can be reduced via hardware as well as policy optimization, where rules are manipulated to reduce the number of comparisons. For a given firewall installation, it can be determined that certain security rules have a higher probability of matching a packet than others. As a result, it is possible to develop a *policy profile* over time that indicates frequency of rule matches (similar to cache hit ratio). Given this information, trie-based methods are described herein to minimize the average number of comparisons required per packet. Although most firewall systems still utilize an ordered list representation, the proposed enhancements still are applicable to current firewall systems since a policy trie can be converted into an ordered list using an inorder traversal.

Rule Sorting

As described above, rule sorting of neighboring rules based on ascending probabilities in a manner that considers rules intersection and rule actions can be used to improve firewall performance by reducing the number of packet comparisons. The methods described above use Directed Acyclic Goal Graphs (DAGs) to represent firewalls. The methods described in this section will use the rule sorting algorithms in combination with policy trie representations to perform sorting of groups of rules in a manner that improves firewall performance.

In this example, it is assumed that a security policy contains a list of n ordered rules, $\{r_1, r_2, ..., r_n\}$. In addition, let p_i represent the probability that a packet will match rule i (first match in the policy). Therefore, the policy is comprehensive, which means every packet will have a match, if $\sum_{i=1}^{n} p_i = 1$.

Using this information, the average number of rule comparisons required can be calculated as

$$E[n] = \sum_{i=1}^{n} i \cdot p_i$$

The average number of comparisons is minimized if the rules are sorted in non-ascending order according to the probabilities. However, this can only be achieved if the sorting algorithm considers the probabilities and whether one rule is a superset of another. For example, sorting algorithms must use the following comparison to determine if neighboring rules should be interchanged Note, a_i denotes the action associated with the ith rule.

if ($p_i < p_{i+1}$ **AND** $r_i \not\cap r_{i+1}$ **OR** $a_i == a_{i+1}$)) **then**

Sorting rules in this fashion can have positive impact on the average number of comparisons required. Figure 5A is a table illustrating a firewall policy prior to rule sorting. The expected number of comparisons for the policy of Figure 5A is 4.26 comparisons per packet. Figure 5B is a table illustrating the firewall policy of Figure 5A after sorting using the above-described algorithm. In Figure 5B, the expected number of comparisons per packet has been reduced to 3.94. Thus, using the method described above, the number of comparisons per packet can be reduced by 8%.

However, it can be seen from Figures 5A and 5B that one rule can prevent another rule from being reordered. For example in Figure 5B, rule r_1 prevents rule r_4 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_4 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be reduced.

To solve this problem, rule sets can be sorted a using policy tries. First, the rule list is converted into an equivalent policy trie. Each sub-trie will have an associated probability $\overline{p}$ that is average probability (hit-ratio) of the rules comprising the sub-trie. Sub-tries can be rotated around their parent node to increase performance, using the method described earlier. Since the policy trie (or equivalent rule set) is tested from left to right, rotation should occur if the

probability of the right sub-trie is greater than the left sub-trie. As a result, the average number of comparisons required will be reduced and the policy integrity is maintained. Figure 6A is a trie representation of the rules in Figure 5B. Figure 6B is a table representing resulting rule set after rotating the TCP and UDP sub-tries. The TCP sub-trie in Figure 6A has an expected packet matching probability of 0.095 while the UDP sub-trie has an expected packet matching probability of 0.155. Thus, the UDP sub-trie and the TCP sub-trie should be rotated so that the UDP sub-trie becomes the left sub-trie and the TCP sub-trie becomes the right sub-trie. In the table illustrated in Figure 6B, which lists the ordering of the rules after rotating the sub-tries, the average number of comparisons per packets has been reduced to 3.70.

Rule Splitting

Rule splitting takes a general rule and creates more specific rules that collectively perform the same action over the same set of packets. Here, rule splitting is used to reduce the average number of comparisons. For example in Figure 7A, rule r_5 is split into two separate rules, r_{5a} for UDP and r_{5b} for TCP. Figure 7B is a table corresponding to the policy trie of Figure 7A. Once the rules are positioned based on their probabilities and their relation to other rules, the average number of rule comparisons is reduced to 2.98 (after sort, trie rotation, and splitting) which is a 30% less.

It many not be advantageous to split a general rule since it adds another rule to the policy. For example, assume a policy contains 20 rules where the first 19 rules have the same probability. Assume the last rule can be split and the new specific rule has a probability that is $\frac{3}{4}$ of the last rule. The impact of the probability of the last rule and the location of the new split rule, m, is depicted in Figures 8A and 8B. More particularly, Figure 8A is a graph illustrating the average number of comparisons for firewalls with and without rule splitting. Figure 8B is a graph illustrating average number of comparisons versus different locations of the new rule and probabilities. The average number of comparisons is reduced as the split rule is located closer to the first rule (surface decreases as m approaches one). Furthermore, splitting yields

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better results when the general rule has a high probability. However as illustrated in Figure 8B, the closer the specific rule is to the location of the original rule the average number of comparisons increases, which is the penalty of adding one more rule to the policy.

The effect of splitting a single rule can be described mathematically as follows. Consider n rules where rule r_n can be split into rules $r_{n,1}$ and $r_{n,r}$ (whose union is the original rule). In addition, assume the split rule $r_{n,1}$ will be located at the mth position ($1 \leq m < n$), while rule $r_{n,r}$ will remain at the nth location. The goal is to determine the best location m, which yields a lower average number of comparisons as compared to the original rule set. This can be defined mathematically in the following formula.

$$\sum_{i=1}^{n} i \cdot p_i > \sum_{i=1}^{m-1} i \cdot p_i + m \cdot p_{n,l} + \sum_{i=m}^{n-1} (i+1) \cdot p_i + (n+1) \cdot p_{n,r}$$

The left side of the inequality is the average number of comparisons for the original rule set. The right hand side of the inequality is the average number of comparisons with the specific rule at location m. If it is assumed that the rules located between m and n have an equal probability (denoted as p) the previous equation can be solved for m.

$$m < \frac{n \cdot p - n \cdot p_n + (n+1) \cdot p_{n,r}}{p - p_{n,l}}$$

The new rule must be located between the first and m^{th}; however, its final location will depend on the relationship with the other rules (cannot be placed before any rule for which it is a superset). This result can be applied iteratively to multiple rules and repeatedly to the same rule.

Rule Optimization for QoS

In the preceding sections, optimizing the entire security policy has been discussed. However, it may be desirable to optimize the rules for a certain type of traffic, in order to reduce the average number of comparisons this traffic encounters. This can be done by organizing the policy trie via traffic

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classification, then optimizing the sub-tries. The result is an ordering where the rules for the most important traffic are tested first.

Network Firewall Optimization Using Rule Compression

Another method for network firewall optimization is referred to as rule compression. Given a security policy R, one objective in optimizing firewall performance is to reduce number of rules in the policy while maintaining the original integrity. A method for reducing the number of rules called *rule compression*, which combines and replaces two rules in the policy will now be described. Although compression does reduce the number of rules, it can only be done if the integrity of the original policy is maintained.

Consider two rules r_i and r_j in policy R, where r_i appears before r_j. The two rules can be compressed if and only if the following conditions are true

1. The two rules intersect, $r_i \cap r_j \neq \emptyset$ (an edge between r_i and r_j exists in the policy DAG) (Tuples that are proper subsets and supersets are considered. Compression may still occur if the rules do not intersect or are adjacent in the set space, the resulting rule may contain ranges.)
2. The action of r_i and r_j is the same.
3. Rule r_i is not dependent on any rule r_k that is directly or indirectly dependent on r_j (only one path from r_i to r_j exists in the policy DAG).

The result of compression is a new rule, $r_{i,j}$ whose tuples are the union of the corresponding tuples of rules r_i and r_j. The new rule $r_{i,j}$ replaces both r_i and r_j in R; however, the location of $r_{i,j}$ in R may require the relocation of other rules. Let D_j be the ordered set of rules that appear after r_i that directly or indirectly depend upon r_j. The new rule is placed at the original location of r_i in R and the rules D_j are placed before $r_{i,j}$.

For example, consider the policy given in Table 2. It is possible to compress rules r_1 and r_5, creating the new rule $r_{1,5}$ =[TCP, *, *, 2.*, *, accept]. The ordered set D_j in this example consists of the rules r_3 and r_4. As a result, the new rule $r_{1,5}$ is placed at the original location of r_1 while the rules in D_j are placed before the new rule. Figures 9A and 9B respectively illustrate the

original policy DAG for Table 2 and the policy DAG after rules r_1 and r_5 are compressed.

No.	Proto.	Source IP	Source Port	Destination IP	Destination Port	Action
1	TCP	1.1.*	*	2.2.*	*	accept
2	TCP	1.*	*	*	80	deny
3	TCP	3.3.*	*	*	80	accept
4	TCP	3.*	*	*	*	deny
5	TCP	*	*	2.*	90	accept

Table 2: Example Policy Consisting of Multiple Ordered Rules

Theorem *Compressing rules r_i and r_j of policy R will maintain integrity if the three conditions are met and method described is used.*

Proof Before r_i and r_j are compressed, relocate the rules D_j immediately before r_i and D_i. This relocation will maintain integrity due to the third requirement for compression (no rule in D_i can be dependent on any rule in D_j). Now place r_j directly after r_i. This relocation will not affect integrity since no rule in D_i can have an edge to r_j (again, due to the third condition). Compressing the neighboring rules r_i and r_j creates $r_{i,j}$. This does not affect integrity since the resulting rule only matches the packets that match r_i or r_j in the original policy. Therefore, the result is the compression of rule r_i and r_j, and the integrity of the policy is maintained.

Determining if Compression Should Occur

Although compression may be possible, it may not improve the performance of the policy due to the relocation of rules. Compression should only occur if the average number of comparisons required for the new policy R_c is less than the original policy R; therefore, $E[R_c] < E[R]$.

Firewall Rule Sub-Trie and Sub-List Ordering

Policy Sub-Trie Ordering

Additional methods for firewall optimization are referred to as firewall sub-trie and sub-list ordering. Given a policy trie T, it may be desirable to order all sub-tries such that the average number of tuple comparisons is reduced and policy integrity is maintained. Consider a policy trie T that contains sub-tries T_i and T_j having the same parent node, as seen in Figures 10A-10C. Let P_i denote the sum of the probabilities of the rules contained in sub-trie i, while C_i denotes the number of comparisons required to completely traverse sub-trie i (which is equal to the number of branches). In order to reduce the average number of tuple comparisons, sub-tries that share the same parent node should be ordered such that the following two conditions are observed.

1. Sub-tries that share a parent node are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-tries that share a parent node have the same probability (P_i equals P_j), then order the sub-tries such that the C_i values are non-descending (sub-tries consisting of fewer comparisons occur first, from left to right).

These conditions are recursively applied throughout the policy trie as seen in Figures 11A-11D. However, these conditions do not necessarily maintain policy integrity.

Consider a group of n sub-tries that share the same parent node that are numbered sequentially from left to right. Consider any two non-intersecting sub-tries T_i and T_{i+k} in this group that are out of order. If two sub-tries do not intersect, denoted as $T_i \pitchfork T_j$, then no rule in one sub-trie will intersect with any rule in the other sub-trie, $r_k \pitchfork r_l$, $\forall r_k \in T_i$, $\forall r_l \in T_j$. The following *integrity condition* must be observed when reordering the sub-tries. The two sub-tries can be exchanged (rotated about the parent) if and only the sub-tries T_i through T_{i+k-1} do not intersect with T_{i+k} and the sub-tries T_{i+1} through T_{i+k} do not intersect with T_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. This is observed in Figure 10A,

where no edge exists between any rule in T_1 and T_2. More particularly, Figure 10A is a policy DAG of a six-rule firewall list. Figure 10B is a policy trie representation of the firewall rule list represented by Figure 10A. In Figure 10B, the average number of tuple compares required per packet is 5.5. Figure 10C illustrates the policy trie after rotating sub-tries T_1 and T_2. In Figure 10C, the average number of tuple compares required is 4.5. In Figures 10A-10C, the following probabilities are assumed:

$P_1 = 0.5$

$C_1 = 4$

$P_2 = 0.5$; and

$C_2 = 2$.

The average number of tuple comparisons is an estimate based on the longest trie path.

Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-tries that share the same parent node.

```
m = a parent node in T
done = false
while(!done)
    done = true
    for each sub-trie Ti having parent m AND a right neighboring sub-trie
        if((Pi < Pi+1 AND (Pi == Pi+1 AND Ci > Ci+1)) AND Ti ⋔ Ti+1) then
        interchange Ti and Ti+1
        done = false
        endif
    endfor
endwhile
```

Figures 11A-11D illustrate policy trie rotation for an eight-rule firewall policy. More particularly, Figure 11A illustrates the policy DAG representation of an eight-rule firewall policy. Figure 11B is a policy trie representation of the original firewall policy. In this example, ordering occurs in three stages, starting at the bottom level and moving towards the top level of the trie. In Figure 11C, the leaves are ordered at the lowest level. More particularly, nodes r_1 and r_2 are exchanged with nodes r_7 and r_8. The average number of tuple compares for the ordering represented by Figure 11C is 10.45. In Figure 11D, the sub-

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tries on the second lowest level (T_3, T_4, T_5, and T_6) are ordered. More particularly, Figure 11D illustrates the policy trie after exchanging sub-tries T_3 and T_4. The average number of tuple compares for the representation in Figure 11D is 10.275. In Figure 11E, the sub-tries on the second highest level, (T_1 and T_2) are ordered. Figure 11E illustrates the final ordering after exchanging T_1 and T_2. In the policy trie of Figure 11E, the average number of tuple compares required is 6.775. The average number of tuple comparisons is an estimate based on the longest trie path.

Policy Sub-List Ordering

The preceding section describes conditions for sorting policy sub-tries, which allow the exchange of groups of rules (sub-tries). The same conditions can be applied to list based policies, where sub-lists are ordered to improve the average number of rule comparisons.

In the sections above relating to rule sorting, a method is described to exchange neighboring rules in a list-based security policy, as seen in Figure 12B. However, it was observed that when ordering rules in this fashion it is possible that one rule can block the exchange of another. If groups of rules were allowed to be exchanged the average number of rule comparisons could be further reduced.

Given a policy list L, it may be desirable to order all sub-lists such that the average number of rule comparisons is reduced and policy integrity is maintained. Consider a policy list L that contains sub-tries L_i and L_j. Let P_i denote the sum of the probabilities of the rules contained in sub-list i, while C_i denotes the number of rules in sub-list i. In order to reduce the average number of rule comparisons, sub-lists should be ordered such that the following two conditions are observed.

1. Sub-lists are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-lists have the same probability (P_i equals P_j), then order the sub-lists such that the C_i values are non-descending (sub-lists consisting of fewer comparisons occur first, from left to right).

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These conditions are applied throughout the policy list; however as with policy tries, these conditions do not necessarily maintain policy integrity.

Consider a group of n sub-lists that are numbered sequentially from left to right. Consider any two non-intersecting sub-lists L_i and L_{i+k} in this group that are out of order. If two sub-lists do not intersect, denoted as $L_i \pitchfork L_j$, then no rule in one sub-list will intersect with any rule in the other sub-list, $r_k \pitchfork r_l$, $\forall r_k \in L_i$, $\forall r_l \in L_j$. The following *integrity condition* must be observed when reordering the sub-lists. The two sub-lists can be exchanged if and only if the sub-lists L_i through L_{i+k-1} do not intersect with any rule in L_{i+k} and sub-lists L_{i+1} through L_{i+k} do not intersect with L_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. For example, consider the sub-lists $L_1 = \{r_1, r_3\}$ and $L_2 = \{r_2, r_4\}$ given in Figure 12B. No edge exists between any rule in L_1 and L_2. The two sub-lists are out of order with respect to P and should be exchanged. The resulting list is given in Figure 12C. Figure 12A illustrates the original policy order and results in an average number of rule comparisons of 3.4. In the sorted version in Figure 12B, the average number of rule comparisons is 3.3. In Figure 12C, the average number of rule comparisons has been reduced to 2.7. Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-lists.

```
done = false
while(!done)
    done = true
    for each sub-list Li having a right neighboring sub-list
        if ((Pi < Pi+1 OR (Pi == Pi+1 AND Ci > Ci+1)) AND Li ⋔ Li+1)then
            interchange rules and probabilities
            done = false
        endif
    endfor
endwhile
```

Summary of Firewall Policy Optimization Techniques and Methods

As stated above, the methods and systems described herein for a network firewall policy optimization can be implemented using any combination of hardware, software, and/or firmware. Alternatively, the steps for firewall policy optimization can be performed manually with the number of rules being optimized is small enough. Figure 13 is a flow chart illustrating an exemplary process for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 13, in block **1300**, a firewall policy including an ordered list of firewall rules is defined. In block **1302**, for each rule, a probability indicating a likelihood of receiving a packet that matches each rule is specified. In block **1304**, neighboring rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. In block **1306**, groups of rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. For example, any of the policy-trie-based methods described above may be used. In block **1308**, one or more rules are split to reduce the number of average packet comparisons. In block **1310**, intersecting rules having common actions are identified and collapsed into single rules.

As described above, the subject matter described herein may be implemented in hardware, software, and/or firmware. In one implementation, the subject matter described herein for firewall policy optimization may be implemented on a general purpose computing platform. Figure 14 is a block diagram of a general purpose computing platform including software for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 14, computing platform **1400** may be a general purpose computer, such as a personal computer, that includes a microprocessor **1402**, memory **1404**, and I/O interfaces **1406**. Microprocessor **1400** may be any suitable microprocessor, such as any of the Intel or AMD families of microprocessors. Memory **1404** may include volatile memory for running programs and persistent memory, such as one or more disk storage devices. I/O interface **1406** may include interfaces with I/O devices, such as user input devices and output devices.

In the illustrated example, software that may be resident in memory **1404** includes a firewall policy editor **1408** and a firewall policy optimizer **1410**. Firewall policy editor **1408** may allow a user to define a firewall policy. For example, firewall policy editor **1408** may allow a user to define a firewall policy by specifying different rules. The rules may be specified in a graphical manner, for example using policy DAGs as described above. Alternatively, firewall policy editor **1408** may allow a user to input rules in a tabular manner, as illustrated in any of the tables described herein. Firewall policy optimizer **1410** may implement any or all of the firewall policy optimization techniques to order rules entered via firewall policy editor **1408** in a manner that preserves policy integrity and that enhances firewall performance.

A firewall rule set that is optimized using the subject matter described herein may be implemented on any firewall system that includes one or more firewalls. For example, an optimized firewall rule set according to embodiments of the subject matter described herein may be implemented using any of the hierarchical, multi-node firewall systems described in commonly assigned, co-pending U.S. patent application no. 11/316,331, filed December 22, 2005, the disclosure of which is incorporated herein by reference in its entirety. Figure 15 illustrates an example of a multi-node firewall system suitable for implementing the firewall rules according to an embodiment of the subject matter described herein. Referring to Figure 15, a plurality of firewall nodes **1500**, **1502**, **1504**,and **1506** may collectively implement any of the optimized firewall policies described herein. For example, the firewall nodes may collectively implement different portions of a firewall policy data structure including an ordered list of firewall rules. A firewall policy engine **1508** resident on each firewall node may filter packets using its local portion **1510** of the firewall policy data structure. A control node **1512** may include a firewall policy optimizer **1514** that measures the average number of comparisons per packets for the current rule configuration and may dynamically reorder the rules to reduce the average number of comparisons per packet. For example, firewall policy optimizer **1514** may utilize any of the methods described herein to rearrange rules and improve firewall performance. Rules may be tested for rearrangement at user-specified

intervals or when average number of packet comparisons increases by a user-specified amount.

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The disclosure of each of the following references is hereby incorporated herein by reference in its entirety.

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It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

It will be understood that various details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

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CLAIMS

The claims defining the invention are as follows:

1. A method for producing a performance optimized firewall policy, the method comprising:
   (a) defining a firewall policy including an ordered list of firewall rules;
   (b) for each rule, defining a first match probability indicating the likelihood that the rule will be the first match for a given packet;
   (c) sorting neighboring rules in order of non-increasing probability for the first match probabilities and in a manner that preserves the firewall policy; and
   (d) sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy, wherein at least one of the groups of two or more rules includes a first rule that prevents a second rule in the group from being moved, within the group, closer to a beginning of the ordered list that implements the firewall policy and wherein sorting the groups of rules includes moving the first and second rules closer to the beginning of the ordered list while maintaining their relative position.

2. The method of claim 1 wherein sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes rearranging the rules if a first rule has a lower probability than a second rule and the first rule is not a subset of the second rule with a different action.

3. The method of claim 1 comprising sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy.

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4. The method of claim 3 wherein sorting groups of two or more rules in a manner that preserves firewall policy includes assigning each group of rules to a sub-trie in a policy trie, computing a sum of packet matching probabilities for rules in each sub-trie, and, in response to determining that a first sub-trie has a lower sum than a second sub-trie, rotating the first and second sub-tries about a common parent so that rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

5. The method of claim 4 comprising, in response to determining that the first and second sub-tries have equal sums, determining whether the second sub-trie has an lower number of branches than the first sub-trie, and, in response to determining that the second sub-trie has a lower number of branches than the first sub-trie, rotating the first and second sub-tries about a common parent so that the rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

6. The method of claim 3 wherein sorting groups of two or more rules in a manner that preserves the firewall policy includes:
   (a) identifying first and second sub-lists of rules in the ordered list of firewall rules, the first sub-list preceding the second sub-list in the ordered list of firewall rules;
   (b) determining a sum of packet matching probabilities for each of the first and second sub-lists;
   (c) determining whether the first and second sub-lists intersect; and
   (d) in response to determining that the sum of the packet matching probabilities for the second sub-list is greater than the sum of the packet matching probabilities for the first sub-list and that the first and second sub-lists do not intersect, switching the order of the first and second sub-lists in the ordered list of firewall rules.

7. The method of claim 6 comprising, in response to determining that the sums of the packet matching probabilities for the first and sub-lists are

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equal, determining whether the second sub-list has a lower number of rules than the first sub-list, and, in response to determining that the second sub-list has a lower number of rules than the first sub-list, switching the order of the first and second sub-lists in the ordered list of firewall rules.

8. The method of claim 1 comprising splitting at least one of the firewall rules to reduce an average number of comparisons required per received packet.

9. The method of claim 1 comprising identifying intersecting rules having a common action and collapsing the rules into a single rule representing a union of the intersecting rules.

10. The method of claim 1 wherein sorting neighboring rules includes sorting rules such that comparisons for a particular class of packets are reduced.

11. The method of claim 1 comprising assigning the rules to vertices in a directed acyclical graph (DAG), determining precedence relationships between the rules, assigning the precedence relationships to edges that connect the vertices in the DAG, and wherein sorting the neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes sorting the neighboring rules in a manner that preserves the precedence relationships represented by the DAG.

12. The method of claim 1 wherein the rules comprise intrusion detection rules.

13. The method of claim 1 wherein the rules comprise intrusion protection rules.

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2006230171 06 Jun 2012

14. A system for firewall policy optimization, for implementing the steps of any one of claims 1-13.

15. A network firewall comprising:
    (a) a firewall policy data structure for storing an ordered list of firewall rules;
    (b) a firewall policy engine for implementing a firewall policy by comparing packets to the rules in the order specified by the firewall policy data structure; and
    (c) a firewall policy optimizer for optimizing performance of the network firewall by reordering the rules in a manner that reduces an average number of rule comparisons per packet and that preserves the firewall policy, wherein the firewall policy optimizer is further configured to sort groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy, wherein at least one of the groups of two or more rules includes a first rule that prevents a second rule in the group from being moved, within the group, closer to a beginning of the ordered list that implements the firewall policy and wherein sorting the groups of rules includes moving the first and second rules closer to the beginning of the ordered list while maintaining their relative position.

16. The network firewall of claim 15 wherein the firewall policy optimizer is adapted to measure average number of comparisons per packet for a rule ordering specified by the firewall policy data structure and to dynamically re-order to rules to reduce the average number of comparisons per packet.

17. A computer program product comprising computer executable instructions embodied in a computer readable medium which, when executed on one or more computing devices or platforms, performs steps in accordance with any one of claims 1 - 13.

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18. A method for producing a performance optimized firewall policy, the method substantially as herein described with reference to the accompanying drawings.

19. A network firewall substantially as herein described with reference to the accompanying drawings.

COMS ID No: ARCS-372276 Received by IP Australia: Time (H:m) 11:49 Date (Y-M-d) 2012-06-06

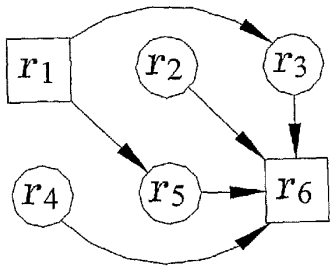


FIG. 1A

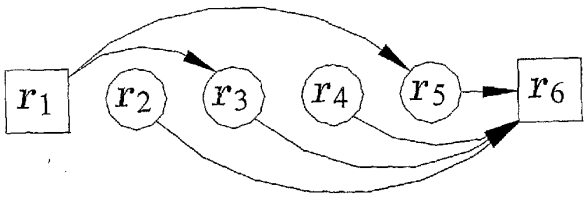


FIG. 1B

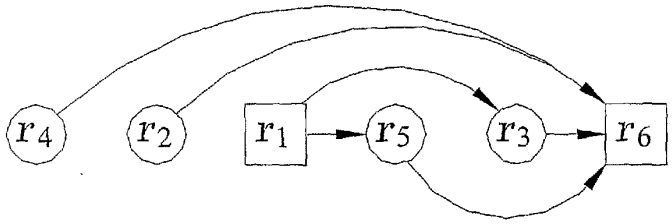


FIG. 2A

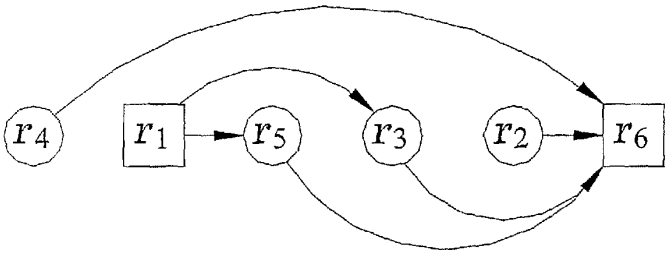


FIG. 2B

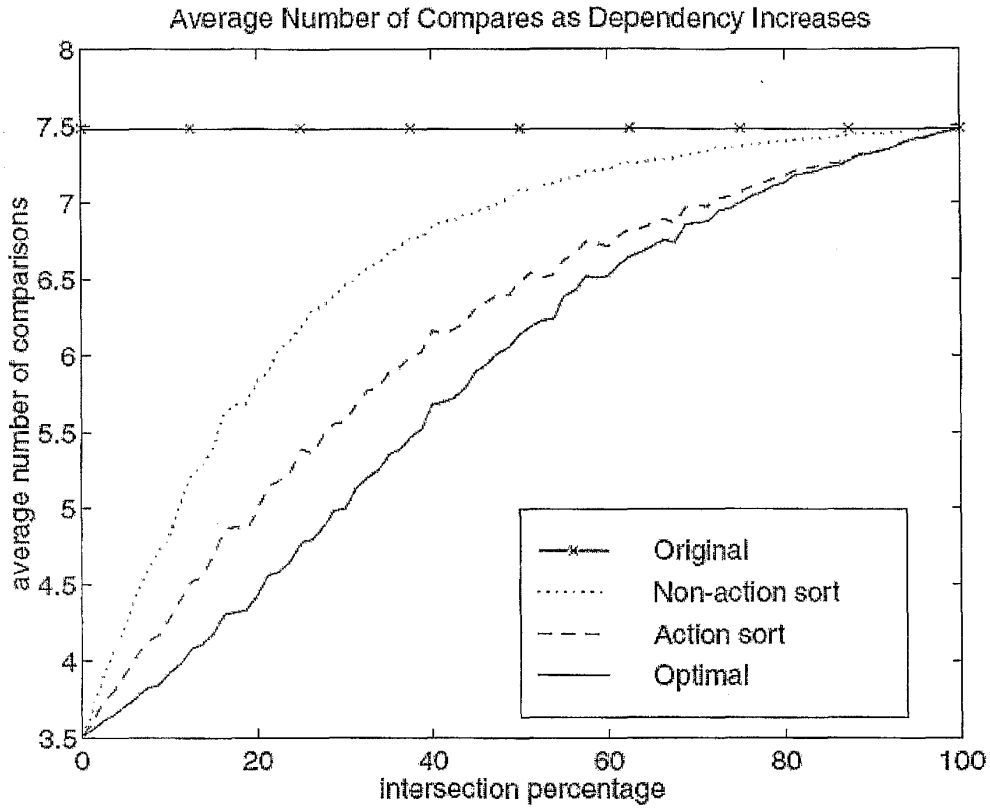

Average Number of Compares as Dependency Increases
average number of comparisons
intersection percentage
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
0
20
40
60
80
100
Original
Non-action sort
Action sort
Optimal

FIG. 3A

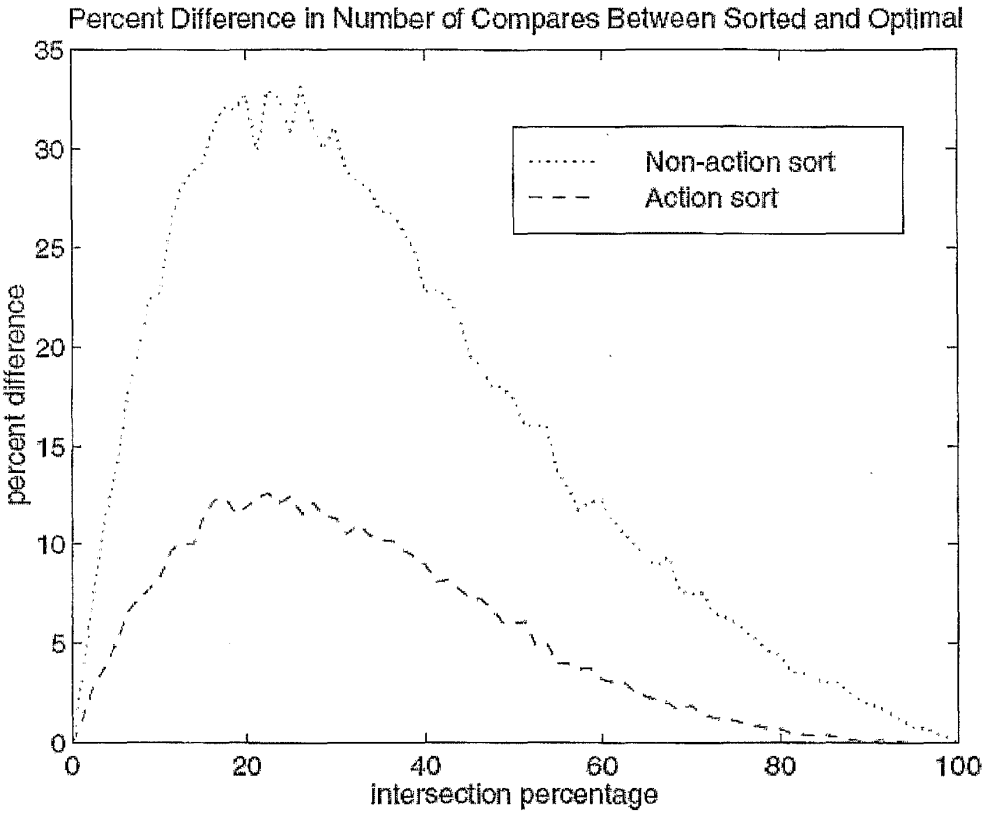

Percent Difference in Number of Compares Between Sorted and Optimal
percent difference
intersection percentage
Non-action sort
Action sort
0
5
10
15
20
25
30
35
0
20
40
60
80
100

FIG. 3B

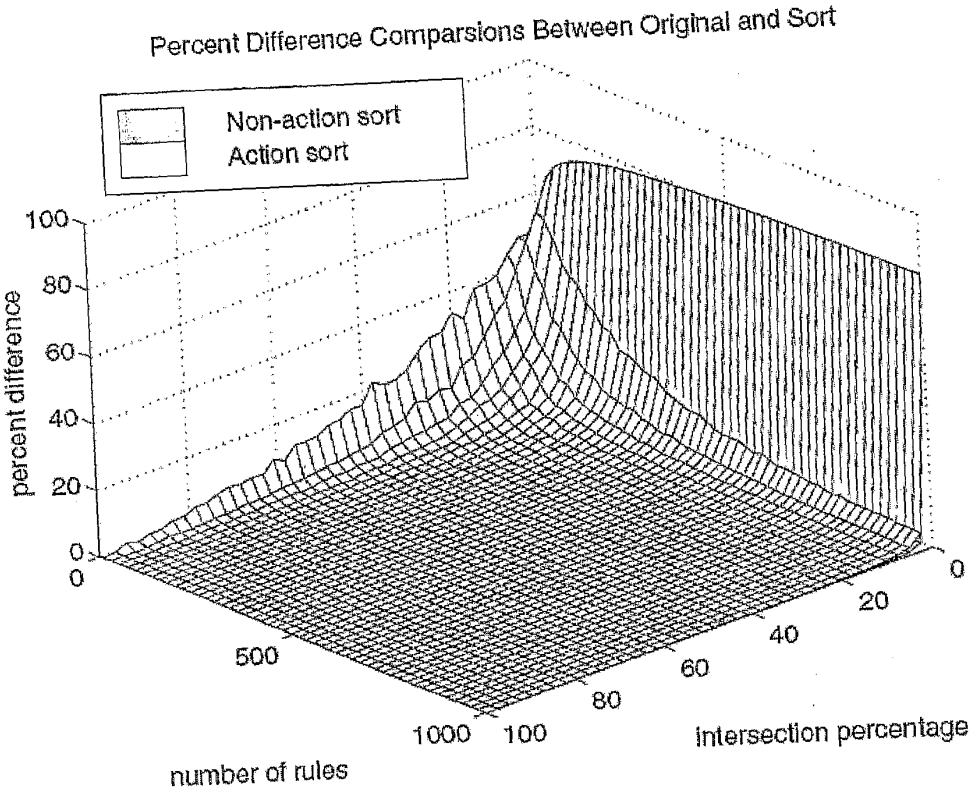

Percent Difference Comparsions Between Original and Sort
Non-action sort
Action sort
percent difference
100
80
60
40
20
0
0
500
1000
number of rules
0
20
40
60
80
100
intersection percentage

FIG. 4A

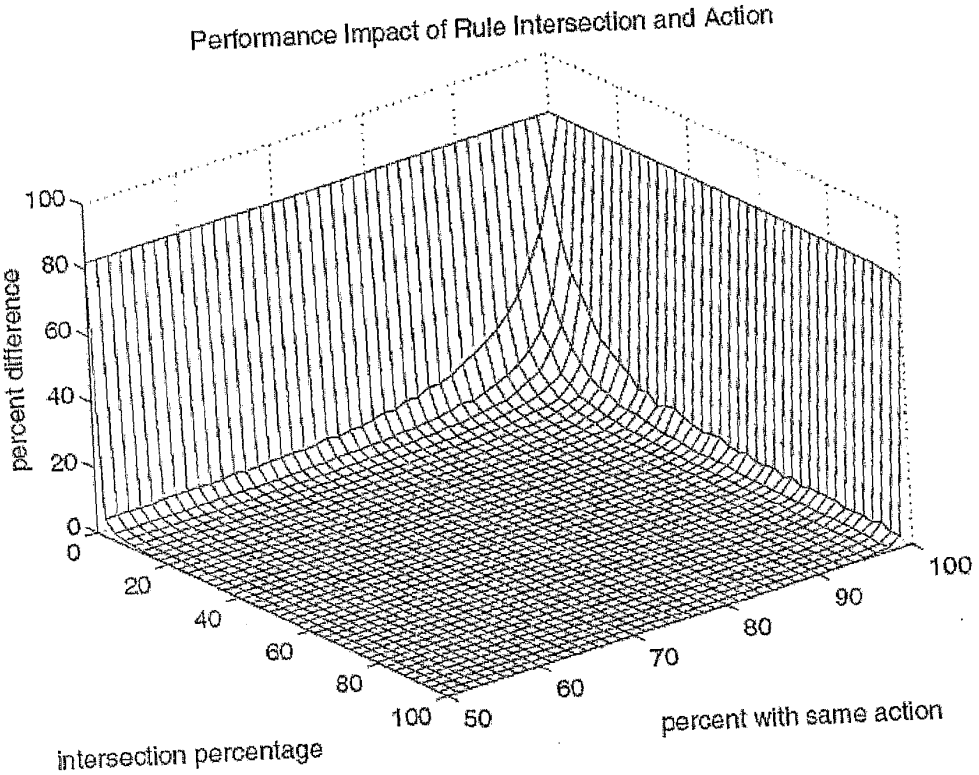

Performance Impact of Rule Intersection and Action
percent difference
0
20
40
60
80
100
intersection percentage
0
20
40
60
80
100
percent with same action
50
60
70
80
90
100

FIG. 4B

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5A

r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5B

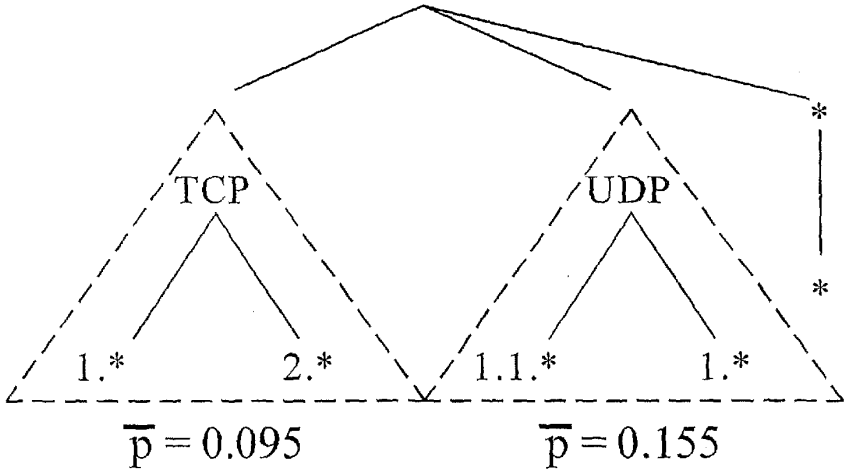


FIG. 6A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 6B

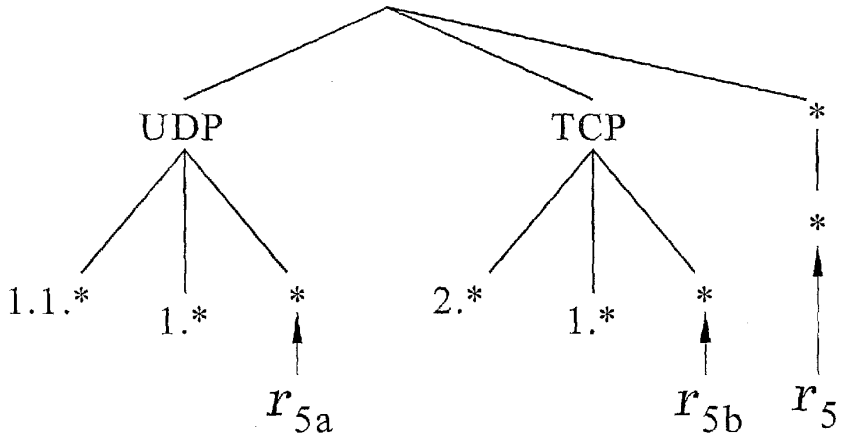


FIG. 7A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	ACCEPT)	$p_4 = 0.30$
r_{5a}	(UDP,	*,	DENY)	$p_{5a} = 0.47$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_{5b}	(TCP,	*,	DENY)	$p_{5b} = 0.03$

FIG. 7B

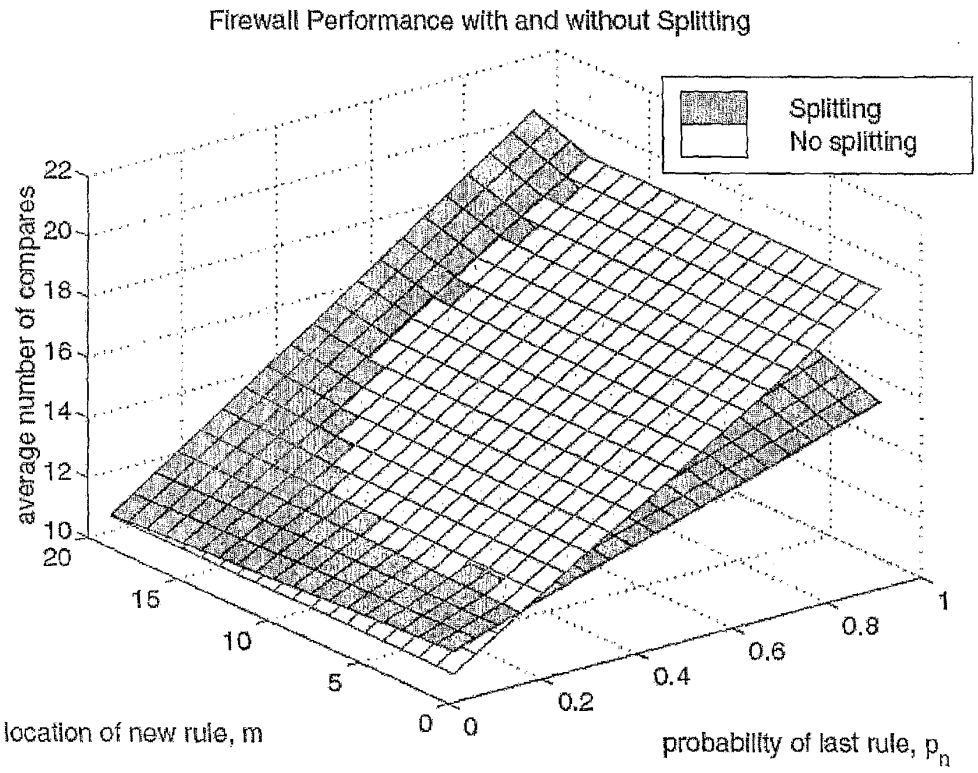

Firewall Performance with and without Splitting
Splitting
No splitting
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8A

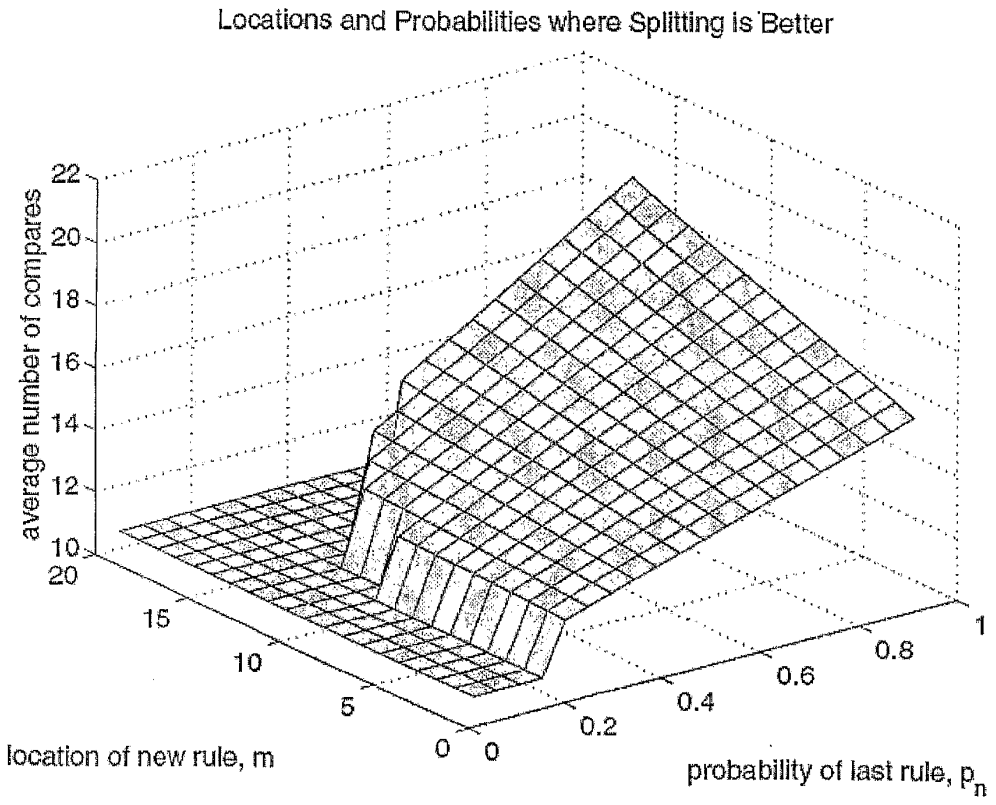

Locations and Probabilities where Splitting is Better
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8B

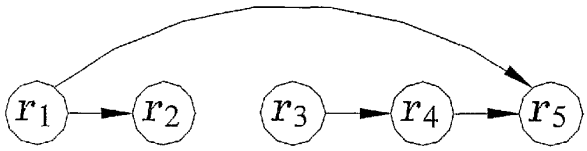


FIG. 9A

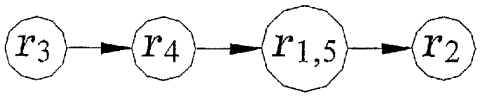


FIG. 9B

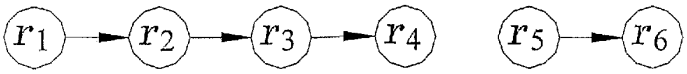


FIG. 10A

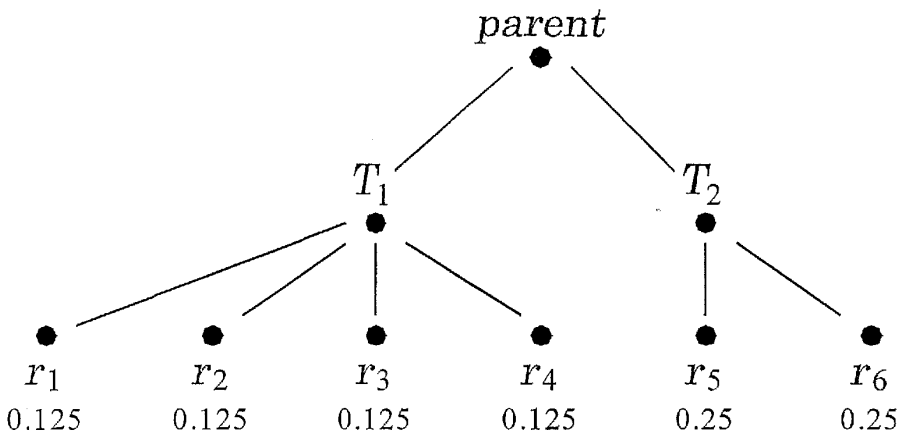


FIG. 10B

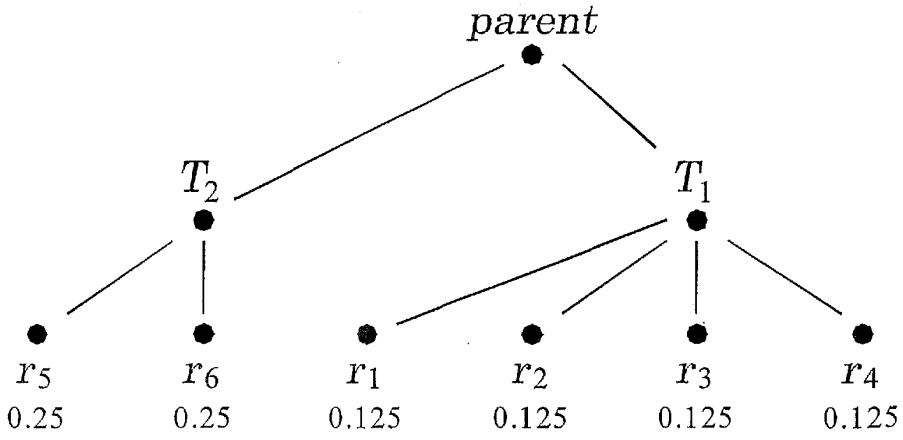


FIG. 10C

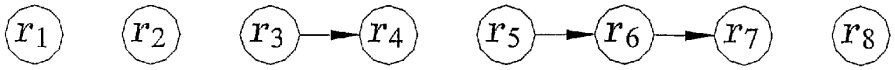


FIG. 11A

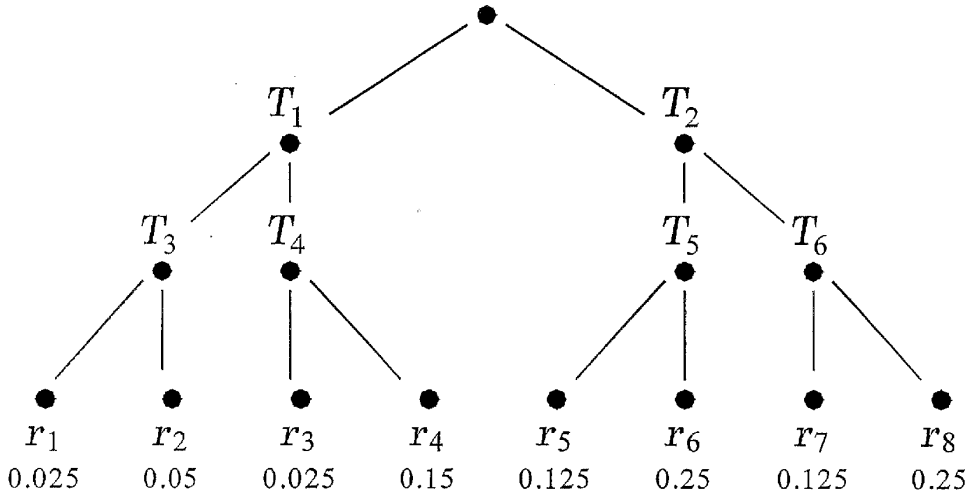


FIG. 11B

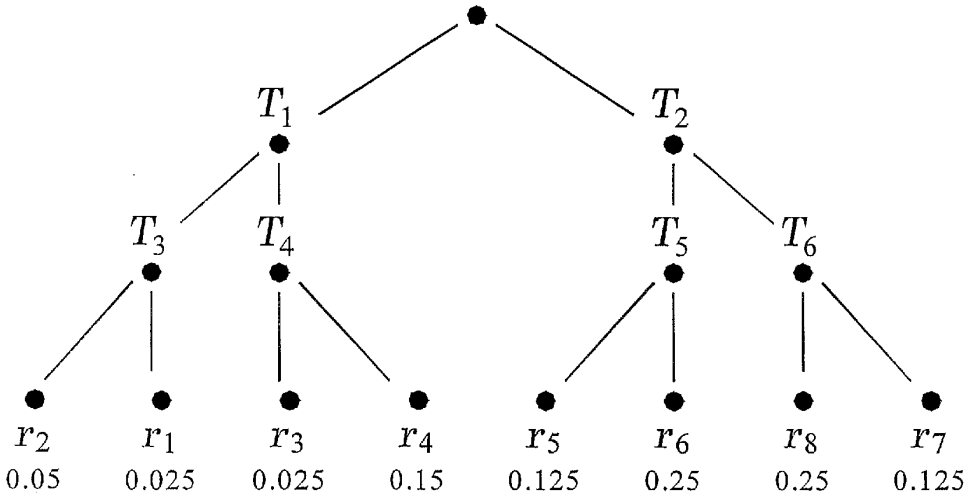


FIG. 11C

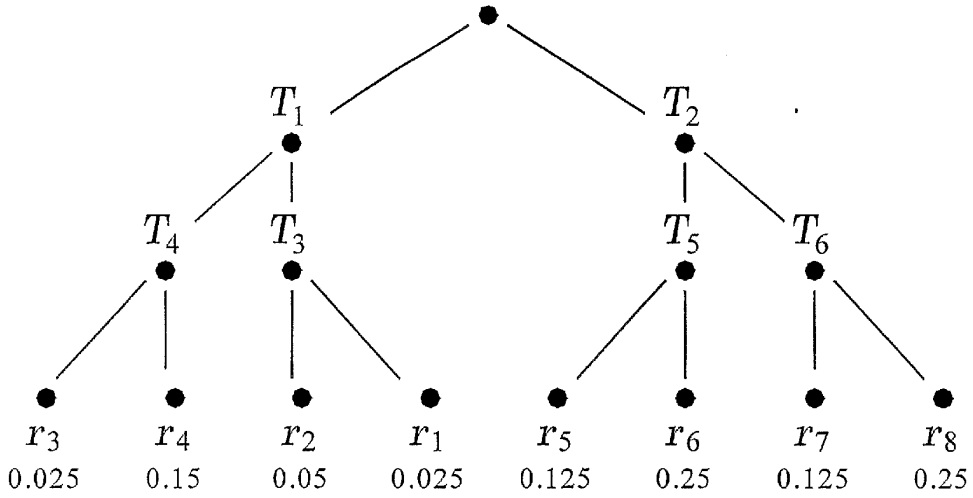


FIG. 11D

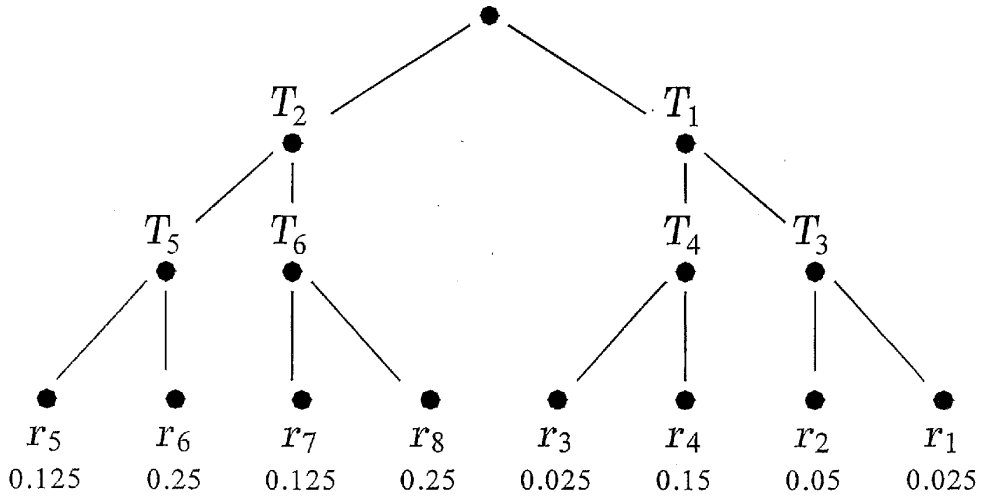


FIG. 11E

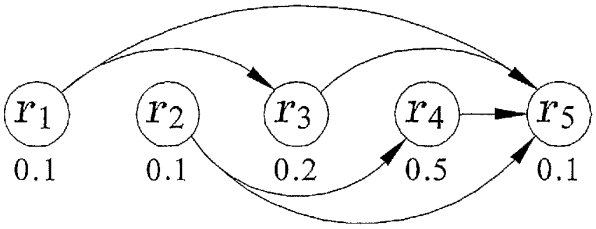


FIG. 12A

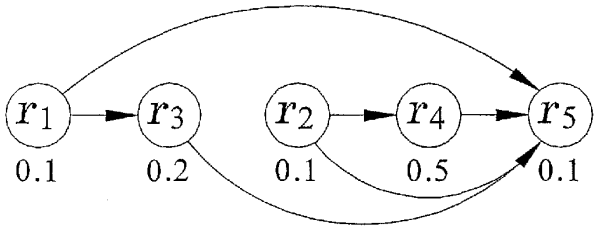


FIG. 12B

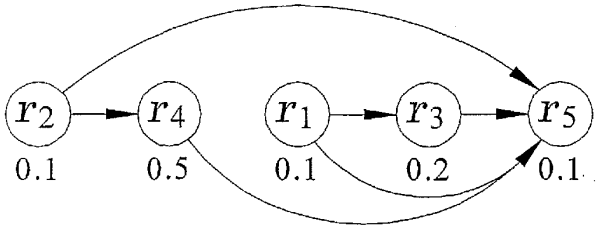


FIG. 12C

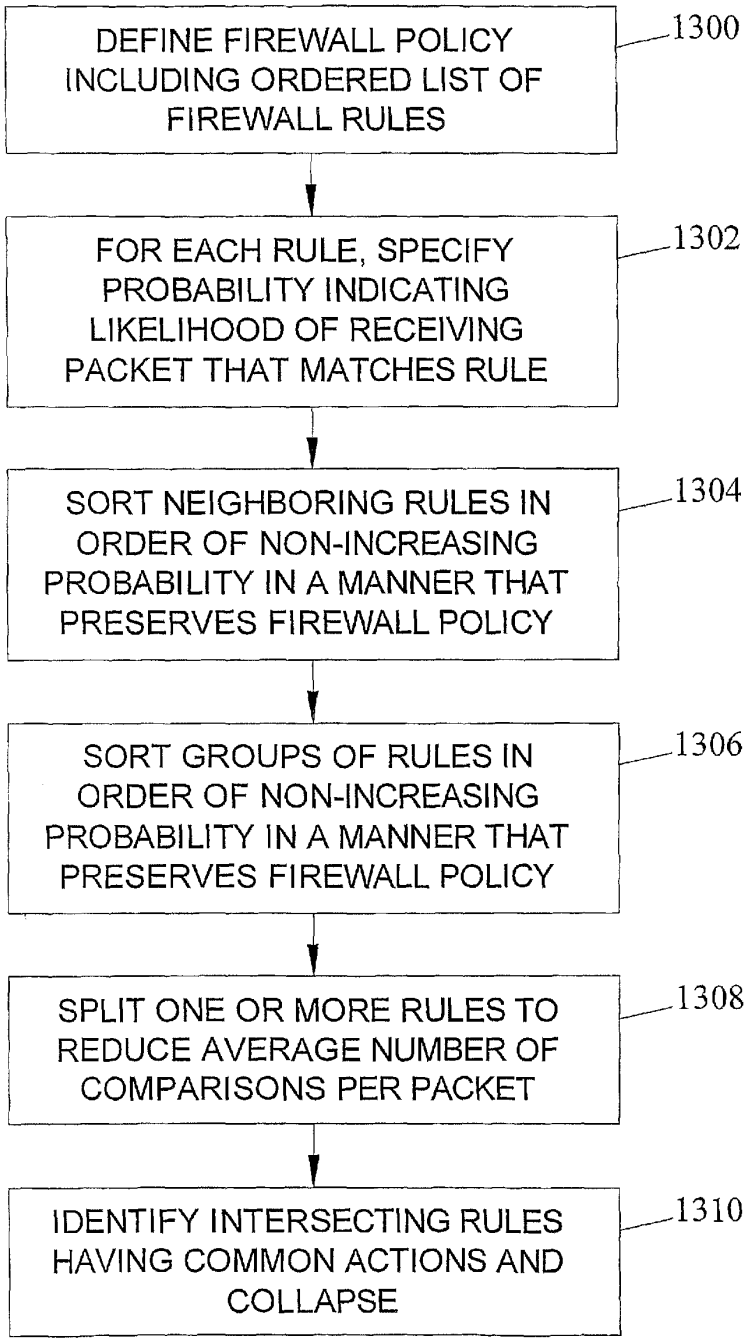

DEFINE FIREWALL POLICY INCLUDING ORDERED LIST OF FIREWALL RULES
1300
FOR EACH RULE, SPECIFY PROBABILITY INDICATING LIKELIHOOD OF RECEIVING PACKET THAT MATCHES RULE
1302
SORT NEIGHBORING RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1304
SORT GROUPS OF RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1306
SPLIT ONE OR MORE RULES TO REDUCE AVERAGE NUMBER OF COMPARISONS PER PACKET
1308
IDENTIFY INTERSECTING RULES HAVING COMMON ACTIONS AND COLLAPSE
1310

FIG. 13

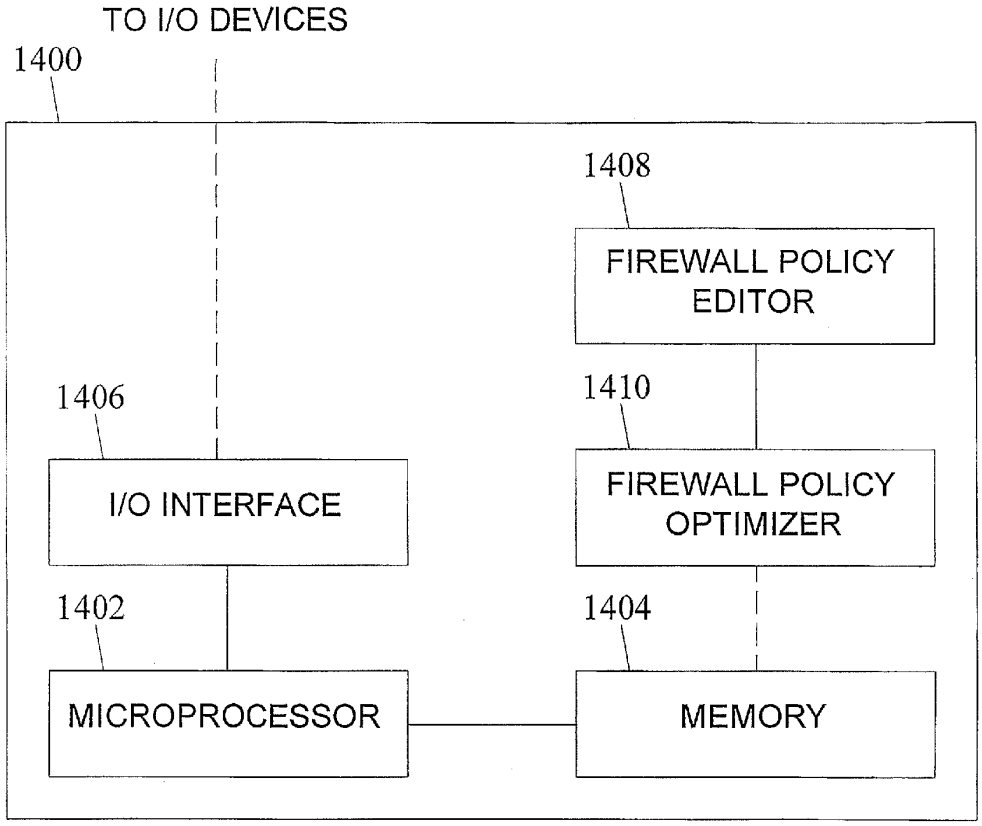

TO I/O DEVICES
1400
1408
FIREWALL POLICY EDITOR
1406
1410
I/O INTERFACE
FIREWALL POLICY OPTIMIZER
1402
1404
MICROPROCESSOR
MEMORY

FIG. 14

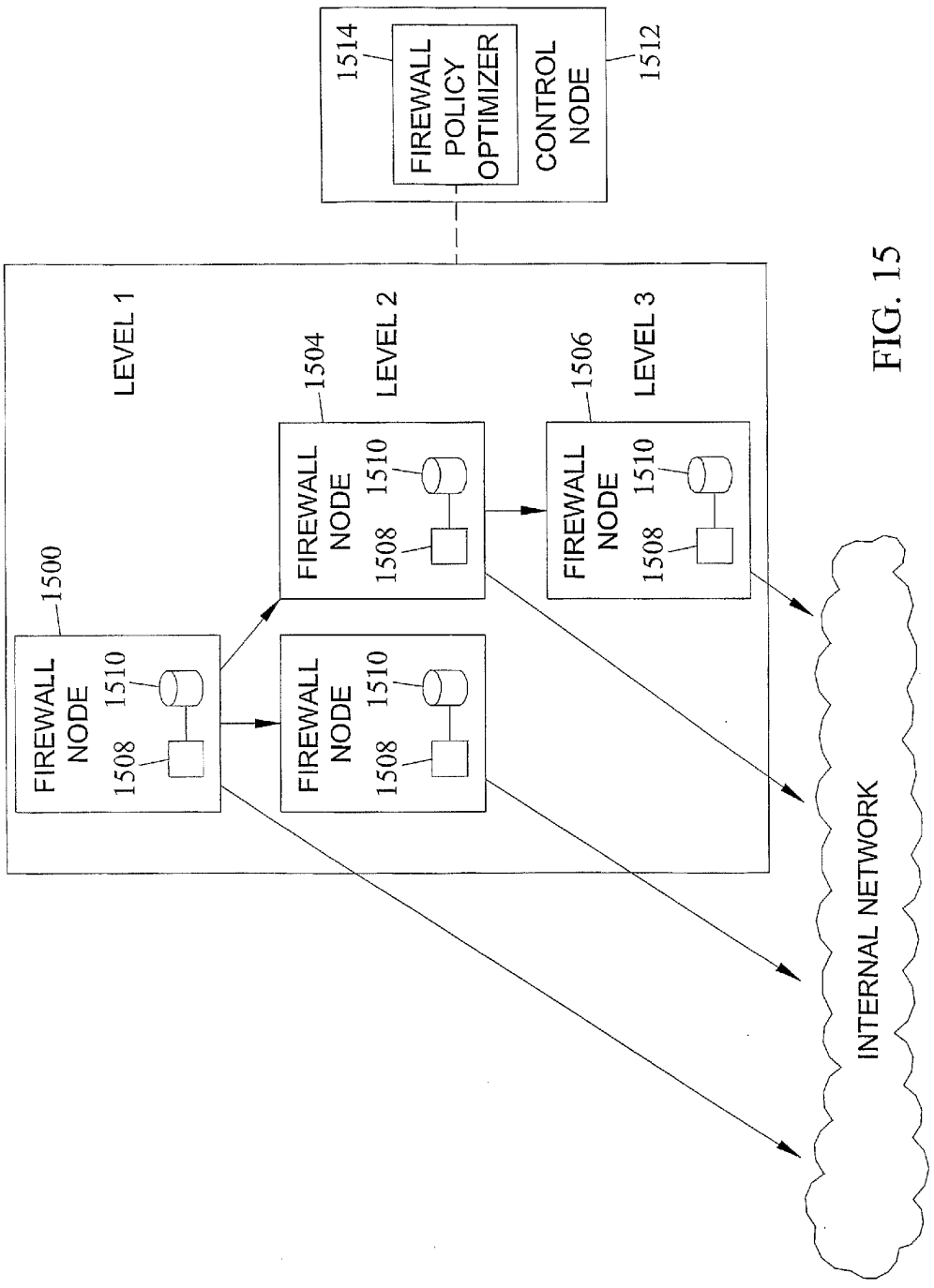

1514
FIREWALL POLICY OPTIMIZER
CONTROL NODE
1512
LEVEL 1
LEVEL 2
LEVEL 3
1500
1504
1506
FIREWALL NODE
1508
1510
INTERNAL NETWORK

FIG. 15

Espacenet

Bibliographic data: EP1864226 (B1) — 2013-05-15

METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION

Inventor(s): FULP ERRIN W [US]; TARSA STEPHEN J [US] ± (FULP, ERRIN, W, ; TARSA, STEPHEN, J)

Applicant(s): UNIV WAKE FOREST [US] ± (WAKE FOREST UNIVERSITY)

Classification: **- international:** ***H04L29/06***
- cooperative: **H04L63/0263**; **H04L63/20**

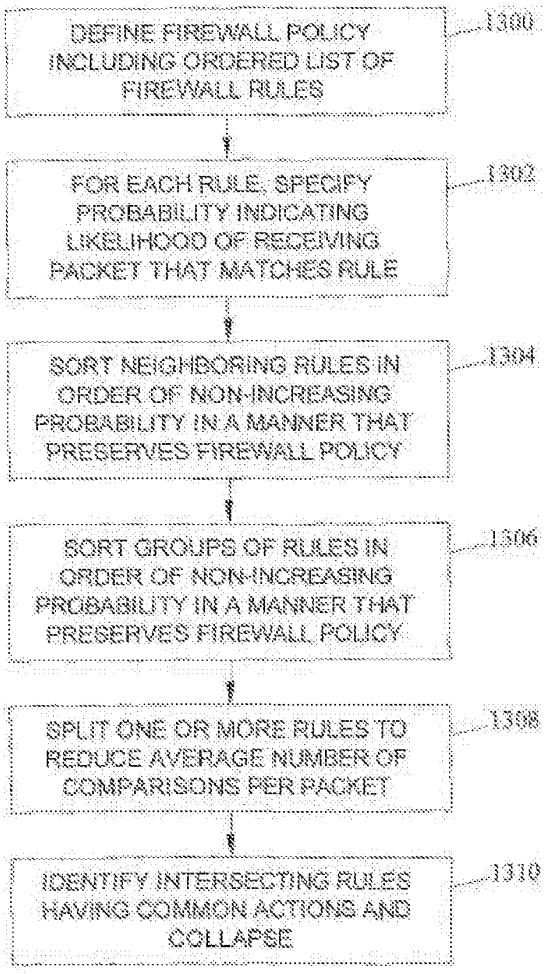
Application number: EP20060758213 20060328

Priority number (s): WO2006US11291 20060328 ; US20050665664P 20050328

Also published as: EP1864226 (A2) EP1864226 (A4) WO2006105093 (A2) WO2006105093 (A3) US2006248580 (A1) more

Abstract not available for EP1864226 (B1)
Abstract of corresponding document: WO2006105093 (A2)

Methods, systems, and computer program products for firewall policy optimization are disclosed. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is determined. The rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.


DEFINE FIREWALL POLICY INCLUDING ORDERED LIST OF FIREWALL RULES
1300
FOR EACH RULE, SPECIFY PROBABILITY INDICATING LIKELIHOOD OF RECEIVING PACKET THAT MATCHES RULE
1302
SORT NEIGHBORING RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1304
SORT GROUPS OF RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1306
SPLIT ONE OR MORE RULES TO REDUCE AVERAGE NUMBER OF COMPARISONS PER PACKET
1308
IDENTIFY INTERSECTING RULES HAVING COMMON ACTIONS AND COLLAPSE
1310

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 864 226 B1

(12) **EUROPEAN PATENT SPECIFICATION**

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15.05.2013 Bulletin 2013/20

(21) Application number: **06758213.0**

(22) Date of filing: **28.03.2006**

(51) Int Cl.:
H04L 29/06 *(2006.01)*

(86) International application number:
PCT/US2006/011291

(87) International publication number:
WO 2006/105093 (05.10.2006 Gazette 2006/40)

(54) **METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION**

VERFAHREN, SYSTEME UND COMPUTERPROGRAMM ZUR OPTIMIERUNG DER FIREWALL-REGELUNG EINES NETZWERKES

PROCEDES, SYSTEMES ET PRODUITS DE PROGRAMMES INFORMATIQUES POUR L'OPTIMISATION DE LA POLITIQUE DE PARE-FEU D'UN RESEAU

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR

(30) Priority: **28.03.2005 US 665664 P**

(43) Date of publication of application:
12.12.2007 Bulletin 2007/50

(73) Proprietor: **Wake Forest University**
Winston Salem, NC 27101 (US)

(72) Inventors:
- **FULP, Errin, W.**
  Winston-Salem, North Carolina 27104 (US)
- **TARSA, Stephen, J.**
  Duxbury, Massachusetts 02332-3503 (US)

(74) Representative: **Isarpatent**
Patent- und Rechtsanwälte
Postfach 44 01 51
80750 München (DE)

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US-B2- 7 237 267
WO-A2-2006/093557
US-B1- 6 484 261
US-B1- 7 089 581

- **Errin W. Fulp: "Optimization of Network Firewall Policies Using Ordered Sets and Directed Acyclical Graphs", Wake Forest University , 2004, pages 1-12, XP002618343, Retrieved from the Internet: URL:www.cs.wfu.edu/~fulp/Papers/ewflist.ps [retrieved on 2011-01-24]**
- **Errin W. Fulp and Stephen J. Tarsa: "Network Firewall Policy Tries", Wake Forest University , 2004, pages 1-17, XP002618344, Retrieved from the Internet: URL:http://citeseerx.ist.psu.edu/viewdoc/s ummary?doi=10.1.1.143.5727 [retrieved on 2011-01-24]**
- **Lili Qiu, George Varghese, Subhash Suri: "Fast Firewall Implementations for Software and Hardware-based Routers", , 2001, pages 241-250, XP002618345, Retrieved from the Internet: URL: http://www.ieee-icnp.org/2001/papers/2001-26.pdf [retrieved on 2011-01-25]**
- **Errin W. Fulp: "Errin Fulp", , 2010, XP002618346, Retrieved from the Internet: URL: www.cs.wfu.edu/~fulp/ewfPub.html [retrieved on 2011-01-24]**

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EP 1 864 226 B1

Description

TECHNICAL FIELD

[0001] The subject matter described herein relates to optimizing polices for network firewalls. More particularly, the subject matter described herein relates to methods, systems, and computer program products for optimizing performance of network firewalls.

BACKGROUND ART

[0002] Network firewalls remain the forefront defense for most computer systems. Guided by a security policy, these devices provide access control, auditing, and traffic control [3, 30, 31]. A security policy is a list of ordered rules, as seen in Table 1, that defines the action to perform on matching packets. For example, an accept action passes the packet into or from the secure network, while deny causes the packet to be discarded. In many implementations, the rule set is stored internally as a linked list. A packet is sequentially compared to the rules, starting with the first, until a match is found; otherwise, a default action is performed [30, 31]. This is referred to as a first- match policy and is used in many firewall systems including the Linux firewall implementation iptables [25].

Table 1: Example Security Policy Consisting of Multiple Ordered Rules

		Source		Destination			
No.	Proto.	IP	Port	IP	Port	Action	Prob.
1	UDP	1.1.*	*	*	80	deny	0.01
2	TCP	2.*	*	1.*	90	accept	0.02
3	UDP	*	*	1.*	*	accept	0.10
4	TCP	2.*	*	1.*	20	accept	0.17
5	UDP	1.*	*	*	*	accept	0.20
6	*	*	*	*	*	deny	0.50

[0003] Traditional firewall implementations consist of a single, dedicated machine, similar to a router, that sequentially applies rules to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [24, 29, 31]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [30]. Successfully handling these traffic loads becomes more difficult as rule sets become more complex [4, 22, 31]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 9, 13, 14]. An attacker could simply inundate the firewall with traffic, delaying or preventing legitimate packets from being processed.

[0004] One approach to increase firewall performance focuses on improving hardware design. Current research is investigating different distributed firewall designs to reduce processing delay [4, 9, 22], and possibly provide service differentiation [11]. Another approach focuses on improving performance via better firewall software [6, 7, 12, 16, 17, 24]. Similar to approaches that address the longest matching prefix problem for packet classification [8,10,25, 28], solutions typically represent the firewall rule set in different fashions (e.g. tree structures) to improve performance. While both approaches, together or separate, show great promise, each requires radical changes to the firewall system, and therefore are not amenable to current or legacy systems.

[0005] EP Patent Publication No. 1006701 discloses a packet data filter which stores ordered rules and sequentially applies the rules to received data packets to determine the disposition of the data packet. The packet filter maintains a match count in memory which indicates the number of times each rule matched an incoming data packet. Periodically, at the initiation of a user, or based on operating parameters of the filter, the rules are automatically re-ordered based on the match count. As a result of the re-ordering, rules with higher match counts are moved earlier in the sequential evaluation order and rules with lower match counts are moved later in the sequential evaluation order. As such, rules which are more likely to match incoming data packets are evaluated earlier, thus avoiding the evaluation of later rules.; In order to prevent a re-ordering which would change the overall security policy of the packet filter, pairs of rules are compared to determine if they conflict (i.e., the swapping of the two rules would result in a change in the overall security policy). During re-ordering, the swapping of conflicting rules is prevented.

[0006] US Patent Publication No. 2002/198981 discloses a method and system for determining whether to enforce a

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plurality of filter rules for a packet including a key in a computer network is disclosed. Each of the plurality of filter rules has a priority. The method and system include accumulating statistics for each of the plurality of filter rules. The statistics indicate a frequency of enforcement for each of the plurality of filter rules. The method and system also include placing the plurality of filter rules in an order for testing against the key. The order is based on the frequency of each filter rule of the portion of the plurality of filter rules. Consequently, more frequently enforced filter rules may be tested first.

[0007] WO Publication No. 2006093557 discloses methods, systems, and computer program products for providing function-paralell firewalls are disclosed. According to one aspect, a function-parallel firewall includes a first firewall node for filtering received packets using a first portion of a rule set including a plurality of rules. The first portion includes less than all of the rules in the rule set. At least one second firewall node filters packets using a second portion of the rule set. The second portion includes at least one rule in the rule set that is not present in the first portion. The first and second portions together include all of the rules in the rule set.

[0008] Accordingly, there exists a need for improved methods, systems, and computer program products for network firewall policy optimization.

SUMMARY

[0009] The subject matter described herein includes methods, systems, and computer program products for network firewall policy optimization. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is defined. Neighbouring rules are sorted in order of non- increasing probability in a manner that preserves the firewall policy.

[0010] As used herein, the term "firewall" refers to a logical entity that is adapted to filter packets at the ingress and/or egress portions of a network based on a policy. The term "firewall" is intended to include systems that block packets from entering or leaving a network and systems that perform intrusion detection and intrusion protection functions for packets entering or leaving a network. Thus, the methods and systems described herein for firewall policy optimization can be used to optimize policies for intrusion detection and intrusion protection firewalls.

[0011] The subject matter described herein includes a method to improve firewall performance and lower packet delay that can be applied to both legacy and current systems. In one implementation, a firewall rule set may be reordered to minimize the average number of rule comparisons to determine the action, while maintaining the integrity of the original policy. Integrity is preserved if the reordered and original rules always arrive at the same result. To maintain integrity, a firewall rule set may be modeled as a Directed Acyclical Graph (DAG), where vertices are firewall rules and edges indicate precedence relationships. Given this representation, any linear arrangement of the DAG is proven to maintain the original policy integrity. Unfortunately, determining the optimal rule order from all the possible linear arrangements is proven to be NP- complete, since it is equivalent to sequencing jobs with precedence constraints for a single machine [15]. Although determining the optimal order is NP- complete, a heuristic will be described below to order firewall rules that reduces the average number of comparisons while maintaining integrity. Simulation results show the proposed reordering method yields rule orders that are comparable to optimal; thus, provides a simple means to significantly improve firewall performance and lower packet delay.

[0012] The subject matter described herein for network firewall policy optimization may be implemented using any combination of hardware, software, or firmware. For example, the subject matter described herein may be implemented using a computer program product comprising computer executable instructions embodied in a computer readable medium. Exemplary computer readable media suitable for implementing the subject matter described herein include disk memory devices, chip memory devices, programmable logic devices, application specific integrated circuits, and downloadable electrical signals. In addition, a computer program product that implements the subject matter described herein may be implemented using a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Preferred embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings of which:

Figure 1A is a block diagram of a rule list Directed Acyclical Graph (DAG) for the firewall rules in Table 1;
Figure 1 B is a linear arrangement of firewall rules corresponding to the original rule order;
Figure 2A is a policy DAG representing a reordered version of the firewall rule set in Figure 1 after sorting;
Figure 2B is a policy DAG for the rule set illustrated in Table 1 illustrating an optimal rule order;
Figure 3A is a graph illustrating average numbers of packet comparisons versus intersection percentage for different orderings of a firewall policy;
Figure 3B is a graph illustrating the percent difference in average numbers of packet comparisons between sorted

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and optimal sortings of a firewall policy;
Figure 4A is a graph of percent difference comparisons between original and sorted versions of a firewall policy;
Figure 4B is a graph illustrating the performance impact of considering rule intersection and actions in performing firewall rule sorting;
Figure 5A is a table illustrating a firewall policy before sorting;
Figure 5B is a table illustrating a sorted version of the firewall policy of Figure 5A;
Figure 6A is a policy trie representation of the firewall policy of Figure 5B;
Figure 6B is a table representing the firewall policy of Figure 5A after TCP and UDP sub-trie rotation;
Figure 7A is a policy trie illustrating the splitting of rule r_5 into rules r_{5a} and r_{5b};
Figure 7B is a table illustrating the firewall policy of Figure 5A after splitting rule r_5 into rules r_{5a} and r_{5b};
Figure 8A is a graph illustrating firewall performance with and without rule splitting;
Figure 8B is a graph illustrating locations and probabilities where splitting is better;
Figure 9A is a policy DAG of a firewall rule set;
Figure 9B is a policy DAG illustrating compression of rules r_1 and r_5;
Figure 10A is a policy DAG of a firewall rule list;
Figure 10B is an original policy trie before sorting;
Figure 10C is a policy trie illustrating the firewall rules after rotating sub-tries T_1 and T_2;
Figure 11A is a policy DAG illustrating a firewall policy;
Figure 11B is a policy trie illustrating firewall rules of the policy before sorting;
Figure 11C is a policy trie illustrating the firewall policy after exchanging nodes r_1 and r_2 and nodes r_7 and r_8;
Figure 11 D is a policy trie illustrating the firewall policy after exchanging sub-tries T_3 and T_4;
Figure 11 E is a policy trie illustrating the firewall policy after exchanging sub-tries T_1 and T_2;
Figure 12A is a policy DAG illustrating an original order for a firewall policy;
Figure 12B is a policy DAG illustrating a sorted version of the firewall policy of Figure 12A after exchanging neighbors;
Figure 12C is a policy DAG illustrating a sorted version of the firewall policy after exchanging lists L_1 including rules r_1 and r_3 and lists L_2 including rules r_2 and r_4;
Figure 13 is a flow chart illustrating exemplary steps for network firewall policy optimization according to an embodiment of the subject matter described herein;
Figure 14 is a block diagram illustrating exemplary components of a system for firewall policy optimization according to an embodiment of the subject matter described herein; and
Figure 15 is a block diagram illustrating a plurality of firewall nodes for implementing a firewall policy according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION OF THE INVENTION

Modeling Firewall Security Policies

[0014] As described above, a firewall rule set, also known as a firewall policy, is traditionally an ordered list of firewall rules. Firewall policy models have been the subject of recent research [1, 2, 16]; however, the primary purpose is anomaly detection and policy verification. In contrast, the policy model described in this herein is designed for firewall performance optimization and integrity. Firewall performance refers to reducing the average number of comparisons required to determine an action, while integrity refers to maintaining the original policy intent. Although improving the worst-case performance is important, it is not possible without changing the list-based representation [16, 24].

Firewall Rule and Policy Models

[0015] In the examples described herein, a rule r is modeled as an ordered tuple of sets, r= (r[1], r[2], ..., r[k]). Order is necessary among the tuples since comparing rules and packets requires the comparison of corresponding tuples. Each tuple $r[l]$ is a set that can be fully specified, specify a range, or contain wildcards '*' in standard prefix format. For the Internet, security rules are commonly represented as a 5-tuple consisting of: protocol type, IP source address, source port number, IP destination address, and destination port number [30, 31]. Given this model, the ordered tuples can be supersets and subsets of each other, which forms the basis of precedence relationships. In addition to the prefixes, each filter rule has an action, which is to accept or deny. However, the action will not be considered when comparing packets and rules. Similar to a rule, a packet (IP datagram) d can be viewed as an ordered k-tuple d = (d[1], d[2], ..., d[k]); however, ranges and wildcards are not possible for any packet tuple.

[0016] Using the previous rule definition, a standard security policy can be modeled as an ordered set (list) of n rules, denoted as $R = \{r_1, r_2, ..., r_n\}$. A packet d is sequentially compared against each rule r_i starting with the first, until a match is found ($d \Rightarrow r_i$) then the associated action is performed. A match is found between a packet and rule when every tuple

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of the packet is a subset of the corresponding tuple in the rule.
Definition Packet d matches r_i if

$$d \Rightarrow r_i \quad \text{iff} \quad d[l] \subseteq r_i[l], \quad l = 1, \ldots, k$$

[0017] The rule list R is comprehensive if for every possible legal packet d a match is found using R. Furthermore, two rule lists R and R' are equivalent if for every possible legal packet d the same action is performed by the two rule lists. If R and R' are different (e.g. a reorder) and the lists are equivalent, then the policy integrity is maintained.

[0018] As previously mentioned, a rule list has an implied precedence relationship where certain rules must appear before others if the integrity of the policy is to be maintained. For example consider the rule list in Table 1. Rule r_1 must appear before rules r_3 and r_5, likewise rule r_6 must be the last rule in the policy. If for example, rule r_3 was moved to the beginning of the policy, then it will shadow [2] the original rule r_1. However, there is no precedence relationship between rules r_2 and r_4 given in Table 1. Therefore, the relative ordering of these two rules will not impact the policy integrity and can be changed to improve performance. The present example assumes that the original policy is free from any anomalies. Likewise, when a policy is reordered to improve performance it should not introduce any anomalies, which will occur if precedence relationships are not maintained. As a result, a model is needed to effectively represent precedence relationships.

Modeling Rule List Precedence Relationships

[0019] The precedence relationship between rules in a policy will be modeled as a Directed Acyclical Graph (DAG) [23, 18]. Such graphs have been successfully used to represent the relative order of individual tasks that must take place to complete a job (referred to as a task graph model). Since certain rules must appear before others to maintain policy integrity, this structure is well suited for modeling the precedence of firewall rules. Let $G = (R, E)$ be a rule list DAG for a rule list R, where vertices are rules and edges E are the precedence relationships (constraint). A precedence relationship, or edge, exists between rules r_i and r_j, if $i < j$, the actions for each rule are different, and the rules intersect.
Definition The intersection of rule r_i and r_j, denoted as $r_i \cap r_j$ is

$$r_i \cap r_j = (r_i[l] \cap r_j[l]), \quad l = 1, \ldots, k$$

Therefore, the intersection of two rules results in an ordered set of tuples that collectively describes the packets that match both rules. The rules r_i and r_j intersect if every tuple of the resulting operation is non-empty. In contrast, the rules r_i and r_j do not intersect, denoted as $r_i \not\cap r_j$, if at least one tuple is the empty set. Note the intersection operation is symmetric; therefore, if r_i intersects r_j then r_j will intersect r_i. The same is true for rules that do not intersect.

[0020] For example consider the rules given in Table 1, the intersection of r_1 and r_3 yields (UDP, 1.1.*, *, 1.*, 80). Again, the rule actions are not considered in the intersection or match operation. Since these two rules intersect, a packet can match both rules for example d = (UDP, 1.1.1.1, 80, 1.1.1.1, 80). Furthermore, the actions of the two rules are different. Therefore, the relative order must be maintained between these two rules and an edge drawn from r_1 to r_3 must be present in the rule list DAG, as seen in Figures 1A and 1B. More particularly, Figure 1 A illustrates a rule list DAG for the rules in Table 1. Figure 1B illustrates a linear arrangement of the rules in Figure 1A. In Figures 1A and 1 B, the vertices represent rules, the circles represents an accept rules, and the squares represents deny rules. Edges that connect the vertices represent precedence requirements. As can be seen from Figure 1 B, because of the edge between rules r_1 and r_3, precedence between rules r_1 and r_3 must be maintained. In contrast consider the intersection of rules r_3 and r_5. These two rules intersect, indicating packets belonging to the set (UDP, 1.*, *, 1.*, *) would match both rules. However, it does not matter which of the two rules a packet matches first, since the action is the same for both rules. Therefore, an edge does not exist between rules r_3 and r_5 in the diagram. Similarly, rules r_2 and r_4 do not intersect due to the fifth tuple (destination port). A packet cannot match both rules indicating the relative order can change; therefore, an edge will not exist between them.

[0021] The match operation can be used to identify precedence relationships, but it cannot do so in every case. Consider a partial-match example [1], where r_a = (UDP, *, 80, 10.*, 90, accept) and r_b = (UDP, 10.*, 80, *, 90, deny). The intersection of r_a and r_b is (UDP, 10.*, 80, 10.*, 90); therefore a packet, such as d = (UDP, 10.10.10.10, 80, 10.10.10.10, 90), can match both rules. If r_a appears before r_b then the packet d is accepted, but if r_b occurs before r_a then d is rejected. As a result, the order of r_a and r_b in the original policy must be maintained. However, the match operation is unable to identify the precedence in this example. A partial match exists in between rules r_3 and r_5 in Table

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1, but as previously discussed an edge does not exist between the rules since the actions are the same.

[0022] Using the rule list DAG representation a linear arrangement is sought that improves the firewall performance. As depicted in Figure 1 B, a linear arrangement (permutation or topological sort) is a list of DAG vertices where all the successors of a vertex appear in sequence after that vertex [23]. Therefore it follows that a linear arrangement of a rule list DAG represents a rule order, if the vertices are read from left to right. Furthermore, it is proven in the following theorem that any linear arrangement of a rule list DAG maintains integrity: **Theorem** Any linear arrangement of a rule list DAG maintains integrity.

[0023] **Proof** Assume a rule list DAG G is constructed from the security policy R that is free of anomalies. Consider any two rules r_i and r_j in the policy, where $i < j$. If an edge between r_i and r_j in G does not exist, then a linear arrangement of G can interchange the order of the two rules. An edge will not exist if the rules do not intersect; however, a reorder will not affect integrity since a packet cannot match both rules. Shadowing is not introduced due to the reorder since the intersection operation is symmetric. An edge will not exist if the two rules intersect but have the same action; however, a reorder will not affect integrity since the same action will occur regardless of which rule is matched first. If an edge does exist between the rules, then their relative order will be maintained in every linear arrangement of G; thus maintaining precedence and integrity.

Rule List Optimization

[0024] As described above, it is important to inspect packets as quickly as possible given increasing network speeds and QoS requirements. Using the rule list DAG to maintain policy integrity, a linear arrangement is sought that minimizes the average number of comparisons required. However, this will require information not present in the firewall rule list. Certain firewall rules have a higher probability of matching a packet than others. As a result, it is possible to develop a policy profile over time that indicates frequency of rule matches (similar to cache hit ratio). Let $P = \{p_1, p_2, ..., p_n\}$ be the policy profile, where p_i is the probability that a packet will match rule i (first match in the policy). Furthermore, assume a packet will always find a match, $\sum_{i=1}^{n} p_i = 1$; therefore R is comprehensive. Using this information, the average number of rule comparisons required is

$$E[n] = \sum_{i=1}^{n} i \cdot p_i \qquad (1)$$

For example, the average number of comparisons required for the rule set in Table 1 is 5.03.

[0025] Given a rule list DAG $G = (R, E)$ and policy profile $P = \{p_1, p_2, ..., p_n\}$ a linear arrangement π of G is sought that minimizes Equation 1. In the absence of precedence relationships, the average number of comparisons is minimized if the rules are sorted in non-increasing order according to the probabilities [26], which is also referred to as Smith's algorithm [27]. Precedence constraints cause the problem to be more realistic; however, such constraints also make determining the optimal permutation more problematic.

[0026] Determining the optimal rule list permutation can be viewed as job scheduling for a single machine with precedence constraints [15, 21]. The notation for such scheduling problems is $\alpha|\beta|\gamma|\delta$, where α is the number of machines, β is the precedence (or absence of) which can be represented as a DAG, γ is a restriction on processing time, and δ is the optimality criterion [15]. Determining the optimal rule order is similar to the $1|\beta|1|\sum \omega C_i$ scheduling problem, or optimality criterion, where ω is a weight associated with a job (for example, importance) and C_i is the completion time. As previously noted, the $1|||\sum \omega C_i$ problem can be solved in linear time the using Smith's algorithm [27], which orders jobs according to non-decreasing $\frac{t_i}{\omega}$ ratio, where t_i is the processing time of job i. In this case set $t_i = 1$ and $\omega = p_i \forall_i$. However, Lawler [19] and Lenstra et al. [21] proved $1|\beta|1|\sum \omega C_i$ to be *NP*-complete via the linear arrangement problem, which implies determining the optimal firewall rule order is also *NP*-complete. Note, determining the number of possible permutations has been proven to be *NP*-hard [5].

Theorem $1|\beta|1|\sum \omega C_i$ α *Determining the optimal order of a firewall rule list*

[0027] **Proof** Consider the $1|\beta|1|\sum \omega C_i$ problem. Each of n jobs J_i, $i \in I$, has to be processed without preemption on a single machine that can handle at most one job at a time. For each $i \in I$, let ω be the associated weight. Furthermore, let $G = (V, E)$ be a DAG that represents the precedence order of the jobs J_i. Assume the processing time of each job equals 1 time unit, the weights to be $0 \leq \omega \leq 1$ such that $\sum \omega = 1$, and β, which is G, to be a rule list DAG. In this case, the

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optimization criterion $\sum \omega \cdot C_i$ is the same as $\sum p_i \cdot i$, which is given in equation 1. Clearly, the optimal firewall rule ordering problem has a solution if and only if $1|\beta|1|\sum \omega C_j$ has a solution. Therefore, determining the optimal permutation of firewall rules is *NP*-complete.

Exemplary Rule Sorting Algorithm

[0028] Although determining the optimal rule permutation was proven to be *NP*-complete, reducing the average number of comparisons required to process a packet remains an important objective. As previously discussed, a sorting algorithm must maintain the precedence relationships among rules. Of course an exhaustive search is possible if the number of rules is small (generate and test all possible topological orders); however as proven in the previous section, this is not feasible with a realistic rule list.

[0029] One exemplary algorithm starts with the original the rule set, then sorts neighboring rules based on nonincreasing probabilities. However, an exchange of neighbors should never occur if the rules intersect and have different actions. This test preserves any precedence relationships in the policy. For example, the following sorting algorithm uses such a comparison to determine if neighboring rules should be exchanged. Note a_i denotes the action associated with the ith rule.

```
done = false
while(!done)
    done = true
    for(i = 1; i <n; i++)
        if(p_i < p_i+1 AND (r_i ∩ r_i+1 OR a_i == a_i+1))then
            exchange rules, actions, and probabilities
            done = false
        endif
    endfor
endwhile
```

[0030] Other sorting algorithms are possible if the completion time of the sort is an issue; however, the method presented is easy to implement and only requires a simple neighbor comparison. Assume the match probabilities for the rule list given in Table 1. Applying the sorting algorithm to this rule list results in the ordering depicted in Figure 2A, which has 10% fewer comparisons on average. However when using the algorithm, it is possible that one rule can prevent another rule from being reordered. For example, rule r_1 prevents rule r_5 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_5 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be further reduced, 15% fewer. This is the optimal order for the 6 rule set, which is depicted in Figure 2B. Although this simple sorting algorithm is unable to move groups of rules, it can still improve the performance of the firewall system. Its effectiveness is measured experimentally in the next section.

Experimental Results

[0031] In this section, the average number of rule comparisons required after sorting the rules is compared with average number of comparisons required using the original order and the optimal order. Note the optimal rule ordering was determined via an exhaustive search. As a result, it was not feasible to determine the optimal ordering once the number of rules equaled 15 given the number of permutations to consider. Two different variations of the rule sorting method described in the preceding section were implemented. The difference between the methods was the comparison used to determine if neighboring rules should be exchanged. The first sorting algorithm exchanged neighboring rules if they were out of order and did not intersect. The if-condition was as follows.

if $(p_i < p_{i+1}$ **AND** $r_i \cap r_{i+1})$ **then**

Therefore, rule actions were not considered and the method will be referred to as *non-action sort*. The second sorting method did consider the rule action (as described in the preceding section) and will be referred to as *action sort*. The comparison between the two sorting algorithms will indicate the importance of considering rule actions when ordering rules.

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[0032] In the first experiment, lists of 10 firewall rules were generated with random precedence relationships. The match probability of each rule was given by a Zipf distribution [20], which assigns probabilities according to the rank of an item. For this simulation, the last rule had the highest probability which is consistent with most policies (last rules are more general). As a result, the original order yields the worst average number of comparisons. The intersection percentage measured the percentage of rules that intersect in the policy. This metric gives a value for the dependency level in the policy; however note, rule action is not considered when calculating this metric. Rules were equally likely to have an accept or deny action and the results (average number of rule comparisons) for a particular intersection percentage were averaged over 1000 simulations.

[0033] Results of the first experiment are given in Figures 3A and 3B. More particularly, Figure 3A is a graph illustrating the average number of packet comparisons versus intersection percentage for the original rule sorting, the non-action sort, the action sort, and the optimal sort. Figure 3B is a graph illustrating the percent difference in the average number of comparisons required between the sorted and optimal firewall policy configurations. The average number of comparisons required was lower for the sorted and the optimal lists when the intersection percentage was low, as seen in Figure 3A. This was expected since there is a large number of possible rule permutations (few edges in the DAG). When the intersection percentage approached 100%, the values converged to the number required for the original list. This is due to the limited number of possible rule orders, only one order in the extreme case. The percent difference between the sorted and optimal order is shown in Figure 3B. At zero intersection percentage the sorted and optimal orders are equal, since any ordering is possible. Similarly at an intersection percentage of 100, the sorted and optimal orders are equal since only one order is possible. Between these two extremes, the action sorting algorithm remains close to the optimal value. In contrast, the non-action sort had a maximum difference of 33%.

[0034] The benefit of rule sorting on larger policies is also of interest; however as previously described, it was not possible to determine the optimal ordering once the number of rules approaches 15. Therefore, the second experiment used larger rule sets, but only compared the original order and the sorted orders. The number of rules ranged from 10 to 1000, while the matching probabilities and intersection percentages were the same as the previous experiment. The results of this experiment are depicted in Figure 4A. The sorted rule sets always performed equal to or better than the original order, while the action sort consistently performed better than the non-action sort. As noted in the previous experiment, the percent difference is very large given few intersections (e.g. 80% decrease for 1000 rules with 0% dependency), but approaches zero as all the rules intersect. As the number of rules increases, sorting is increasingly beneficial, although only at low intersection percentages. The benefit of sorting drops more significantly as the intersection percentage increases with larger rule sets. This is primarily due to the low matching probabilities of each rule, which requires a complete reordering to have a significant impact on the average number of comparisons. As a result, large rule sets can benefit from sorting if the intersection percentage is low.

[0035] The impact of considering rule actions when sorting is illustrated in Figure 4B. In this experiment lists of 1000 rules were generated, where the intersection percentages ranged from 0% to 100% and the percentage of rules with the same action varied from 50% to 100%. The performance of the action sort to the original list was then compared. As the percentage of rules with the same action increased, the percent difference (reduction) in the average number of comparisons also increased. This is due to the increased number of permutations possible when the rule actions are increasingly the same (fewer edges in the rule list DAG to consider). This is depicted in Figure 4B where a policy with a 100% intersection percentage can significantly reduce the number of comparisons (80% reduction) if all the rules have the same action. This performance increase is not possible with the non-action sort. Therefore, considering the rule action increases the number of possible rule orders, thereby providing more possibilities to improve firewall performance.

Conclusions

[0036] Network firewalls enforce a security policy by comparing arriving packets to a list of rules. An action, such as accept or deny, is then performed on the packet based on the matching rule. Unfortunately packet filtering can impose significant delays on traffic due to the complexity and size of rule sets. Therefore, improving firewall performance is important, given network Quality of Service (QoS) requirements and increasing network traffic loads.

[0037] The sections above describe rule ordering methods to improve the performance of network firewalls. Assuming each rule has a probability of a packet matching, firewall rules should be sorted such that the matching probabilities are non-increasing. This reduces the average number of comparisons and the delay across the firewall. However, a simple sort is not possible given precedence relations across rules. It is common in a security policy that two rules may match the same packet yet have different actions. It is this precedence relationship between rules that must be maintained to preserve integrity. The method described above uses Directed Acyclical Graphs (DAG) to represent the precedence order rules must maintain. Given this representation, a topological sort can be used to determine the optimal order (minimum average number of comparisons); however, the examples above prove this problem to be *NP*-complete (similar to job scheduling for a single nonpreemptive machine with precedence constraints). As an alternative, a simple sorting method was introduced that maintained the precedence order of the rules. Simulation results indicate this method can

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significantly reduce the average number of comparisons required and is comparable to optimal ordering.

[0038] Several areas exist for future research in optimizing firewall rule lists. The sorting method proposed above is based on a simple algorithm. Although it can offer an improvement over the original rule order, algorithms that can move groups of rules could provide a larger reduction in the average number of comparisons. The effect of stateful firewalls should also be addressed in future research. Security can be enhanced with connection state and packet audit information. For example, a table can be used to record the state of each connection, which is useful for preventing certain types of attacks (e.g., TCP SYN flood) [30, 31]. The impact of such rules on the firewall needs to be investigated and whether sorting can be done on-line to reflect temporal changes. In addition, more research is needed to determine more accurate probability distributions for packet matching and dependency percentages. Given this information, better algorithms can be designed and more realistic simulations can be performed.

Trie-Based Network Firewall Optimization Methods and Rule Splitting Overview

[0039] As described above, while assuring firewall policy integrity is critical, performance is equally important given increasing network speeds and traffic volumes. Firewall processing delay can be reduced via hardware as well as policy optimization, where rules are manipulated to reduce the number of comparisons. For a given firewall installation, it can be determined that certain security rules have a higher probability of matching a packet than others. As a result, it is possible to develop a *policy profile* over time that indicates frequency of rule matches (similar to cache hit ratio). Given this information, trie-based methods are described herein to minimize the average number of comparisons required per packet. Although most firewall systems still utilize an ordered list representation, the proposed enhancements still are applicable to current firewall systems since a policy trie can be converted into an ordered list using an inorder traversal.

Rule Sorting

[0040] As described above, rule sorting of neighboring rules based on ascending probabilities in a manner that considers rules intersection and rule actions can be used to improve firewall performance by reducing the number of packet comparisons. The methods described above use Directed Acyclic Goal Graphs (DAGs) to represent firewalls. The methods described in this section will use the rule sorting algorithms in combination with policy trie representations to perform sorting of groups of rules in a manner that improves firewall performance.

[0041] In this example, it is assumed that a security policy contains a list of n ordered rules, $\{r_1, r_2, ..., r_n\}$. In addition, let p_i represent the probability that a packet will match rule i (first match in the policy). Therefore, the policy is comprehensive, which means every packet will have a match, if $\sum_{i=1}^{n} p_i = 1$. Using this information, the average number of rule comparisons required can be calculated as

$$E[n] = \sum_{i=1}^{n} i \cdot p_i$$

The average number of comparisons is minimized if the rules are sorted in non-ascending order according to the probabilities. However, this can only be achieved if the sorting algorithm considers the probabilities and whether one rule is a superset of another. For example, sorting algorithms must use the following comparison to determine if neighboring rules should be interchanged Note, a_i denotes the action associated with the ith rule.

if ($p_i < p_{i+1}$ **AND** $r_i \not\subset r_{i+1}$ **OR** $a_i == a_{i+1}$)) **then**

[0042] Sorting rules in this fashion can have positive impact on the average number of comparisons required. Figure 5A is a table illustrating a firewall policy prior to rule sorting. The expected number of comparisons for the policy of Figure 5A is 4.26 comparisons per packet. Figure 5B is a table illustrating the firewall policy of Figure 5A after sorting using the above-described algorithm. In Figure 5B, the expected number of comparisons per packet has been reduced to 3.94. Thus, using the method described above, the number of comparisons per packet can be reduced by 8%.

[0043] However, it can be seen from Figures 5A and 5B that one rule can prevent another rule from being reordered. For example in Figure 5B, rule r_1 prevents rule r_4 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_4 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be reduced.

[0044] To solve this problem, rule sets can be sorted using policy tries. First, the rule list is converted into an equivalent

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policy trie. Each sub-trie will have an associated probability $\bar{p}$ that is average probability (hit-ratio) of the rules comprising the sub-trie. Sub-tries can be rotated around their parent node to increase performance, using the method described earlier. Since the policy trie (or equivalent rule set) is tested from left to right, rotation should occur if the probability of the right sub-trie is greater than the left sub-trie. As a result, the average number of comparisons required will be reduced and the policy integrity is maintained. Figure 6A is a trie representation of the rules in Figure 5B. Figure 6B is a table representing resulting rule set after rotating the TCP and UDP sub-tries. The TCP sub-trie in Figure 6A has an expected packet matching probability of 0.095 while the UDP sub-trie has an expected packet matching probability of 0.155. Thus, the UDP sub-trie and the TCP sub-trie should be rotated so that the UDP sub-trie becomes the left sub-trie and the TCP sub-trie becomes the right sub-trie. In the table illustrated in Figure 6B, which lists the ordering of the rules after rotating the sub-tries, the average number of comparisons per packets has been reduced to 3.70.

Rule Splitting

[0045] Rule splitting takes a general rule and creates more specific rules that collectively perform the same action over the same set of packets. Here, rule splitting is used to reduce the average number of comparisons. For example in Figure 7A, rule r_5 is split into two separate rules, r_{5a} for UDP and r_{5b} for TCP. Figure 7B is a table corresponding to the policy trie of Figure 7A. Once the rules are positioned based on their probabilities and their relation to other rules, the average number of rule comparisons is reduced to 2.98 (after sort, trie rotation, and splitting) which is a 30% less.

[0046] It many not be advantageous to split a general rule since it adds another rule to the policy. For example, assume a policy contains 20 rules where the first 19 rules have the same probability. Assume the last rule can be split and the new specific rule has a probability that is $\frac{3}{4}$ of the last rule. The impact of the probability of the last rule and the location of the new split rule, m, is depicted in Figures 8A and 8B. More particularly, Figure 8A is a graph illustrating the average number of comparisons for firewalls with and without rule splitting. Figure 8B is a graph illustrating average number of comparisons versus different locations of the new rule and probabilities. The average number of comparisons is reduced as the split rule is located closer to the first rule (surface decreases as m approaches one). Furthermore, splitting yields better results when the general rule has a high probability. However as illustrated in Figure 8B, the closer the specific rule is to the location of the original rule the average number of comparisons increases, which is the penalty of adding one more rule to the policy.

[0047] The effect of splitting a single rule can be described mathematically as follows. Consider n rules where rule r_n can be split into rules $r_{n,1}$ and $r_{n,r}$ (whose union is the original rule). In addition, assume the split rule $r_{n,1}$ will be located at the mth position ($1 \leq m < n$), while rule $r_{n,r}$ will remain at the nth location. The goal is to determine the best location m, which yields a lower average number of comparisons as compared to the original rule set. This can be defined mathematically in the following formula.

$$\sum_{i=1}^{n} i \cdot p_i > \sum_{i=1}^{m-1} i \cdot p_i + m \cdot p_{n,l} + \sum_{i=m}^{n-1} (i+1) \cdot p_i + (n+1) \cdot p_{n,r}$$

The left side of the inequality is the average number of comparisons for the original rule set. The right hand side of the inequality is the average number of comparisons with the specific rule at location m. If it is assumed that the rules located between m and n have an equal probability (denoted as p) the previous equation can be solved for m.

$$m < \frac{n \cdot p - n \cdot p_n + (n+1) \cdot p_{n,r}}{p - p_{n,l}}$$

The new rule must be located between the first and m^{th}; however, its final location will depend on the relationship with the other rules (cannot be placed before any rule for which it is a superset). This result can be applied iteratively to multiple rules and repeatedly to the same rule.

Rule Optimization for QoS

[0048] In the preceding sections, optimizing the entire security policy has been discussed. However, it may be desirable to optimize the rules for a certain type of traffic, in order to reduce the average number of comparisons this traffic

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encounters. This can be done by organizing the policy trie via traffic classification, then optimizing the sub-tries. The result is an ordering where the rules for the most important traffic are tested first.

Network Firewall Optimization Using Rule Compression

[0049] Another method for network firewall optimization is referred to as rule compression. Given a security policy R, one objective in optimizing firewall performance is to reduce number of rules in the policy while maintaining the original integrity. A method for reducing the number of rules called *rule compression*, which combines and replaces two rules in the policy will now be described. Although compression does reduce the number of rules, it can only be done if the integrity of the original policy is maintained.

[0050] Consider two rules r_i and r_j in policy R, where r_i appears before r_j. The two rules can be compressed if and only if the following conditions are true

1. The two rules intersect, $r_i \cap r_j \neq 0$ (an edge between r_i and r_j exists in the policy DAG) (Tuples that are proper subsets and supersets are considered. Compression may still occur if the rules do not intersect or are adjacent in the set space, the resulting rule may contain ranges.)
2. The action of r_i and r_j is the same.
3. Rule r_i is not dependent on any rule r_k that is directly or indirectly dependent on r_j (only one path from r_i to r_j exists in the policy DAG).

[0051] The result of compression is a new rule, $r_{i,j}$ whose tuples are the union of the corresponding tuples of rules r_i and r_j. The new rule $r_{i,j}$ replaces both r_i and r_j in R; however, the location of $r_{i,j}$ in R may require the relocation of other rules. Let D_j be the ordered set of rules that appear after r_i that directly or indirectly depend upon r_j. The new rule is placed at the original location of r_i in R and the rules D_j are placed before $r_{i,j}$.

[0052] For example, consider the policy given in Table 2. It is possible to compress rules r_1 and r_5, creating the new rule $r_{1,5}$ =[TCP, *, *, 2.*, *, accept]. The ordered set D_j in this example consists of the rules r_3 and r_4. As a result, the new rule $r_{1,5}$ is placed at the original location of r_1 while the rules in D_j are placed before the new rule. Figures 9A and 9B respectively illustrate the original policy DAG for Table 2 and the policy DAG after rules r_1 and r_5 are compressed.

Table 2: Example Policy Consisting of Multiple Ordered Rules

		Source		Destination		
No.	Proto.	IP	Port	IP	Port	Action
1	TCP	1.1.*	*	2.2.*	*	accept
2	TCP	1.*	*	*	80	deny
3	TCP	3.3.*	*	*	80	accept
4	TCP	3.*	*	*	*	deny
5	TCP	*	*	2.*	90	accept

[0053] **Theorem** *Compressing rules r_i and r_j of policy R will maintain integrity if the three conditions are met and method described is used.*

[0054] **Proof** Before r_i and r_j are compressed, relocate the rules D_j immediately before r_i and D_i. This relocation will maintain integrity due to the third requirement for compression (no rule in D_i can be dependent on any rule in D_j). Now place r_j directly after r_i. This relocation will not affect integrity since no rule in D_i can have an edge to r_j (again, due to the third condition). Compressing the neighboring rules r_i and r_j creates $r_{i,j}$. This does not affect integrity since the resulting rule only matches the packets that match r_i or r_j in the original policy. Therefore, the result is the compression of rule r_i and r_j, and the integrity of the policy is maintained.

Determining if Compression Should Occur

[0055] Although compression may be possible, it may not improve the performance of the policy due to the relocation of rules. Compression should only occur if the average number of comparisons required for the new policy R_c is less than the original policy R; therefore, $E[R_c] < E[R]$.

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Firewall Rule Sub-Trie and Sub-List Ordering

Policy Sub-Trie Ordering

[0056] Additional methods for firewall optimization are referred to as firewall sub-trie and sub-list ordering. Given a policy trie T, it may be desirable to order all sub-tries such that the average number of tuple comparisons is reduced and policy integrity is maintained. Consider a policy trie T that contains sub-tries T_i and T_j having the same parent node, as seen in Figures 10A-10C. Let P_i denote the sum of the probabilities of the rules contained in sub-trie i, while C_i denotes the number of comparisons required to completely traverse sub-trie i (which is equal to the number of branches). In order to reduce the average number of tuple comparisons, sub-tries that share the same parent node should be ordered such that the following two conditions are observed.

1. Sub-tries that share a parent node are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-tries that share a parent node have the same probability (P_i equals P_j), then order the sub-tries such that the C_i values are non-descending (sub-tries consisting of fewer comparisons occur first, from left to right).

These conditions are recursively applied throughout the policy trie as seen in Figures 11A-11D. However, these conditions do not necessarily maintain policy integrity.

[0057] Consider a group of n sub-tries that share the same parent node that are numbered sequentially from left to right. Consider any two non-intersecting sub-tries T_i and T_{i+k} in this group that are out of order. If two sub-tries do not intersect, denoted as $T_i \pitchfork T_j$, then no rule in one sub-trie will intersect with any rule in the other sub-trie, $r_k \pitchfork r_l$, $\forall r_k \in T_i$, $\forall r_l \in T_j$. The following *integrity condition* must be observed when reordering the sub-tries. The two sub-tries can be exchanged (rotated about the parent) if and only the sub-tries T_i through T_{i+k-1} do not intersect with T_{i+k} and the sub-tries T_{i+1} through T_{i+k} do not intersect with T_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. This is observed in Figure 10A, where no edge exists between any rule in T_1 and T_2. More particularly, Figure 10A is a policy DAG of a six-rule firewall list. Figure 10B is a policy trie representation of the firewall rule list represented by Figure 10A. In Figure 10B, the average number of tuple compares required per packet is 5.5. Figure 10C illustrates the policy trie after rotating sub-tries T_1 and T_2. In Figure 10C, the average number of tuple compares required is 4.5. In Figures 10A-10C, the following probabilities are assumed:

$P_1 = 0.5$
$C_1 = 4$
$P_2 = 0.5$; and
$C_2 = 2$.

The average number of tuple comparisons is an estimate based on the longest trie path.

[0058] Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-tries that share the same parent node.

```
m = a parent node in T
done = false
while(!done)
    done = true
    for each sub-trie Ti having parent m AND a right neighboring sub-trie
        if((Pi < Pi+1 AND (Pi == Pi+1 AND Ci > Ci+1)) AND Ti ⋔ Ti+1) then
        interchange Ti and Ti+1
        done = false
        endif
    endfor
endwhile
```


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[0059] Figures 11A-11D illustrate policy trie rotation for an eight-rule firewall policy. More particularly, Figure 11A illustrates the policy DAG representation of an eight-rule firewall policy. Figure 11B is a policy trie representation of the original firewall policy. In this example, ordering occurs in three stages, starting at the bottom level and moving towards the top level of the trie. In Figure 11C, the leaves are ordered at the lowest level. More particularly, nodes r_1 and r_2 are exchanged with nodes r_7 and r_8. The average number of tuple compares for the ordering represented by Figure 11C is 10.45. In Figure 11D, the sub-tries on the second lowest level (T_3, T_4, T_5, and T_6) are ordered. More particularly, Figure 11 D illustrates the policy trie after exchanging sub-tries T_3 and T_4. The average number of tuple compares for the representation in Figure 11 D is 10.275. In Figure 11 E, the sub-tries on the second highest level, (T_1 and T_2) are ordered. Figure 11E illustrates the final ordering after exchanging T_1 and T_2. In the policy trie of Figure 11E, the average number of tuple compares required is 6.775. The average number of tuple comparisons is an estimate based on the longest trie path.

Policy Sub-List Ordering

[0060] The preceding section describes conditions for sorting policy sub-tries, which allow the exchange of groups of rules (sub-tries). The same conditions can be applied to list based policies, where sub-lists are ordered to improve the average number of rule comparisons.

[0061] In the sections above relating to rule sorting, a method is described to exchange neighboring rules in a list-based security policy, as seen in Figure 12B. However, it was observed that when ordering rules in this fashion it is possible that one rule can block the exchange of another. If groups of rules were allowed to be exchanged the average number of rule comparisons could be further reduced.

[0062] Given a policy list L, it may be desirable to order all sub-lists such that the average number of rule comparisons is reduced and policy integrity is maintained. Consider a policy list L that contains sub-tries L_i and L_j. Let P_i denote the sum of the probabilities of the rules contained in sub-list i, while C_i denotes the number of rules in sub-list i. In order to reduce the average number of rule comparisons, sub-lists should be ordered such that the following two conditions are observed.

1. Sub-lists are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-lists have the same probability (P_i equals P_j), then order the sub-lists such that the C_i values are non-descending (sub-lists consisting of fewer comparisons occur first, from left to right).

These conditions are applied throughout the policy list; however as with policy tries, these conditions do not necessarily maintain policy integrity.

[0063] Consider a group of n sub-lists that are numbered sequentially from left to right. Consider any two non-intersecting sub-lists L_i and L_{i+k} in this group that are out of order. If two sub-lists do not intersect, denoted as $L_i \pitchfork L_j$ then no rule in one sub-list will intersect with any rule in the other sub-list, $r_k \pitchfork r_l, \forall r_k \in L_i, \forall r_l \in L_j$. The following *integrity condition* must be observed when reordering the sub-lists. The two sub-lists can be exchanged if and only if the sub-lists L_i through L_{i+k-1} do not intersect with any rule in L_{i+k} and sub-lists L_{i+1} through L_{i+k} do not intersect with L_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. For example, consider the sub-lists $L_1 = \{r_1, r_3\}$ and $L_2 = \{r_2, r_4\}$ given in Figure 12B. No edge exists between any rule in L_1 and L_2. The two sub-lists are out of order with respect to P and should be exchanged. The resulting list is given in Figure 12C. Figure 12A illustrates the original policy order and results in an average number of rule comparisons of 3.4. In the sorted version in Figure 12B, the average number of rule comparisons is 3.3. In Figure 12C, the average number of rule comparisons has been reduced to 2.7. Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-lists.

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```
done = false
while(!done)
    done = true
    for each sub-list Li having a right neighboring sub-list
        if ((Pi < Pi+1 OR (Pi == Pi+1 AND Ci > Ci+1)) AND Li ⋔ Li+1)then
            interchange rules and probabilities
            done = false
        endif
    endfor
endwhile
```

Summary of Firewall Policy Optimization Techniques and Methods

[0064] As stated above, the methods and systems described herein for a network firewall policy optimization can be implemented using any combination of hardware, software, and/or firmware. Alternatively, the steps for firewall policy optimization can be performed manually with the number of rules being optimized is small enough. Figure 13 is a flow chart illustrating an exemplary process for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 13, in block **1300**, a firewall policy including an ordered list of firewall rules is defined. In block **1302**, for each rule, a probability indicating a likelihood of receiving a packet that matches each rule is specified. In block **1304**, neighboring rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. In block **1306**, groups of rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. For example, any of the policy-trie-based methods described above may be used. In block **1308**, one or more rules are split to reduce the number of average packet comparisons. In block **1310**, intersecting rules having common actions are identified and collapsed into single rules.

[0065] As described above, the subject matter described herein may be implemented in hardware, software, and/or firmware. In one implementation, the subject matter described herein for firewall policy optimization may be implemented on a general purpose computing platform. Figure 14 is a block diagram of a general purpose computing platform including software for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 14, computing platform **1400** may be a general purpose computer, such as a personal computer, that includes a microprocessor **1402**, memory **1404**, and I/O interfaces **1406**. Microprocessor **1400** may be any suitable microprocessor, such as any of the Intel or AMD families of microprocessors. Memory **1404** may include volatile memory for running programs and persistent memory, such as one or more disk storage devices. I/O interface **1406** may include interfaces with I/O devices, such as user input devices and output devices.

[0066] In the illustrated example, software that may be resident in memory 1404 includes a firewall policy editor 1408 and a firewall policy optimizer 1410. Firewall policy editor 1408 may allow a user to define a firewall policy. For example, firewall policy editor 1408 may allow a user to define a firewall policy by specifying different rules. The rules may be specified in a graphical manner, for example using policy DAGs as described above. Alternatively, firewall policy editor 1408 may allow a user to input rules in a tabular manner, as illustrated in any of the tables described herein. Firewall policy optimizer 1410 may implement any or all of the firewall policy optimization techniques to order rules entered via firewall policy editor 1408 in a manner that preserves policy integrity and that enhances firewall performance.

[0067] A firewall rule set that is optimized using the subject matter described herein may be implemented on any firewall system that includes one or more firewalls. For example, an optimized firewall rule set according to embodiments of the subject matter described herein may be implemented using any of the hierarchical, multi-node firewall systems described in commonly assigned, co- pending U.S. patent application no. 11/316,331, filed December 22, 2005. Figure 15 illustrates an example of a multi-node firewall system suitable for implementing the firewall rules according to an embodiment of the subject matter described herein. Referring to Figure 15, a plurality of firewall nodes 1500, 1502, 1504, and 1506 may collectively implement any of the optimized firewall policies described herein. For example, the firewall nodes may collectively implement different portions of a firewall policy data structure including an ordered list of firewall rules. A firewall policy engine 1508 resident on each firewall node may filter packets using its local portion 1510

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of the firewall policy data structure. A control node 1512 may include a firewall policy optimizer 1514 that measures the average number of comparisons per packets for the current rule configuration and may dynamically reorder the rules to reduce the average number of comparisons per packet. For example, firewall policy optimizer 1514 may utilize any of the methods described herein to rearrange rules and improve firewall performance. Rules may be tested for rearrangement at user-specified intervals or when average number of packet comparisons increases by a user-specified amount.

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[0068] The disclosure of each of the following references is hereby incorporated herein by reference in its entirety.

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[0069] It will be understood that various details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

Claims

1. A method for producing a performance optimized firewall policy, the method comprising:

   (a) defining a firewall policy including an ordered list of firewall rules;
   (b) for each rule, defining a probability indicating the likelihood of receiving a packet matching each rule; and
   (c) sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy;

   the method **characterized in that**

   (d) sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy, wherein at least one of the groups of two or more rules includes a first rule that prevents a second rule in the group from being moved, within the group, closer to a beginning of the ordered list that implements the firewall policy and wherein sorting the groups of rules includes moving the first and second rules closer to the beginning of the ordered list while maintaining their relative order.

2. The method of claim 1 wherein sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes, for each pair of neighboring rules, rearranging the rules if a first rule of the pair has a lower probability than a second rule of the pair and the first rule of the pair is not a subset of the second rule of the pair with a different action.

3. The method of claim 1, wherein sorting groups of two or more rules in a manner that preserves firewall policy includes assigning each group of rules to a sub-trie in a policy trie, computing a sum of packet matching probabilities for rules in each sub-trie, and, in response to determining that a first sub-trie has a lower sum than a second sub-trie, rotating the first and second sub-tries about a common parent so that rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

4. The method of claim 3, comprising, in response to determining that the first and second sub-tries have equal sums, determining whether the second sub-trie has an lower number of branches than the first sub-trie, and, in response to determining that the second sub-trie has a lower number of branches than the first sub-trie, rotating the first and second sub-tries about a common parent so that the rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

5. The method of claim 1 wherein sorting groups of two or more rules in a manner that preserves the firewall policy includes:

   (e) identifying first and second sub-lists of rules in the ordered list of firewall rules, the first sub-list preceding the second sub-list in the ordered list of firewall rules;
   (f) determining a sum of packet matching probabilities for each of the first and second sub-lists;
   (g) determining whether the first and second sub-lists intersect; and
   (h) in response to determining that the sum of the packet matching probabilities for the second sub-list is greater than the sum of the packet matching probabilities for the first sub-list and that the first and second sub-lists do not intersect, switching the order of the first and second sub-lists in the ordered list of firewall rules.

6. The method of claim 5, comprising, in response to determining that the sums of the packet matching probabilities

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for the first and sub-lists are equal, determining whether the second sub-list has a lower number of rules than the first sub-list, and, in response to determining that the second sub-list has a lower number of rules than the first sub-list, switching the order of the first and second sub-lists in the ordered list of firewall rules.

7. The method of claim 1, comprising splitting at least one of the firewall rules to reduce an average number of comparisons required per received packet.

8. The method of claim 1, comprising identifying intersecting rules having a common action and collapsing the rules into a single rule representing a union of the intersecting rules.

9. The method of claim 1, wherein sorting neighboring rules includes sorting rules such that comparisons for a particular class of packets are reduced.

10. The method of claim 1, comprising assigning the rules to vertices in a directed acyclical graph, DAG, determining precedence relationships between the rules, assigning the precedence relationships to edges that connect the vertices in the DAG, and wherein sorting the neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy incluces sorting the neighboring rules in a manner that preserves the precedence relationships represented by the DAG.

11. The method of claim 1, wherein the rules comprise intrusion detection rules.

12. The method of claim 1, wherein the rules comprise intrusion protection rules.

13. A network firewall, comprising:

(a) a firewall policy data structure (1510) for storing an ordered list of firewall rules;
(b) a firewall policy engine (1508) for implementing a firewall policy by comparing packets to the rules in the order specified by the firewall policy data structure (1510); and
(c) a firewall policy optimizer (1514) for optimizing performance of the network firewall by reordering the rules in a manner that reduces an average number of rule comparisons per packet and hat preserves the firewall policy;

the network firewall **characterized in that** the firewall policy optimizer (1514) is adapted to (d) sort groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy, wherein at least one of the groups of two or more rules includes a first rule that prevents a second rule in the group from being moved, within the group, closer to a beginning of the ordered list that implements the firewall policy and wherein sorting the groups of rules includes moving the first and second rules closer to the beginning of the ordered list while maintaining their relative order.

14. The network firewall of claim 13, wherein the firewall policy optimizer (1514) is adapted to measure average number of comparisons per packet for a rule ordering specified by the firewall policy data structure (1510) and to dynamically re-order to rules to reduce the average number of comparisons per packet.

Patentansprüche

1. Verfahren zum Generieren einer leistungsoptimierten Firewall-Vorschrift, wobei das Verfahren Folgendes umfasst:

(a) Definieren einer Firewall-Vorschrift, die eine geordnete Liste mit Firewall-Regeln umfasst;
(b) für jede Regel, Definieren einer Wahrscheinlichkeit, welche die Wahrscheinlichkeit des Empfangens eines mit jeder Regel übereinstimmenden Paketes anzeigt; und
(c) Sortieren benachbarter Regeln in der Reihenfolge einer nicht-zunehmenden Wahrscheinlichkeit in einer Weise, welche die Firewall-Vorschrift wahrt;

wobei das Verfahren **gekennzeichnet ist durch**:

(d) Sortieren von Gruppen von zwei oder mehr Regeln in der Reihenfolge einer nicht-zunehmenden Wahrscheinlichkeit in einer Weise, welche die Firewall-Vorschrift wahrt, wobei mindestens eine der Gruppen von zwei oder mehr Regeln eine erste Regel umfasst, die verhindert, dass eine zweite Regel in der Gruppe innerhalb

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der Gruppe näher zu einem Anfang der geordneten Liste, welche die Firewall-Vorschrift implementiert, verschoben wird, und wobei das Sortieren der Gruppen von Regeln umfasst, die erste und die zweite Regel näher an den Anfang der geordneten Liste zu bewegen, während ihre relative Reihenfolge beibehalten wird.

2. Verfahren nach Anspruch 1, wobei das Sortieren benachbarter Regeln in der Reihenfolge einer nicht-zunehmenden Wahrscheinlichkeit in einer Weise, welche die Firewall-Vorschrift wahrt, für jedes Paar benachbarter Regeln umfasst, die Regeln umzuordnen, wenn eine erste Regel das Paares einer geringere Wahrscheinlichkeit als eine zweite Regel das Paares hat und die erste Regel das Paares keine Teilmenge der zweiten Regel das Paares mit einer anderen Aktion ist.

3. Verfahren nach Anspruch 1, wobei das Sortieren von Gruppen von zwei oder mehr Regeln in einer Weise, welche die Firewall-Vorschrift wahrt, Folgendes umfasst: Zuordnen jeder Gruppe von Regeln zu einem Sub-Trie in einem Vorschrifts-Trie; Berechnen einer Summe von Wahrscheinlichkeiten der Paketübereinstimmung für Regeln in jedem Sub-Trie; und in Reaktion auf die Feststellung, dass ein erster Sub-Trie eine kleinere Summe als ein zweiter Sub-Trie hat, Drehen des ersten und des zweiten Sub-Tries um einen gemeinsamen Ursprung, so dass Regeln in dem zweiten Sub-Trie vor den Regeln in dem ersten Sub-Trie in der Firewall-Vorschrift angewendet werden.

4. Verfahren nach Anspruch 3, das in Reaktion auf die Feststellung, dass der erste und der zweite Sub-Trie gleiche Summen haben, das Feststellen umfasst, ob der zweite Sub-Trie eine kleinere Anzahl von Abzweigungen als der erste Sub-Trie hat, und in Reaktion auf die Feststellung, dass der zweite Sub-Trie eine kleinere Anzahl von Abzweigungen als der erste Sub-Trie hat, das Drehen des ersten und des zweiten Sub-Tries um einen gemeinsamen Ursprung umfasst, so dass die Regeln in dem zweiten Sub-Trie vor den Regeln in dem ersten Sub-Trie in der Firewall-Vorschrift angewendet werden.

5. Verfahren nach Anspruch 1, wobei das Sortieren von Gruppen von zwei oder mehr Regeln in einer Weise, welche die Firewall-Vorschrift wahrt, Folgendes umfasst:

(e) Identifizieren einer ersten und einer zweiten Teilliste von Regeln in der geordneten Liste mit Firewall-Regeln, wobei die erste Teilliste der zweiten Teilliste in der geordneten Liste mit Firewall-Regeln vorausgeht;
(f) Bestimmen einer Summe von Wahrscheinlichkeiten der Paketübereinstimmung für die erste und für die zweite Teilliste;
(g) Feststellen, ob sich die erste und die zweite Teilliste überschneiden; und
(h) in Reaktion auf die Feststellung, dass die Summe der Wahrscheinlichkeiten der Paketübereinstimmung für die zweite Teilliste größer als die Summe der Wahrscheinlichkeiten der Paketübereinstimmung für die erste Teilliste ist und dass sich die erste und die zweite Teilliste nicht überschneiden, Wechseln der Reihenfolge der ersten und der zweiten Teilliste in der geordneten Liste mit Firewall-Regeln.

6. Verfahren nach Anspruch 5, das, in Reaktion auf die Feststellung, dass die Summen der Wahrscheinlichkeiten der Paketübereinstimmung für die erste und Teilliste gleich sind, das Feststellen umfasst, ob die zweite Teilliste eine kleinere Anzahl von Regeln als die erste Teilliste hat, und in Reaktion auf die Feststellung, dass die zweite Teilliste eine kleinere Anzahl von Regeln als die erste Teilliste hat, das Wechseln der Reihenfolge der ersten und der zweiten Teilliste in der geordneten Liste mit Firewall-Regeln umfasst.

7. Verfahren nach Anspruch 1, das umfasst, mindestens eine der Firewall-Regeln zu teilen, um eine durchschnittliche Anzahl von Vergleichen, die je empfangenem Paket erforderlich sind, zu verringern.

8. Verfahren nach Anspruch 1, das umfasst, sich überschneidende Regeln zu identifizieren, die eine gemeinsame Aktion haben, und die Regeln zu einer einzigen Regel zusammenzulegen, die eine Vereinigung der sich überschneidenden Regeln darstellt.

9. Verfahren nach Anspruch 1, wobei das Sortieren benachbarter Regeln umfasst, die Regeln so zu sortieren, dass Vergleiche für eine bestimmte Klasse von Paketen verringert werden.

10. Verfahren nach Anspruch 1, das Folgendes umfasst: Zuweisen der Regeln zu Scheitelpunkten in einem gerichteten azyklischen Graph (DAG); Bestimmen von Präzedenzbeziehungen zwischen den Regeln; Zuweisen der Präzedenzbeziehungen zu Flanken, welche die Scheitelpunkte in dem DAG verbinden; und wobei das Sortieren der benachbarten Regeln in der Reihenfolge einer nicht-zunehmenden Wahrscheinlichkeit in einer Weise, welche die Firewall-Vorschrift wahrt, umfasst, die benachbarten Regeln in einer Weise zu sortieren, welche die durch den DAG

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dargestellten Präzedenzbeziehungen wahrt.

11. Verfahren nach Anspruch 1, wobei die Regeln Eindringdetektionsregeln umfassen.

12. Verfahren nach Anspruch 1, wobei die Regeln Eindringschutzregeln umfassen.

13. Netzwerk-Firewall, die Folgendes umfasst:

(a) eine Firewall-Vorschrifts-Datenstruktur (1510) zum Speichern einer geordneten Liste mit Firewall-Regeln;
(b) eine Firewall-Vorschrifts-Engine (1508) zum Implementieren einer Firewall-Vorschrift durch Vergleichen von Paketen mit den Regeln in der durch die Firewall-Vorschrifts-Datenstruktur (1510) spezifizierten Reihenfolge; und
(c) einen Firewall-Vorschrifts-Optimierer (1514) zum Optimieren der Leistung der Netzwerk-Firewall durch Umordnen der Regeln in einer Weise, die eine durchschnittliche Anzahl von Regelvergleichen je Paket verringert und die Firewall-Vorschrift wahrt;

wobei die Netzwerk-Firewall **dadurch gekennzeichnet ist, dass** der Firewall-Vorschrifts-Optimierer (1514) dafür geeignet ist:

(d) Gruppen von zwei oder mehr Regeln in der Reihenfolge einer nicht-zunehmenden Wahrscheinlichkeit in einer Weise zu sortieren, welche die Firewall-Vorschrift wahrt, wobei mindestens eine der Gruppen von zwei oder mehr Regeln eine erste Regel umfasst, die verhindert, dass eine zweite Regel in der Gruppe innerhalb der Gruppe näher zu einem Anfang der geordneten Liste, welche die Firewall-Vorschrift implementiert, verschoben wird, und wobei das Sortieren der Gruppen von Regeln umfasst, die erste und die zweite Regel näher an den Anfang der geordneten Liste zu bewegen, während ihre relative Reihenfolge beibehalten wird.

14. Netzwerk-Firewall nach Anspruch 13, wobei der Firewall-Vorschrifts-Optimierer (1514) dafür geeignet ist, die durchschnittliche Anzahl von Vergleichen je Paket für eine durch die Firewall-Vorschrifts-Datenstruktur (1510) spezifizierte Regelordnung zu messen und die Regeln dynamisch umzuordnen, um die durchschnittliche Anzahl von Vergleichen je Paket zu verringern.

Revendications

1. Procédé de génération d'une politique de pare-feu à performances optimisées, le procédé consistant à :

(a) définir une politique de pare-feu comprenant une liste ordonnée de règles de pare-feu ;
(b) pour chaque règle, définir une probabilité indiquant la probabilité de recevoir un paquet correspondant à chaque règle ; et
(c) trier des règles voisines dans l'ordre de probabilité non croissante d'une manière qui préserve la politique de pare-feu ;

le procédé étant **caractérisé par** le fait de

(d) trier des groupes de deux règles ou plus dans l'ordre de probabilité non croissante d'une manière qui préserve la politique de pare-feu, dans lequel au moins l'un des groupes de deux règles ou plus comprend une première règle qui empêche une seconde règle du groupe d'être déplacée, au sein du groupe, plus près d'un début de la liste ordonnée qui met en oeuvre la politique de pare-feu, et dans lequel le tri des groupes de règles consiste à déplacer les première et seconde règles plus près du début de la liste ordonnée, tout en maintenant leur ordre relatif.

2. Procédé selon la revendication 1, dans lequel le tri de règles voisines dans l'ordre de probabilité non croissante d'une manière qui préserve la politique de pare-feu consiste, pour chaque paire de règles voisines, à réarranger les règles si une première règle de la paire a une probabilité plus faible qu'une seconde règle de la paire et si la première règle de la paire n'est pas un sous-ensemble de la seconde règle de la paire avec une action différente.

3. Procédé selon la revendication 1, dans lequel le tri de groupes de deux règles ou plus d'une manière qui préserve la politique de pare-feu consiste à affecter chaque groupe de règles à un sous-arbre dans un arbre de politique,

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calculer une somme de probabilités de correspondance de paquet pour les règles de chaque sous-arbre, et, en réponse à la détermination que le premier sous-arbre a une somme inférieure à un second sous-arbre, faire tourner les premier et second sous-arbres autour d'un parent commun, de sorte que les règles du second sous-arbre soient appliquées avant les règles du premier sous-arbre dans la politique de pare-feu.

4. Procédé selon la revendication 3, consistant, en réponse à la détermination que les premier et second sous-arbres ont des sommes égales, à déterminer si le second sous-arbre a un plus petit nombre de branches que le premier sous-arbre, et, en réponse à la détermination que le second sous-arbre a un plus petit nombre de branches que le premier sous-arbre, faire tourner les premier et second sous-arbres autour d'un parent commun, de sorte que les règles du second sous-arbre soient appliquées avant les règles du premier sous-arbre dans la politique de pare-feu.

5. Procédé selon la revendication 1, dans lequel le tri de groupes de deux règles ou plus d'une manière qui préserve la politique de pare-feu consiste à :

(e) identifier de première et seconde sous-listes de règles dans la liste ordonnée de règles de pare-feu, la première sous-liste précédant la seconde sous-liste dans la liste ordonnée de règles de pare-feu ;
(f) déterminer une somme de probabilités de correspondance de paquet pour chacune des première et seconde sous-listes ;
(g) déterminer si les première et seconde sous-listes se croisent ; et
(h) en réponse à la détermination que la somme des probabilités de correspondance de paquet pour la seconde sous-liste est supérieure à la somme des probabilités de correspondance de paquet pour la première sous-liste et que les première et seconde sous-listes ne se croisent pas, inverser l'ordre des première et seconde sous-listes dans la liste ordonnée de règles de pare-feu.

6. Procédé selon la revendication 5, consistant, en réponse à la détermination que les sommes des probabilités de correspondance de paquet pour les première et seconde sous-listes sont égales, déterminer si la seconde sous-liste a un plus petit nombre de règles que la première sous-liste, et, en réponse à la détermination que la seconde sous-liste a un plus petit nombre de règles que la première sous-liste, inverser l'ordre des première et seconde sous-listes dans la liste ordonnée de règles de pare-feu.

7. Procédé selon la revendication 1, consistant à diviser au moins l'une des règles de pare-feu afin de réduire un nombre moyen de comparaisons nécessaire par paquet reçu.

8. Procédé selon la revendication 1, consistant à identifier des règles qui se croisent ayant une action commune et à regrouper les règles en une règle unique qui représente une union des règles qui se croisent.

9. Procédé selon la revendication 1, dans lequel le tri de règles voisines consiste à trier des règles de telle sorte que les comparaisons relatives à une catégorie particulière de paquets sont réduites.

10. Procédé selon la revendication 1, consistant à affecter les règles à des sommets dans un graphe acyclique dirigé, DAG, déterminer des relations de priorité entre les règles, affecter les relations de priorité à des bords qui relient les sommets dans le DAG, et dans lequel le tri des règles voisines dans l'ordre de probabilité non croissante d'une manière qui préserve la politique de pare-feu consiste à trier les règles voisines d'une manière qui préserve les relations de priorité représentées par le DAG.

11. Procédé selon la revendication 1, dans lequel les règles comprennent des règles de détection des intrusions.

12. Procédé selon la revendication 1, dans lequel les règles comprennent des règles de protection contre les intrusions.

13. Pare-feu de réseau, comprenant :

(a) une structure de données de politique de pare-feu (1510) pour stocker une liste ordonnée de règles de pare-feu ;
(b) un moteur de politique de pare-feu (1508) pour mettre en oeuvre une politique de pare-feu en comparant des paquets aux règles dans l'ordre spécifié par la structure de données de politique de pare-feu (1510) ; et
(c) un optimiseur de politique de pare-feu (1514) pour optimiser la performance du pare-feu de réseau en réordonnant les règles d'une manière qui réduit un nombre moyen de comparaisons de règles par paquet et qui préserve la politique de pare-feu ;

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le pare-feu de réseau étant **caractérisé en ce que** l'optimiseur de politique de pare-feu (1514) est conçu pour :

(d) trier des groupes de deux règles ou plus dans l'ordre de probabilité non croissante d'une manière qui préserve la politique de pare-feu, dans lequel au moins l'un des groupes de deux règles ou plus comprend une première règle qui empêche une seconde règle du groupe d'être déplacée, au sein du groupe, plus près d'un début de la liste ordonnée qui met en oeuvre la politique de pare-feu, et dans lequel le tri des groupes de règles consiste à déplacer les première et seconde règles plus près du début de la liste ordonnée, tout en maintenant leur ordre relatif.

14. Pare-feu de réseau selon la revendication 13, dans lequel l'optimiseur de politique de pare-feu (1514) est conçu pour mesurer un nombre moyen de comparaisons par paquet pour un ordonnancement de paquets spécifié par la structure de données de politique de pare-feu (1510) et pour réordonner de manière dynamique les règles afin de réduire le nombre moyen de comparaisons par paquet.

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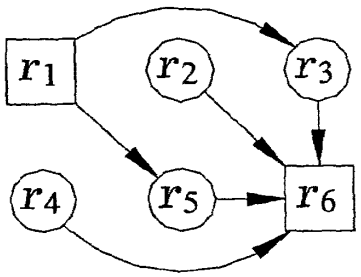

FIG. 1A

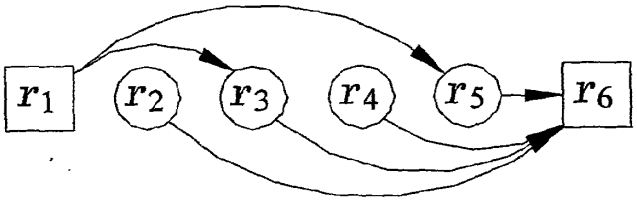

FIG. 1B

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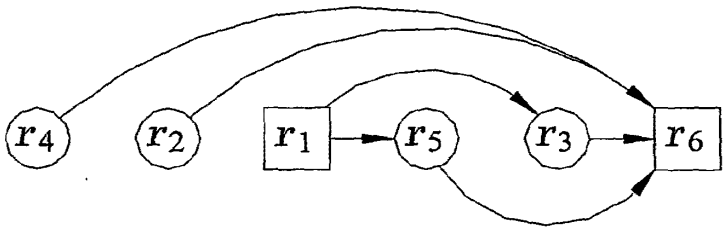

FIG. 2A

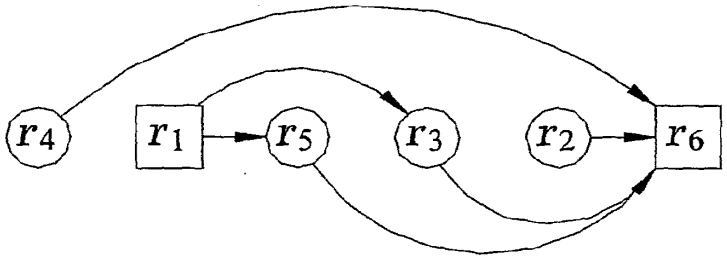

FIG. 2B

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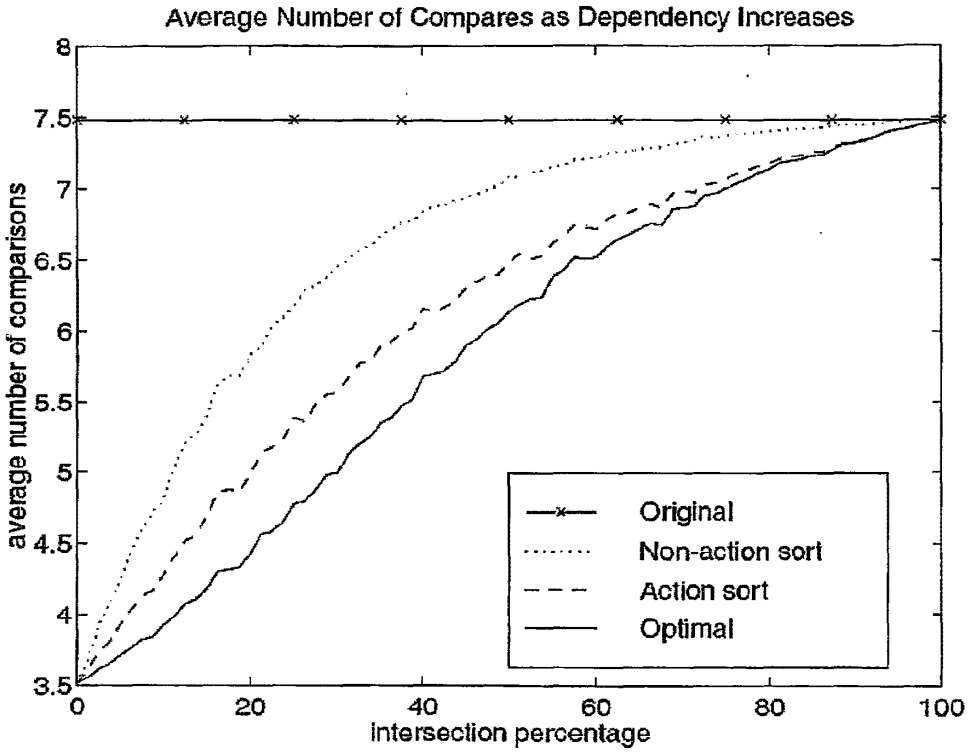

FIG. 3A

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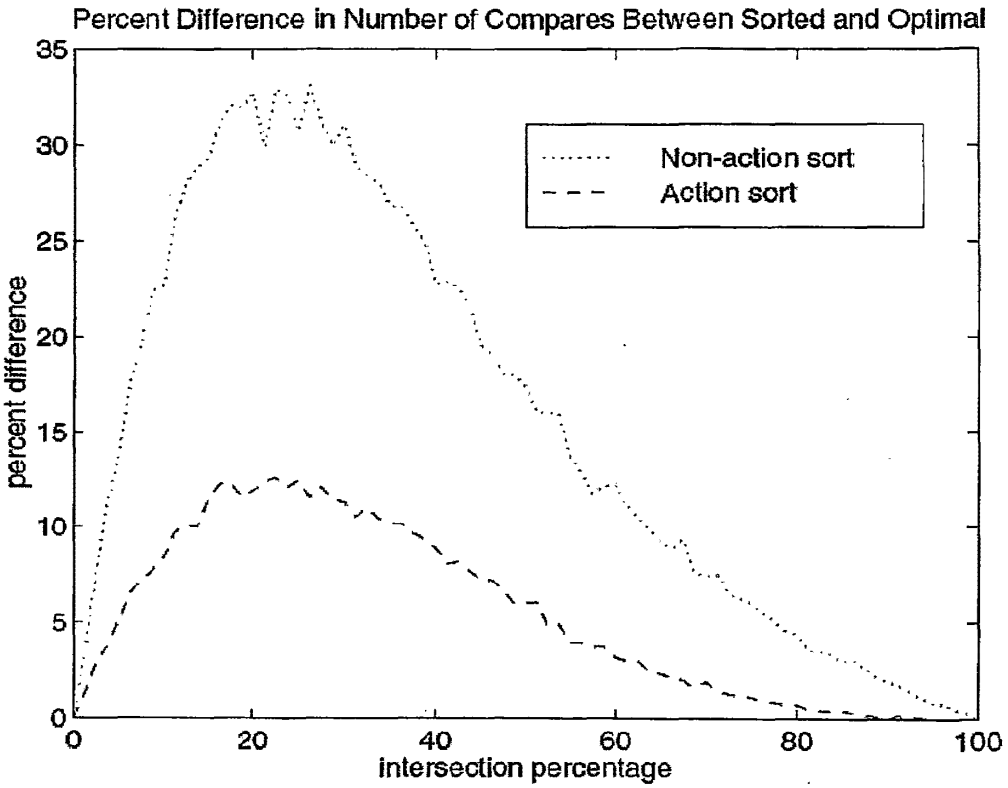

FIG. 3B

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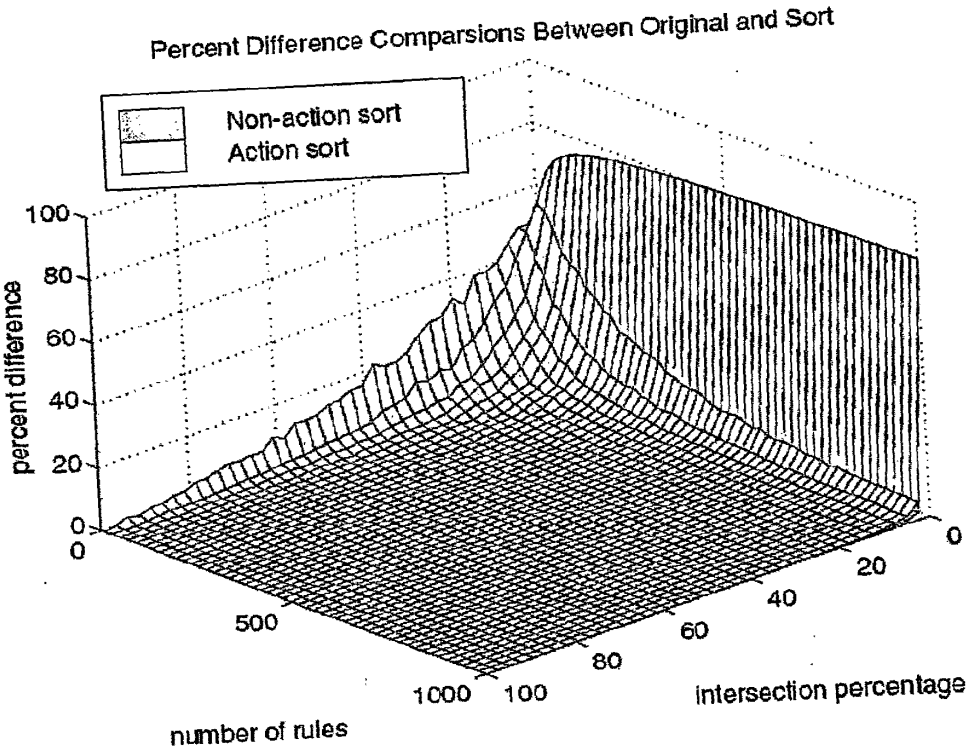
Percent Difference Comparsions Between Original and Sort
Non-action sort
Action sort
percent difference
100
80
60
40
20
0
0
500
1000
number of rules
0
20
40
60
80
100
intersection percentage

FIG. 4A

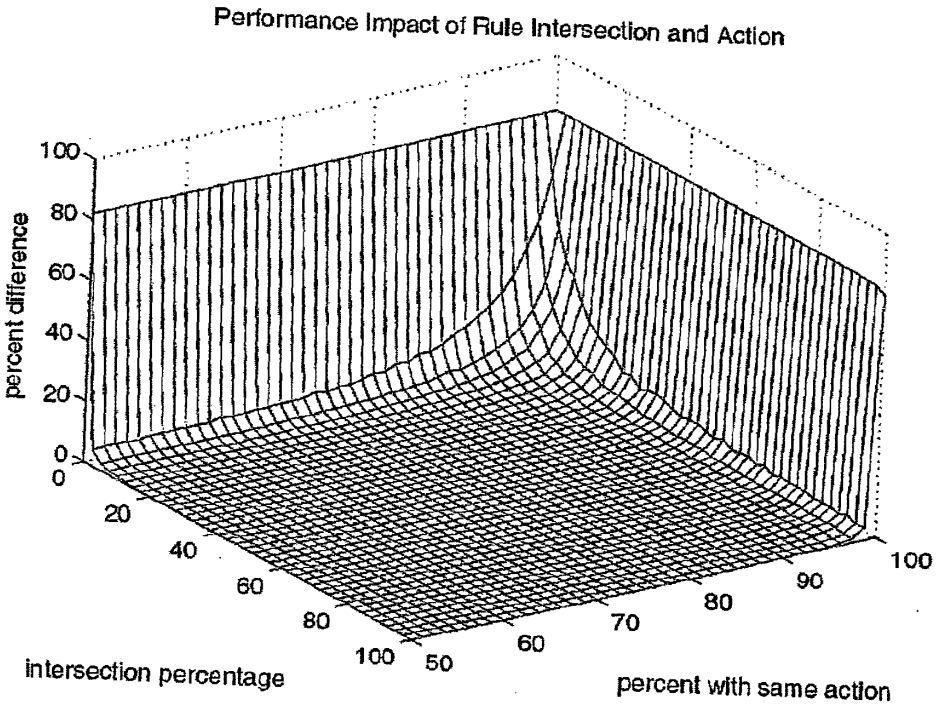

FIG. 4B

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r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5A

r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5B

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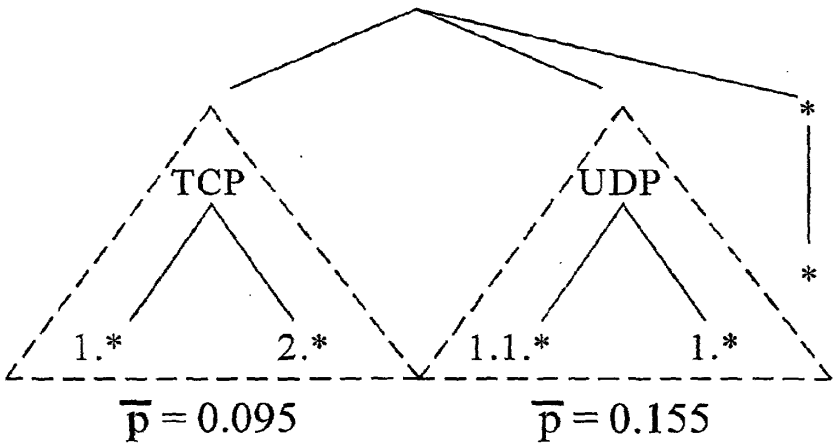

FIG. 6A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 6B

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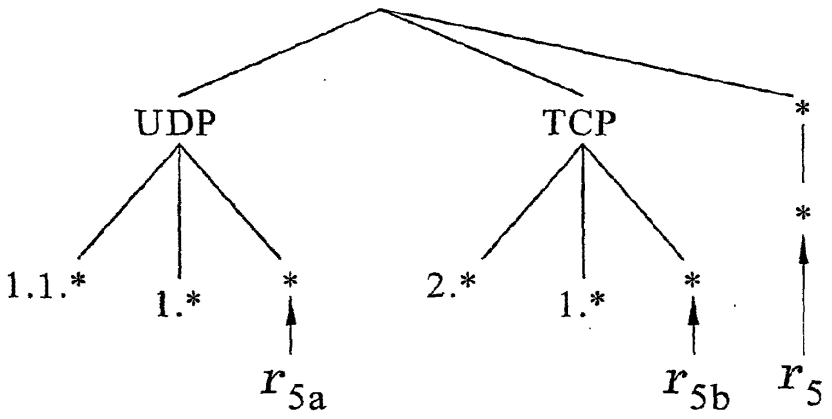

FIG. 7A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	ACCEPT)	$p_4 = 0.30$
r_{5a}	(UDP,	*,	DENY)	$p_{5a} = 0.47$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_{5b}	(TCP,	*,	DENY)	$p_{5b} = 0.03$

FIG. 7B

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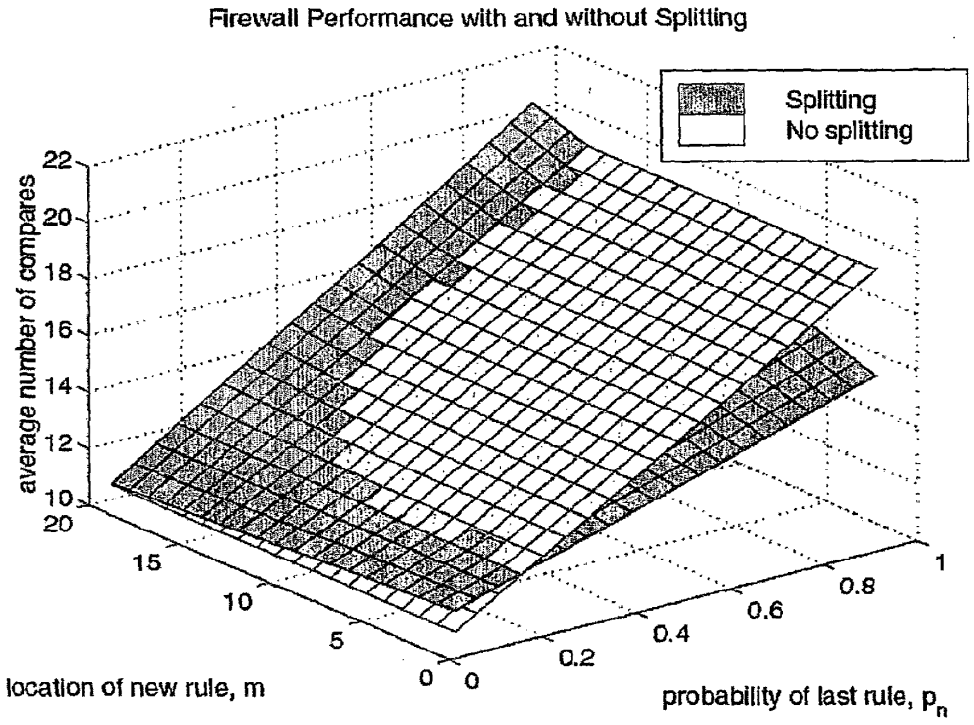
Firewall Performance with and without Splitting
Splitting
No splitting
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8A

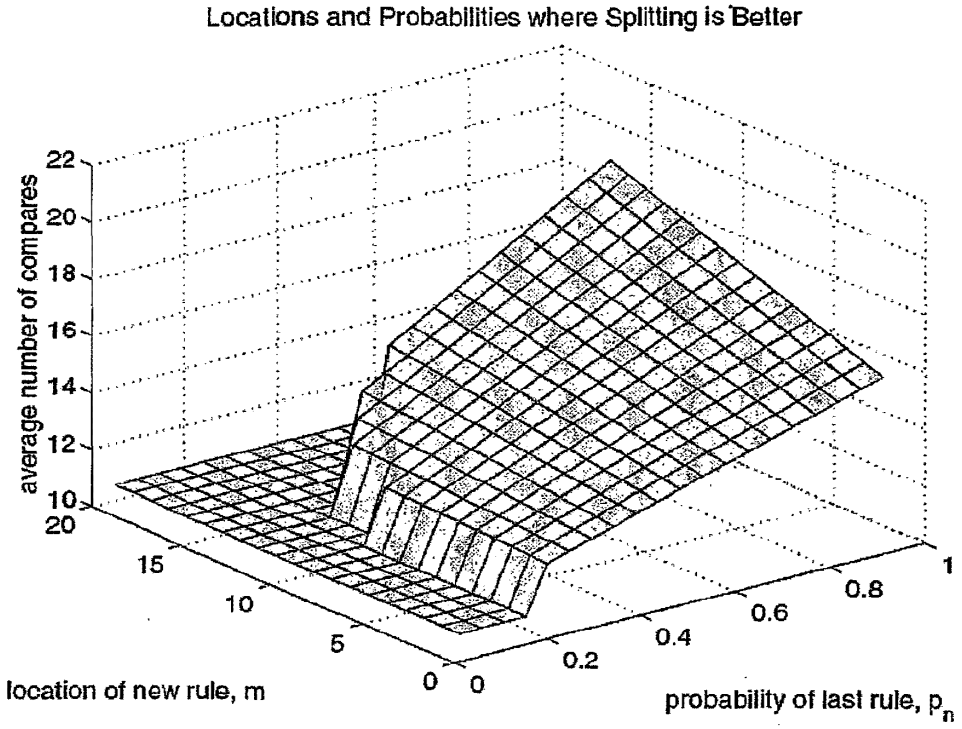
Locations and Probabilities where Splitting is Better
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8B

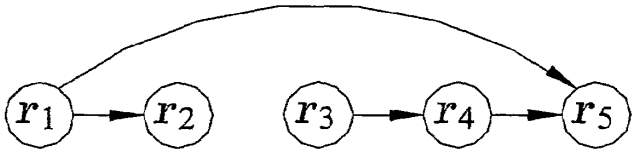

FIG. 9A

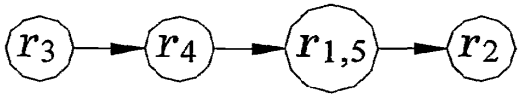

FIG. 9B

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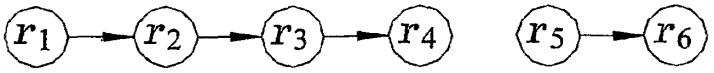

FIG. 10A

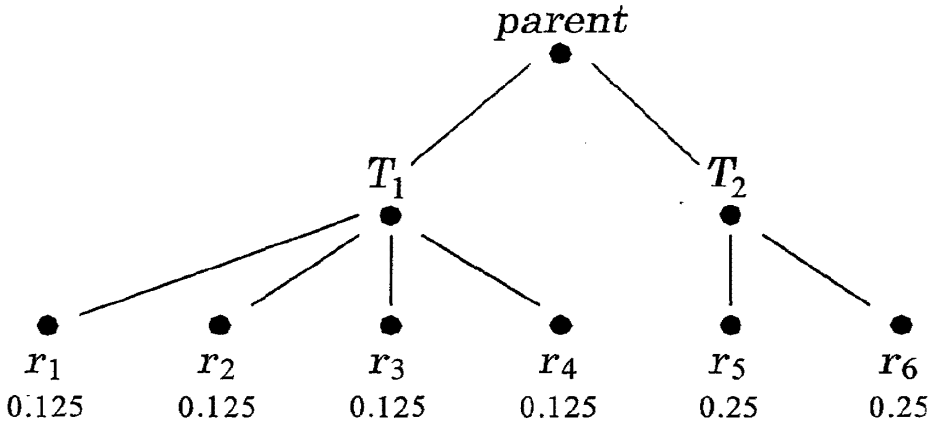

FIG. 10B

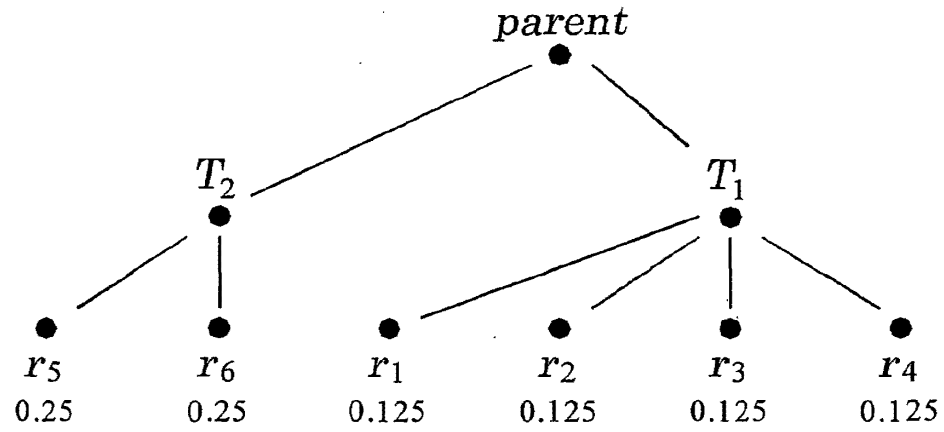

FIG. 10C

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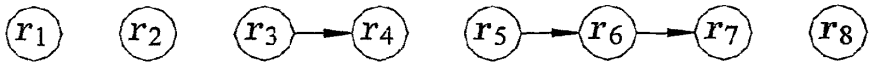

FIG. 11A

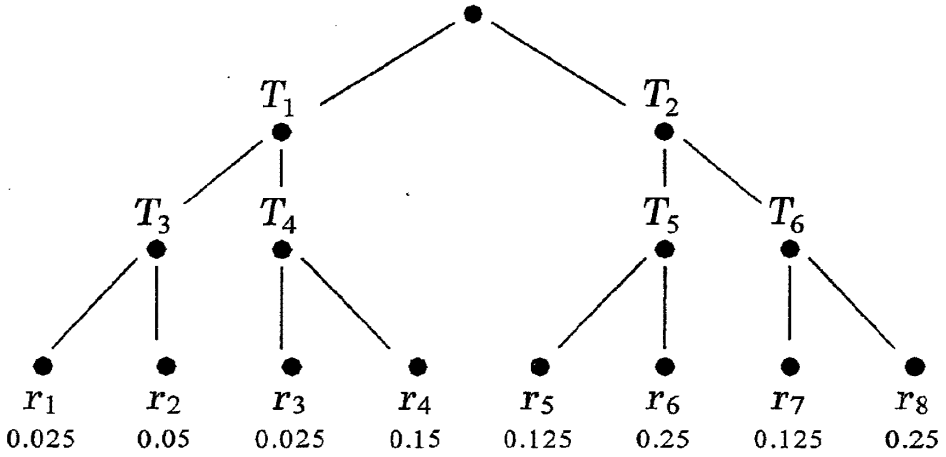

FIG. 11B

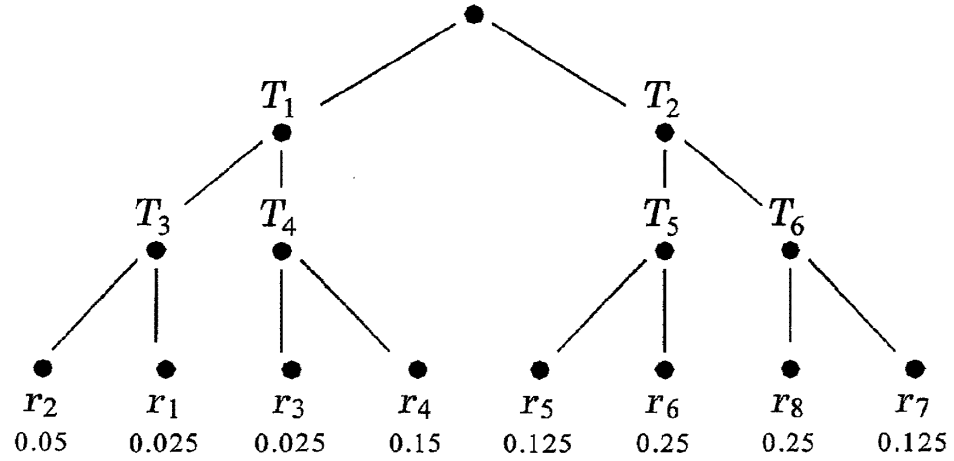

FIG. 11C

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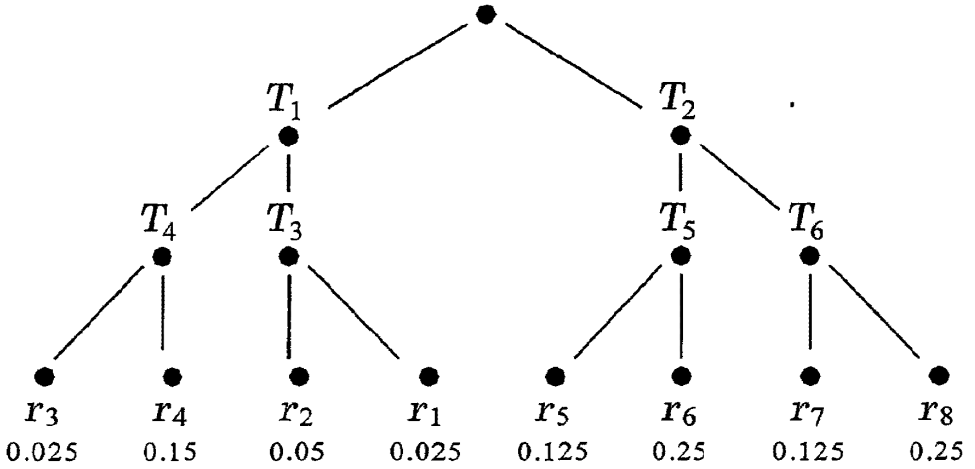

FIG. 11D

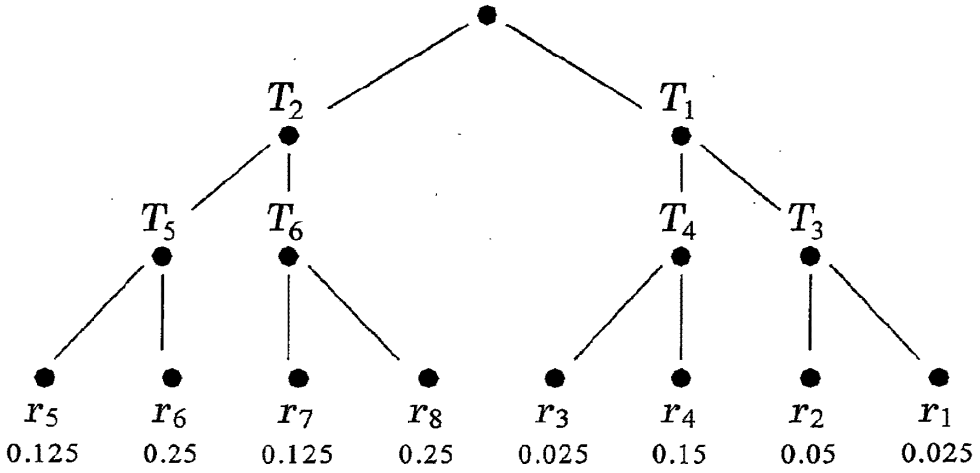

FIG. 11E

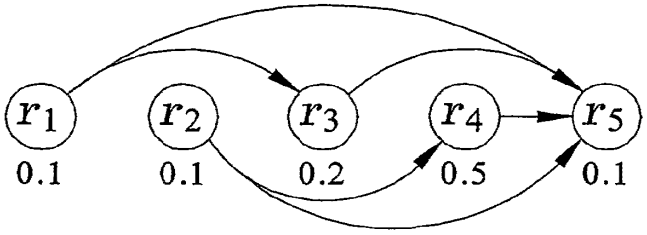

FIG. 12A

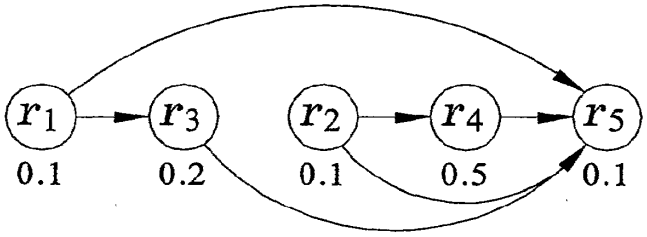

FIG. 12B

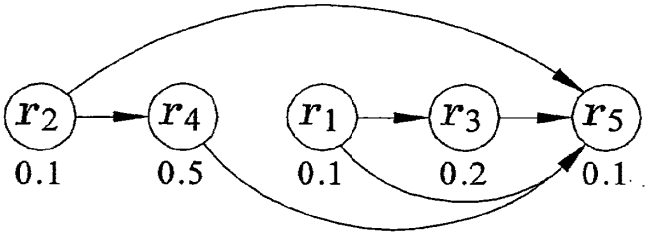

FIG. 12C

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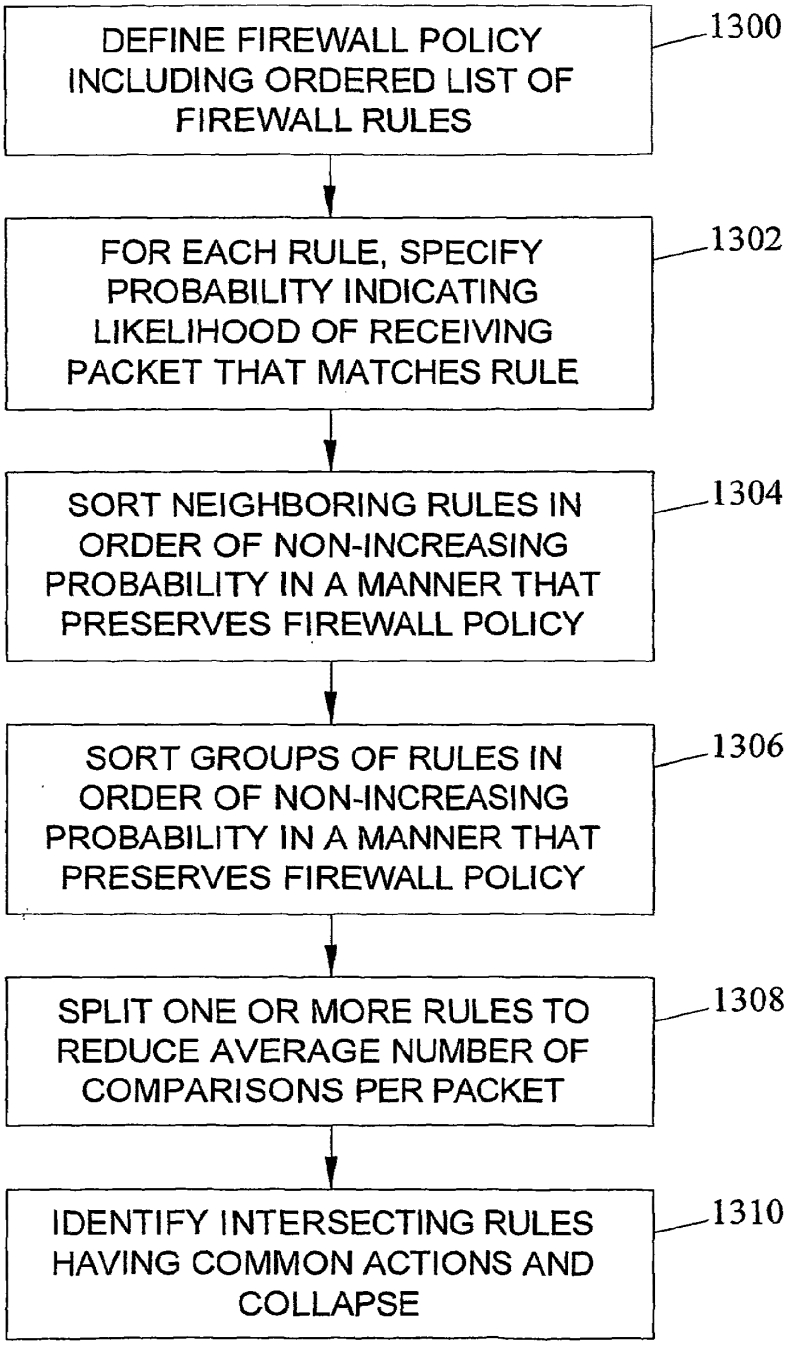
DEFINE FIREWALL POLICY INCLUDING ORDERED LIST OF FIREWALL RULES
1300
FOR EACH RULE, SPECIFY PROBABILITY INDICATING LIKELIHOOD OF RECEIVING PACKET THAT MATCHES RULE
1302
SORT NEIGHBORING RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1304
SORT GROUPS OF RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1306
SPLIT ONE OR MORE RULES TO REDUCE AVERAGE NUMBER OF COMPARISONS PER PACKET
1308
IDENTIFY INTERSECTING RULES HAVING COMMON ACTIONS AND COLLAPSE
1310

FIG. 13

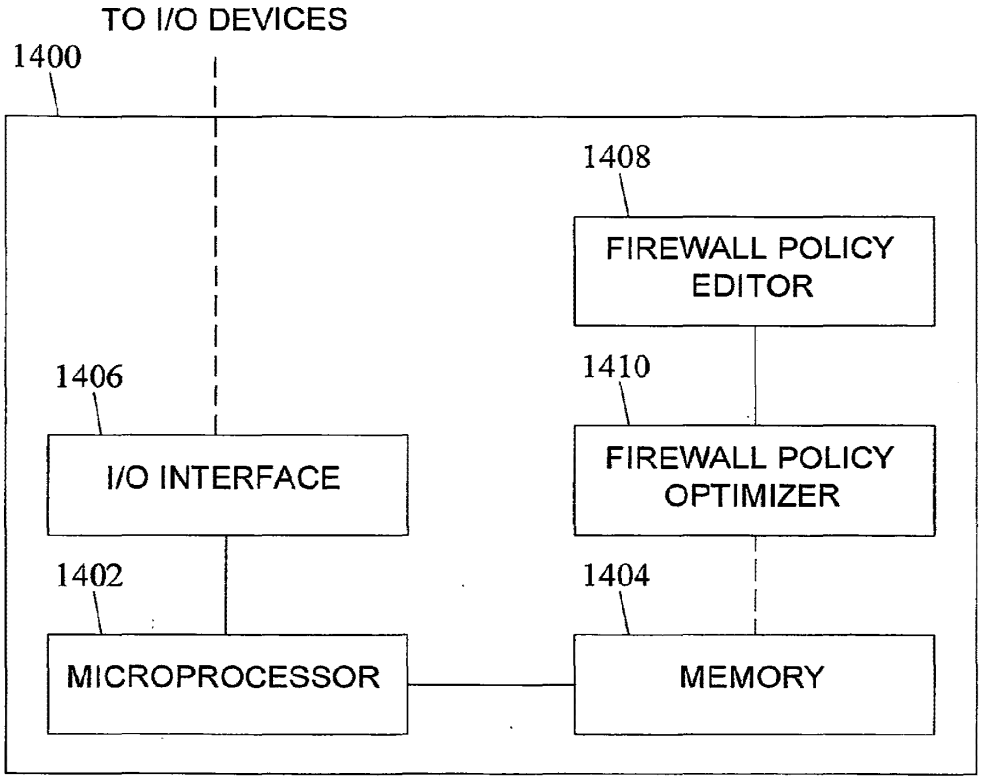

FIG. 14

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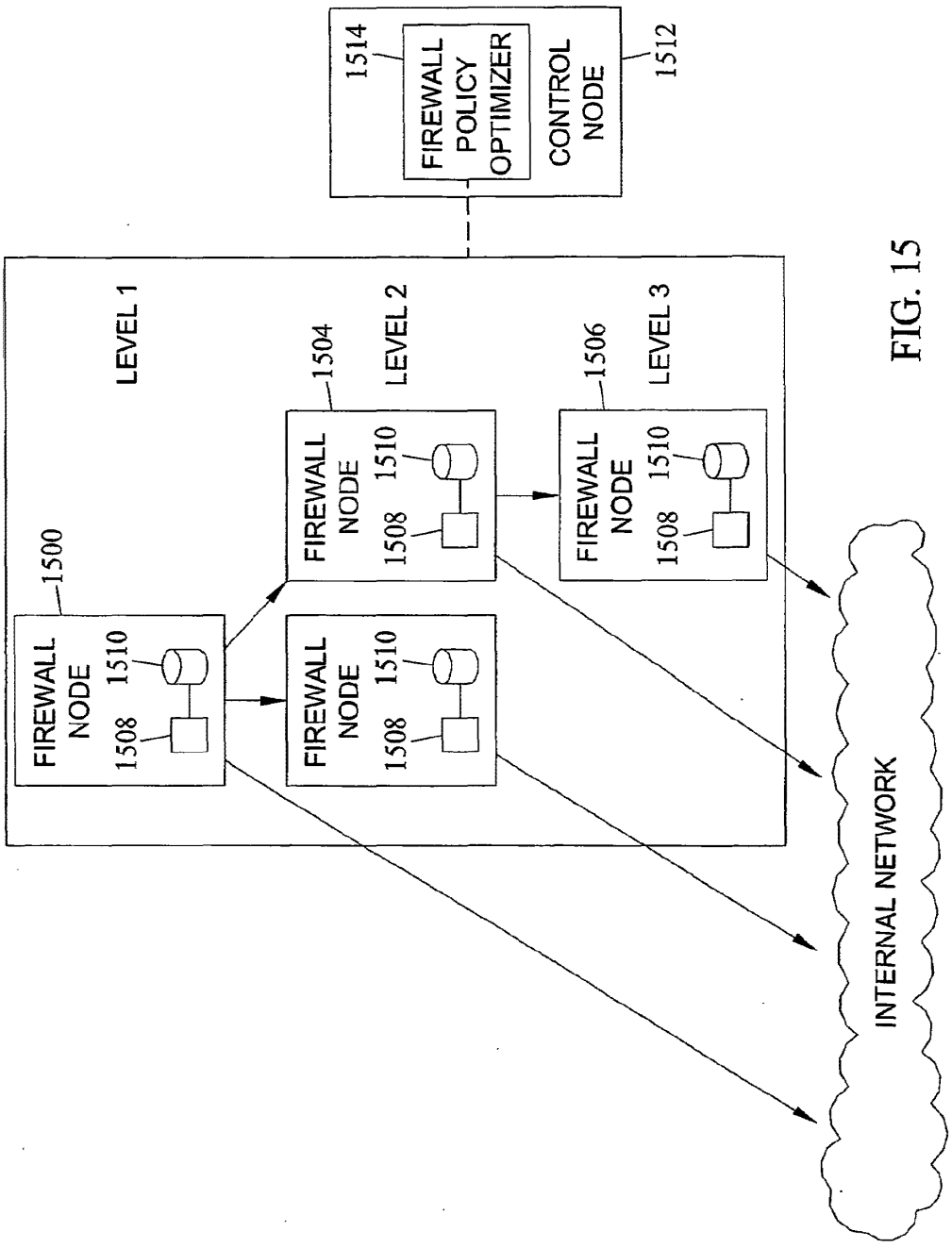
1514
FIREWALL POLICY OPTIMIZER
CONTROL NODE
1512
LEVEL 1
LEVEL 2
LEVEL 3
1500
1504
1506
FIREWALL NODE
1508
1510
INTERNAL NETWORK

FIG. 15

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

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- **E. W. FULP.** Firewall Architectures for High Speed Networks. *Technical Report,* 2002 **[0068]**
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- *High Performance Packet Classification, http://www.hipac.org* **[0068]**
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- Sequencing Jobs to Minimize Total Weighted Completion Time Subject to Precedence Constraints. **E. L. LAWLER.** Annals of Discrete Mathematics. 1978, vol. 2, 75-90 **[0068]**
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- **J. K. LENSTRA ; A. H. G. R. KAN.** Complexity of Scheduling under Precedence Constraints. *Operations Research,* 1978, vol. 26 (1), 22-35 **[0068]**
- **O. PAUL ; M. LAURENT.** A Full Bandwidth ATM Firewall. *Proceedings of the 6th European Symposium on Research in Computer Security ESORICS'2000,* 2000 **[0068]**
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- **V. P. RANGANATH ; D. ANDRESEN.** A Set-Based Approach to Packet Classification. *Proceedings of the IASTED International Conference on Parallel and Distributed Computing and Systems,* 2003, 889-894 **[0068]**
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- **W. E. SMITH.** Various Optimizers for Single-Stage Production. *Naval Research Logistics Quarterly,* 1956, vol. 3, 59-66 **[0068]**
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- **R. L. ZIEGLER.** Linux Firewalls. New Riders. 2002 **[0068]**
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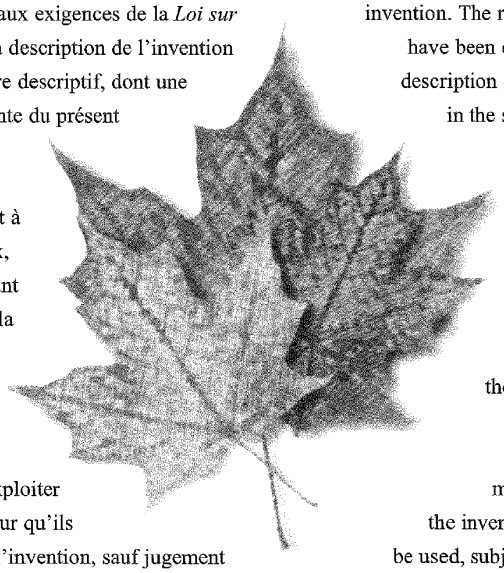
Office de la propriété intellectuelle du Canada
Un organisme d'Industrie Canada

Canadian Intellectual Property Office
An Agency of Industry Canada

Brevet canadien / Canadian Patent

Le commissaire aux brevets a reçu une demande de délivrance de brevet visant une invention. Ladite requête satisfait aux exigences de la *Loi sur les brevets*. Le titre et la description de l'invention figurent dans le mémoire descriptif, dont une copie fait partie intégrante du présent document.

Le présent brevet confère à son titulaire et à ses représentants légaux, pour une période expirant vingt ans à compter de la date du dépôt de la demande au Canada, le droit, la faculté et le privilège exclusif de fabriquer, construire, exploiter et vendre à d'autres, pour qu'ils l'exploitent, l'objet de l'invention, sauf jugement en l'espèce rendu par un tribunal compétent, et sous réserve du paiement des taxes périodiques.



The Commissioner of Patents has received a petition for the grant of a patent for an invention. The requirements of the *Patent Act* have been complied with. The title and a description of the invention are contained in the specification, a copy of which forms an integral part of this document.

The present patent grants to its owner and to the legal representatives of its owner, for a term which expires twenty years from the filing date of the application in Canada, the exclusive right, privilege and liberty of making, constructing and using the invention and selling it to others to be used, subject to adjudication before any court of competent jurisdiction, and subject to the payment of maintenance fees.

BREVET CANADIEN **2,600,236** CANADIAN PATENT

Date à laquelle le brevet a été accordé et délivré	**2014/08/12**	Date on which the patent was granted and issued
Date du dépôt de la demande	**2006/03/28**	Filing date of the application
Date à laquelle la demande est devenue accessible au public pour consultation	**2006/10/05**	Date on which the application was made available for public inspection

Commissaire aux brevets / Commissioner of Patents

Canada

3256 (CIPO 91) 04/14

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An agency of Industry Canada

CA 2600236 C 2014/08/12

(11)(21) 2 600 236

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(86) Date de dépôt PCT/PCT Filing Date: 2006/03/28
(87) Date publication PCT/PCT Publication Date: 2006/10/05
(45) Date de délivrance/Issue Date: 2014/08/12
(85) Entrée phase nationale/National Entry: 2007/09/04
(86) N° demande PCT/PCT Application No.: US 2006/011291
(87) N° publication PCT/PCT Publication No.: 2006/105093
(30) Priorité/Priority: 2005/03/28 (US60/665,664)

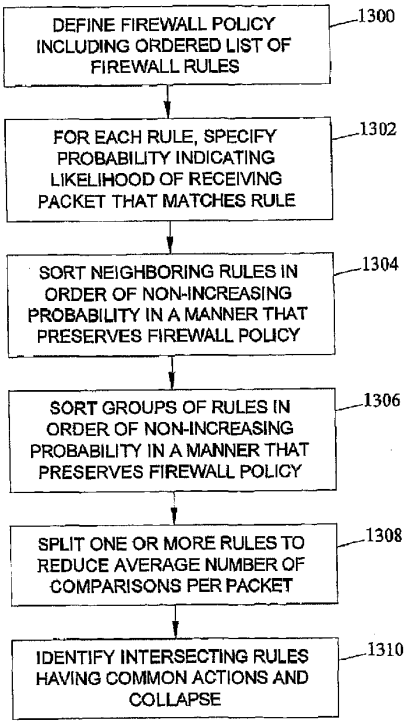
(51) Cl.Int./Int.Cl. *G06F 15/16* (2006.01)
(72) Inventeurs/Inventors:
FULP, ERRIN W., US;
TARSA, STEPHEN J., US

(73) Propriétaire/Owner:
WAKE FOREST UNIVERSITY, US

(74) Agent: NORTON ROSE FULBRIGHT CANADA LLP/S.E.N.C.R.L., S.R.L.

(54) Titre : PROCEDES, SYSTEMES ET PRODUITS DE PROGRAMMES INFORMATIQUES POUR L'OPTIMISATION DE LA POLITIQUE DE PARE-FEU D'UN RESEAU

(54) Title: METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION



(57) Abrégé/Abstract:
Methods, systems, and computer program products for firewall policy optimization are disclosed. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is determined. The rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.

METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION

GOVERNMENT INTEREST

This invention was made with Government support under Grant No. DE-FG02-03ER25581 awarded by U.S. Department of Energy, Mathematical and Computational Information Sciences Division. The Government has certain rights in the invention.

TECHNICAL FIELD

The subject matter described herein relates to optimizing polices for network firewalls. More particularly, the subject matter described herein relates to methods, systems, and computer program products for optimizing performance of network firewalls.

BACKGROUND ART

Network firewalls remain the forefront defense for most computer systems. Guided by a security policy, these devices provide access control, auditing, and traffic control [3, 30, 31]. A security policy is a list of ordered rules, as seen in Table 1, that defines the action to perform on matching, packets. For example, an accept action passes the packet into or from the secure network, while deny causes the packet to be discarded. In many implementations, the rule set is stored internally as a linked list. A packet is sequentially compared to the rules, starting with the first, until a match is found; otherwise, a default action is performed [30, 31]. This is referred to as a first- match policy and is used in many firewall systems including the Linux firewall implementation iptables [25].

No.	Proto.	Source IP	Source Port	Destination IP	Destination Port	Action	Prob.
1	UDP	1.1.*	*	*	80	deny	0.01
2	TCP	2.*	*	1.*	90	accept	0.02
3	UDP	*	*	1.*	*	accept	0.10
4	TCP	2.*	*	1.*	20	accept	0.17
5	UDP	1.*	*	*	*	accept	0.20
6	*	*	*	*	*	deny	0.50

Table 1: Example Security Policy Consisting of Multiple Ordered Rules

Traditional firewall implementations consist of a single, dedicated machine, similar to a router, that sequentially applies rules to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [24, 29, 31]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [30]. Successfully handling these traffic loads becomes more difficult as rule sets become more complex [4, 22, 31]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 9, 13, 14]. An attacker could simply inundate the firewall with traffic, delaying or preventing legitimate packets from being processed.

One approach to increase firewall performance focuses on improving hardware design. Current research is investigating different distributed firewall designs to reduce processing delay [4, 9, 22], and possibly provide service differentiation [11]. Another approach focuses on improving performance via better firewall software [6, 7, 12, 16, 17, 24]. Similar to approaches that address the longest matching prefix problem for packet classification [8, 10, 25, 28], solutions typically represent the firewall rule set in different fashions (e.g. tree structures) to improve performance. While both approaches, together or separate, show great promise, each requires radical changes to the firewall system, and therefore are not amenable to current or legacy systems.

Accordingly, there exists a need for improved methods, systems, and computer program products for network firewall policy optimization.

SUMMARY

The subject matter described herein includes methods, systems, and computer program products for network firewall policy optimization. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is defined. Neighboring rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.

As used herein, the term "firewall" refers to a logical entity that is adapted to filter packets at the ingress and/or egress portions of a network based on a policy. The term "firewall" is intended to include systems that block packets from entering or leaving a network and systems that perform intrusion detection and intrusion protection functions for packets entering or leaving a network. Thus, the methods and systems described herein for firewall policy optimization can be used to optimize policies for intrusion detection and intrusion protection firewalls.

The subject matter described herein includes a method to improve firewall performance and lower packet delay that can be applied to both legacy and current systems. In one implementation, a firewall rule set may be re-ordered to minimize the average number of rule comparisons to determine the action, while maintaining the integrity of the original policy. Integrity is preserved if the reordered and original rules always arrive at the same result. To maintain integrity, a firewall rule set may be modeled as a Directed Acyclical Graph (DAG), where vertices are firewall rules and edges indicate precedence relationships. Given this representation, any linear arrangement of the DAG is proven to maintain the original policy integrity. Unfortunately, determining the optimal rule order from all the possible linear arrangements is proven to be *NP*-complete, since it is equivalent to sequencing jobs with precedence constraints for a single machine [15]. Although determining the optimal order is *NP*-complete, a heuristic will be described below to order firewall rules that reduces the average number of comparisons while maintaining integrity. Simulation

results show the proposed reordering method yields rule orders that are comparable to optimal; thus, provides a simple means to significantly improve firewall performance and lower packet delay.

The subject matter described herein for network firewall policy optimization may be implemented using any combination of hardware, software, or firmware. For example, the subject matter described herein may be implemented using a computer program product comprising computer executable instructions embodied in a computer readable medium. Exemplary computer readable media suitable for implementing the subject matter described herein include disk memory devices, chip memory devices, programmable logic devices, application specific integrated circuits, and downloadable electrical signals. In addition, a computer program product that implements the subject matter described herein may be implemented using a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings of which:

Figure 1A is a block diagram of a rule list Directed Acyclical Graph (DAG) for the firewall rules in Table 1;

Figure 1B is a linear arrangement of firewall rules corresponding to the original rule order;

Figure 2A is a policy DAG representing a reordered version of the firewall rule set in Figure 1 after sorting;

Figure 2B is a policy DAG for the rule set illustrated in Table 1 illustrating an optimal rule order;

Figure 3A is a graph illustrating average numbers of packet comparisons versus intersection percentage for different orderings of a firewall policy;

Figure 3B is a graph illustrating the percent difference in average numbers of packet comparisons between sorted and optimal sortings of a firewall policy;

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Figure 4A is a graph of percent difference comparisons between original and sorted versions of a firewall policy;

Figure 4B is a graph illustrating the performance impact of considering rule intersection and actions in performing firewall rule sorting;

Figure 5A is a table illustrating a firewall policy before sorting;

Figure 5B is a table illustrating a sorted version of the firewall policy of Figure 5A;

Figure 6A is a policy trie representation of the firewall policy of Figure 5B;

Figure 6B is a table representing the firewall policy of Figure 5A after TCP and UDP sub-trie rotation;

Figure 7A is a policy trie illustrating the splitting of rule r_5 into rules r_{5a} and r_{5b};

Figure 7B is a table illustrating the firewall policy of Figure 5A after splitting rule r_5 into rules r_{5a} and r_{5b};

Figure 8A is a graph illustrating firewall performance with and without rule splitting;

Figure 8B is a graph illustrating locations and probabilities where splitting is better;

Figure 9A is a policy DAG of a firewall rule set;

Figure 9B is a policy DAG illustrating compression of rules r_1 and r_5;

Figure 10A is a policy DAG of a firewall rule list;

Figure 10B is an original policy trie before sorting;

Figure 10C is a policy trie illustrating the firewall rules after rotating sub-tries T_1 and T_2;

Figure 11A is a policy DAG illustrating a firewall policy;

Figure 11B is a policy trie illustrating firewall rules of the policy before sorting;

Figure 11C is a policy trie illustrating the firewall policy after exchanging nodes r_1 and r_2 and nodes r_7 and r_8;

Figure 11D is a policy trie illustrating the firewall policy after exchanging sub-tries T_3 and T_4;

Figure 11E is a policy trie illustrating the firewall policy after exchanging sub-tries T_1 and T_2;

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Figure 12A is a policy DAG illustrating an original order for a firewall policy;

Figure 12B is a policy DAG illustrating a sorted version of the firewall policy of Figure 12A after exchanging neighbors;

Figure 12C is a policy DAG illustrating a sorted version of the firewall policy after exchanging lists L_1 including rules r_1 and r_3 and lists L_2 including rules r_2 and r_4;

Figure 13 is a flow chart illustrating exemplary steps for network firewall policy optimization according to an embodiment of the subject matter described herein;

Figure 14 is a block diagram illustrating exemplary components of a system for firewall policy optimization according to an embodiment of the subject matter described herein; and

Figure 15 is a block diagram illustrating a plurality of firewall nodes for implementing a firewall policy according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION OF THE INVENTION

Modeling Firewall Security Policies

As described above, a firewall rule set, also known as a firewall policy, is traditionally an ordered list of firewall rules. Firewall policy models have been the subject of recent research [1, 2, 16]; however, the primary purpose is anomaly detection and policy verification. In contrast, the policy model described in this herein is designed for firewall performance optimization and integrity. Firewall performance refers to reducing the average number of comparisons required to determine an action, while integrity refers to maintaining the original policy intent. Although improving the worst-case performance is important, it is not possible without changing the list-based representation [16, 24].

Firewall Rule and Policy Models

In the examples described herein, a rule r is modeled as an ordered tuple of sets, $r = (r[1], r[2], ..., r[k])$. Order is necessary among the tuples since

comparing rules and packets requires the comparison of corresponding tuples. Each tuple $r[i]$ is a set that can be fully specified, specify a range, or contain wildcards '*' in standard prefix format. For the Internet, security rules are commonly represented as a 5-tuple consisting of: protocol type, IP source address, source port number, IP destination address, and destination port number [30, 31]. Given this model, the ordered tuples can be supersets and subsets of each other, which forms the basis of precedence relationships. In addition to the prefixes, each filter rule has an action, which is to accept or deny. However, the action will not be considered when comparing packets and rules. Similar to a rule, a packet (IP datagram) d can be viewed as an ordered k-tuple $d = (d[1], d[2], ..., d[k])$; however, ranges and wildcards are not possible for any packet tuple.

Using the previous rule definition, a standard security policy can be modeled as an ordered set (list) of n rules, denoted as $R = \{r_1, r_2, ..., r_n\}$. A packet d is sequentially compared against each rule r_i starting with the first, until a match is found ($d \Rightarrow r_i$) then the associated action is performed. A match is found between a packet and rule when every tuple of the packet is a subset of the corresponding tuple in the rule.

Definition Packet d matches r_i if

$$d \Rightarrow r_i \quad \text{iff} \quad d[i] \subseteq r_i[i], \quad i = 1, ..., k$$

The rule list R is comprehensive if for every possible legal packet d a match is found using R. Furthermore, two rule lists R and R' are equivalent if for every possible legal packet d the same action is performed by the two rule lists. If R and R' are different (e.g. a reorder) and the lists are equivalent, then the policy integrity is maintained.

As previously mentioned, a rule list has an implied precedence relationship where certain rules must appear before others if the integrity of the policy is to be maintained. For example consider the rule list in Table 1. Rule r_1 must appear before rules r_3 and r_5, likewise rule r_6 must be the last rule in the policy. If for example, rule r_3 was moved to the beginning of the policy, then it will shadow [2] the original rule r_1. However, there is no precedence relationship between rules r_2 and r_4 given in Table 1. Therefore, the relative ordering of these two rules will not impact the policy integrity and can be

changed to improve performance. The present example assumes that the original policy is free from any anomalies. Likewise, when a policy is reordered to improve performance it should not introduce any anomalies, which will occur if precedence relationships are not maintained. As a result, a model is needed to effectively represent precedence relationships.

Modeling Rule List Precedence Relationships

The precedence relationship between rules in a policy will be modeled as a Directed Acyclical Graph (DAG) [23, 18]. Such graphs have been successfully used to represent the relative order of individual tasks that must take place to complete a job (referred to as a task graph model). Since certain rules must appear before others to maintain policy integrity, this structure is well suited for modeling the precedence of firewall rules. Let $G = (R, E)$ be a rule list DAG for a rule list R, where vertices are rules and edges E are the precedence relationships (constraint). A precedence relationship, or edge, exists between rules r_i and r_j, if $i < j$, the actions for each rule are different, and the rules intersect.

Definition The intersection of rule r_i and r_j, denoted as $r_i \cap r_j$ is

$$r_i \cap r_j = (r_i [l] \cap r_j [l]), \qquad l = 1, ..., k$$

Therefore, the intersection of two rules results in an ordered set of tuples that collectively describes the packets that match both rules. The rules r_i and r_j intersect if every tuple of the resulting operation is non-empty. In contrast, the rules r_i and r_j do not intersect, denoted as $r_i \not\cap r_j$, if at least one tuple is the empty set. Note the intersection operation is symmetric; therefore, if r_i intersects r_j, then r_j will intersect r_i. The same is true for rules that do not intersect.

For example consider the rules given in Table 1, the intersection of r_1 and r_3 yields (UDP, 1.1.*, *, 1.*, 80). Again, the rule actions are not considered in the intersection or match operation. Since these two rules intersect, a packet can match both rules for example d = (UDP, 1.1.1.1, 80, 1.1.1.1, 80). Furthermore, the actions of the two rules are different. Therefore, the relative order must be maintained between these two rules and an edge drawn from r_1 to r_3 must be present in the rule list DAG, as seen in Figures 1A and 1B. More

particularly, Figure 1A illustrates a rule list DAG for the rules in Table 1. Figure 1B illustrates a linear arrangement of the rules in Figure 1A. In Figures 1A and 1B, the vertices represent rules, the circles represents an accept rules, and the squares represents deny rules. Edges that connect the vertices represent precedence requirements. As can be seen from Figure 1B, because of the edge between rules r_1 and r_3, precedence between rules r_1 and r_3 must be maintained. In contrast consider the intersection of rules r_3 and r_5. These two rules intersect, indicating packets belonging to the set (UDP, 1.*, *, 1.*, *) would match both rules. However, it does not matter which of the two rules a packet matches first, since the action is the same for both rules. Therefore, an edge does not exist between rules r_3 and r_5 in the diagram. Similarly, rules r_2 and r_4 do not intersect due to the fifth tuple (destination port). A packet cannot match both rules indicating the relative order can change; therefore, an edge will not exist between them.

The match operation can be used to identify precedence relationships, but it cannot do so in every case. Consider a partial-match example [1], where r_a = (UDP, *, 80, 10.*, 90, accept) and r_b = (UDP, 10.*, 80, *, 90, deny). The intersection of r_a and r_b is (UDP, 10.*, 80, 10.*, 90); therefore a packet, such as d = (UDP, 10.10.10.10, 80, 10.10.10.10, 90), can match both rules. If r_a appears before r_b then the packet d is accepted, but if r_b occurs before r_a then d is rejected. As a result, the order of r_a and r_b in the original policy must be maintained. However, the match operation is unable to identify the precedence in this example. A partial match exists in between rules r_3 and r_5 in Table 1, but as previously discussed an edge does not exist between the rules since the actions are the same.

Using the rule list DAG representation a linear arrangement is sought that improves the firewall performance. As depicted in Figure 1B, a linear arrangement (permutation or topological sort) is a list of DAG vertices where all the successors of a vertex appear in sequence after that vertex [23]. Therefore it follows that a linear arrangement of a rule list DAG represents a rule order, if the vertices are read from left to right. Furthermore, it is proven in the following theorem that any linear arrangement of a rule list DAG maintains integrity.

Theorem Any linear arrangement of a rule list DAG maintains integrity.

Proof Assume a rule list DAG *G* is constructed from the security policy *R* that is free of anomalies. Consider any two rules r_i and r_j in the policy, where $i < j$. If an edge between r_i and r_j in *G* does not exist, then a linear arrangement of *G* can interchange the order of the two rules. An edge will not exist if the rules do not intersect; however, a reorder will not affect integrity since a packet cannot match both rules. Shadowing is not introduced due to the reorder since the intersection operation is symmetric. An edge will not exist if the two rules intersect but have the same action; however, a reorder will not affect integrity since the same action will occur regardless of which rule is matched first. If an edge does exist between the rules, then their relative order will be maintained in every linear arrangement of *G*; thus maintaining precedence and integrity.

Rule List Optimization

As described above, it is important to inspect packets as quickly as possible given increasing network speeds and QoS requirements. Using the rule list DAG to maintain policy integrity, a linear arrangement is sought that minimizes the average number of comparisons required. However, this will require information not present in the firewall rule list. Certain firewall rules have a higher probability of matching a packet than others. As a result, it is possible to develop a policy profile over time that indicates frequency of rule matches (similar to cache hit ratio). Let $P = \{p_1, p_2, ..., p_n\}$ be the policy profile, where p_i is the probability that a packet will match rule *i* (first match in the policy). Furthermore, assume a packet will always find a match, $\sum_{i=1}^{n} p_i = 1$; therefore *R* is comprehensive. Using this information, the average number of rule comparisons required is

$$E[n] = \sum_{i=1}^{n} i \cdot p_i \qquad (1)$$

For example, the average number of comparisons required for the rule set in Table 1 is 5.03.

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Given a rule list DAG $G = (R, E)$ and policy profile $P = \{p_1, p_2, ..., p_n\}$ a linear arrangement π of G is sought that minimizes Equation 1. In the absence of precedence relationships, the average number of comparisons is minimized if the rules are sorted in non-increasing order according to the probabilities [26], which is also referred to as Smith's algorithm [27]. Precedence constraints cause the problem to be more realistic; however, such constraints also make determining the optimal permutation more problematic.

Determining the optimal rule list permutation can be viewed as job scheduling for a single machine with precedence constraints [15, 21]. The notation for such scheduling problems is $\alpha|\beta|\gamma|\delta$, where α is the number of machines, β is the precedence (or absence of) which can be represented as a DAG, γ is a restriction on processing time, and δ is the optimality criterion [15]. Determining the optimal rule order is similar to the $1|\beta|1|\sum \omega C_i$ scheduling problem, or optimality criterion, where ω is a weight associated with a job (for example, importance) and C_i is the completion time. As previously noted, the $1|||\sum \omega C_i$ problem can be solved in linear time the using Smith's algorithm [27], which orders jobs according to non-decreasing $\frac{t_i}{\omega}$ ratio, where t_i is the processing time of job i. In this case set $t_i = 1$ and $\omega = p_i \; \forall i$. However, Lawler [19] and Lenstra et al. [21] proved $1|\beta|1|\sum \omega C_i$ to be *NP*-complete via the linear arrangement problem, which implies determining the optimal firewall rule order is also *NP*-complete. Note, determining the number of possible permutations has been proven to be *NP*-hard [5].

Theorem $1|\beta|1|\sum \omega C_i \; \alpha$ *Determining the optimal order of a firewall rule list*

Proof Consider the $1|\beta|1|\sum \omega C_i$ problem. Each of n jobs J_i, $i \in I$, has to be processed without preemption on a single machine that can handle at most one job at a time. For each $i \in I$, let ω be the associated weight. Furthermore, let $G = (V, E)$ be a DAG that represents the precedence order of the jobs J_i. Assume the processing time of each job equals 1 time unit, the weights to be $0 \leq \omega \leq 1$ such that $\sum \omega = 1$, and β, which is G, to be a rule list DAG. In this case, the

optimization criterion $\sum \omega \cdot C_i$ is the same as $\sum p_i \cdot i$, which is given in equation 1. Clearly, the optimal firewall rule ordering problem has a solution if and only if $1|\beta|1|\sum \omega C_i$ has a solution. Therefore, determining the optimal permutation of firewall rules is *NP*-complete.

Exemplary Rule Sorting Algorithm

Although determining the optimal rule permutation was proven to be *NP*-complete, reducing the average number of comparisons required to process a packet remains an important objective. As previously discussed, a sorting algorithm must maintain the precedence relationships among rules. Of course an exhaustive search is possible if the number of rules is small (generate and test all possible topological orders); however as proven in the previous section, this is not feasible with a realistic rule list.

One exemplary algorithm starts with the original the rule set, then sorts neighboring rules based on nonincreasing probabilities. However, an exchange of neighbors should never occur if the rules intersect and have different actions. This test preserves any precedence relationships in the policy. For example, the following sorting algorithm uses such a comparison to determine if neighboring rules should be exchanged. Note a_i denotes the action associated with the ith rule.

```
done = false
while(!done)
    done = true
    for(i = 1; i <n; i++)
        if(pi < pi+1 AND (ri ∩ ri+1 OR ai == ai+1))then
            exchange rules, actions, and probabilities
            done = false
        endif
    endfor
endwhile
```

Other sorting algorithms are possible if the completion time of the sort is an issue; however, the method presented is easy to implement and only requires a simple neighbor comparison. Assume the match probabilities for the rule list given in Table 1. Applying the sorting algorithm to this rule list results in the ordering depicted in Figure 2A, which has 10% fewer comparisons on

average. However when using the algorithm, it is possible that one rule can prevent another rule from being reordered. For example, rule r_1 prevents rule r_5 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_5 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be further reduced, 15% fewer. This is the optimal order for the 6 rule set, which is depicted in Figure 2B. Although this simple sorting algorithm is unable to move groups of rules, it can still improve the performance of the firewall system. Its effectiveness is measured experimentally in the next section.

Experimental Results

In this section, the average number of rule comparisons required after sorting the rules is compared with average number of comparisons required using the original order and the optimal order. Note the optimal rule ordering was determined via an exhaustive search. As a result, it was not feasible to determine the optimal ordering once the number of rules equaled 15 given the number of permutations to consider. Two different variations of the rule sorting method described in the preceding section were implemented. The difference between the methods was the comparison used to determine if neighboring rules should be exchanged. The first sorting algorithm exchanged neighboring rules if they were out of order and did not intersect. The if-condition was as follows.

if ($p_i < p_{i+1}$ **AND** $r_i \not\cap r_{i+1}$) **then**

Therefore, rule actions were not considered and the method will be referred to as *non-action sort*. The second sorting method did consider the rule action (as described in the preceding section) and will be referred to as *action sort*. The comparison between the two sorting algorithms will indicate the importance of considering rule actions when ordering rules.

In the first experiment, lists of 10 firewall rules were generated with random precedence relationships. The match probability of each rule was given by a Zipf distribution [20], which assigns probabilities according to the rank of an item. For this simulation, the last rule had the highest probability

which is consistent with most policies (last rules are more general). As a result, the original order yields the worst average number of comparisons. The intersection percentage measured the percentage of rules that intersect in the policy. This metric gives a value for the dependency level in the policy; however note, rule action is not considered when calculating this metric. Rules were equally likely to have an accept or deny action and the results (average number of rule comparisons) for a particular intersection percentage were averaged over 1000 simulations.

Results of the first experiment are given in Figures 3A and 3B. More particularly, Figure 3A is a graph illustrating the average number of packet comparisons versus intersection percentage for the original rule sorting, the non-action sort, the action sort, and the optimal sort. Figure 3B is a graph illustrating the percent difference in the average number of comparisons required between the sorted and optimal firewall policy configurations. The average number of comparisons required was lower for the sorted and the optimal lists when the intersection percentage was low, as seen in Figure 3A. This was expected since there is a large number of possible rule permutations (few edges in the DAG). When the intersection percentage approached 100%, the values converged to the number required for the original list. This is due to the limited number of possible rule orders, only one order in the extreme case. The percent difference between the sorted and optimal order is shown in Figure 3B. At zero intersection percentage the sorted and optimal orders are equal, since any ordering is possible. Similarly at an intersection percentage of 100, the sorted and optimal orders are equal since only one order is possible. Between these two extremes, the action sorting algorithm remains close to the optimal value. In contrast, the non-action sort had a maximum difference of 33%.

The benefit of rule sorting on larger policies is also of interest; however as previously described, it was not possible to determine the optimal ordering once the number of rules approaches 15. Therefore, the second experiment used larger rule sets, but only compared the original order and the sorted orders. The number of rules ranged from 10 to 1000, while the matching probabilities and intersection percentages were the same as the previous

experiment. The results of this experiment are depicted in Figure 4A. The sorted rule sets always performed equal to or better than the original order, while the action sort consistently performed better than the non-action sort. As noted in the previous experiment, the percent difference is very large given few intersections (e.g. 80% decrease for 1000 rules with 0% dependency), but approaches zero as all the rules intersect. As the number of rules increases, sorting is increasingly beneficial, although only at low intersection percentages. The benefit of sorting drops more significantly as the intersection percentage increases with larger rule sets. This is primarily due to the low matching probabilities of each rule, which requires a complete reordering to have a significant impact on the average number of comparisons. As a result, large rule sets can benefit from sorting if the intersection percentage is low.

The impact of considering rule actions when sorting is illustrated in Figure 4B. In this experiment lists of 1000 rules were generated, where the intersection percentages ranged from 0% to 100% and the percentage of rules with the same action varied from 50% to 100%. The performance of the action sort to the original list was then compared. As the percentage of rules with the same action increased, the percent difference (reduction) in the average number of comparisons also increased. This is due to the increased number of permutations possible when the rule actions are increasingly the same (fewer edges in the rule list DAG to consider). This is depicted in Figure 4B where a policy with a 100% intersection percentage can significantly reduce the number of comparisons (80% reduction) if all the rules have the same action. This performance increase is not possible with the non-action sort. Therefore, considering the rule action increases the number of possible rule orders, thereby providing more possibilities to improve firewall performance.

Conclusions

Network firewalls enforce a security policy by comparing arriving packets to a list of rules. An action, such as accept or deny, is then performed on the packet based on the matching rule. Unfortunately packet filtering can impose significant delays on traffic due to the complexity and size of rule sets.

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Therefore, improving firewall performance is important, given network Quality of Service (QoS) requirements and increasing network traffic loads.

The sections above describe rule ordering methods to improve the performance of network firewalls. Assuming each rule has a probability of a packet matching, firewall rules should be sorted such that the matching probabilities are non-increasing. This reduces the average number of comparisons and the delay across the firewall. However, a simple sort is not possible given precedence relations across rules. It is common in a security policy that two rules may match the same packet yet have different actions. It is this precedence relationship between rules that must be maintained to preserve integrity. The method described above uses Directed Acyclical Graphs (DAG) to represent the precedence order rules must maintain. Given this representation, a topological sort can be used to determine the optimal order (minimum average number of comparisons); however, the examples above prove this problem to be *NP*-complete (similar to job scheduling for a single nonpreemptive machine with precedence constraints). As an alternative, a simple sorting method was introduced that maintained the precedence order of the rules. Simulation results indicate this method can significantly reduce the average number of comparisons required and is comparable to optimal ordering.

Several areas exist for future research in optimizing firewall rule lists. The sorting method proposed above is based on a simple algorithm. Although it can offer an improvement over the original rule order, algorithms that can move groups of rules could provide a larger reduction in the average number of comparisons. The effect of stateful firewalls should also be addressed in future research. Security can be enhanced with connection state and packet audit information. For example, a table can be used to record the state of each connection, which is useful for preventing certain types of attacks (e.g., TCP SYN flood) [30, 31]. The impact of such rules on the firewall needs to be investigated and whether sorting can be done on-line to reflect temporal changes. In addition, more research is needed to determine more accurate probability distributions for packet matching and dependency percentages.

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Given this information, better algorithms can be designed and more realistic simulations can be performed.

Trie-Based Network Firewall Optimization Methods and Rule Splitting

Overview

As described above, while assuring firewall policy integrity is critical, performance is equally important given increasing network speeds and traffic volumes. Firewall processing delay can be reduced via hardware as well as policy optimization, where rules are manipulated to reduce the number of comparisons. For a given firewall installation, it can be determined that certain security rules have a higher probability of matching a packet than others. As a result, it is possible to develop a *policy profile* over time that indicates frequency of rule matches (similar to cache hit ratio). Given this information, trie-based methods are described herein to minimize the average number of comparisons required per packet. Although most firewall systems still utilize an ordered list representation, the proposed enhancements still are applicable to current firewall systems since a policy trie can be converted into an ordered list using an inorder traversal.

Rule Sorting

As described above, rule sorting of neighboring rules based on ascending probabilities in a manner that considers rules intersection and rule actions can be used to improve firewall performance by reducing the number of packet comparisons. The methods described above use Directed Acyclic Goal Graphs (DAGs) to represent firewalls. The methods described in this section will use the rule sorting algorithms in combination with policy trie representations to perform sorting of groups of rules in a manner that improves firewall performance.

In this example, it is assumed that a security policy contains a list of n ordered rules, $\{r_1, r_2, ..., r_n\}$. In addition, let p_i represent the probability that a packet will match rule i (first match in the policy). Therefore, the policy is comprehensive, which means every packet will have a match, if $\sum_{i=1}^{n} p_i = 1$.

Using this information, the average number of rule comparisons required can be calculated as

$$E[n] = \sum_{i=1}^{n} i \cdot p_i$$

The average number of comparisons is minimized if the rules are sorted in non-ascending order according to the probabilities. However, this can only be achieved if the sorting algorithm considers the probabilities and whether one rule is a superset of another. For example, sorting algorithms must use the following comparison to determine if neighboring rules should be interchanged Note, a_i denotes the action associated with the ith rule.

if ($p_i < p_{i+1}$ **AND** $r_i \not\subset r_{i+1}$ **OR** $a_i == a_{i+1}$)) **then**

Sorting rules in this fashion can have positive impact on the average number of comparisons required. Figure 5A is a table illustrating a firewall policy prior to rule sorting. The expected number of comparisons for the policy of Figure 5A is 4.26 comparisons per packet. Figure 5B is a table illustrating the firewall policy of Figure 5A after sorting using the above-described algorithm. In Figure 5B, the expected number of comparisons per packet has been reduced to 3.94. Thus, using the method described above, the number of comparisons per packet can be reduced by 8%.

However, it can be seen from Figures 5A and 5B that one rule can prevent another rule from being reordered. For example in Figure 5B, rule r_1 prevents rule r_4 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_4 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be reduced.

To solve this problem, rule sets can be sorted a using policy tries. First, the rule list is converted into an equivalent policy trie. Each sub-trie will have an associated probability $\overline{p}$ that is average probability (hit-ratio) of the rules comprising the sub-trie. Sub-tries can be rotated around their parent node to increase performance, using the method described earlier. Since the policy trie (or equivalent rule set) is tested from left to right, rotation should occur if the

probability of the right sub-trie is greater than the left sub-trie. As a result, the average number of comparisons required will be reduced and the policy integrity is maintained. Figure 6A is a trie representation of the rules in Figure 5B. Figure 6B is a table representing resulting rule set after rotating the TCP and UDP sub-tries. The TCP sub-trie in Figure 6A has an expected packet matching probability of 0.095 while the UDP sub-trie has an expected packet matching probability of 0.155. Thus, the UDP sub-trie and the TCP sub-trie should be rotated so that the UDP sub-trie becomes the left sub-trie and the TCP sub-trie becomes the right sub-trie. In the table illustrated in Figure 6B, which lists the ordering of the rules after rotating the sub-tries, the average number of comparisons per packets has been reduced to 3.70.

Rule Splitting

Rule splitting takes a general rule and creates more specific rules that collectively perform the same action over the same set of packets. Here, rule splitting is used to reduce the average number of comparisons. For example in Figure 7A, rule r_5 is split into two separate rules, r_{5a} for UDP and r_{5b} for TCP. Figure 7B is a table corresponding to the policy trie of Figure 7A. Once the rules are positioned based on their probabilities and their relation to other rules, the average number of rule comparisons is reduced to 2.98 (after sort, trie rotation, and splitting) which is a 30% less.

It many not be advantageous to split a general rule since it adds another rule to the policy. For example, assume a policy contains 20 rules where the first 19 rules have the same probability. Assume the last rule can be split and the new specific rule has a probability that is $\frac{3}{4}$ of the last rule. The impact of the probability of the last rule and the location of the new split rule, m, is depicted in Figures 8A and 8B. More particularly, Figure 8A is a graph illustrating the average number of comparisons for firewalls with and without rule splitting. Figure 8B is a graph illustrating average number of comparisons versus different locations of the new rule and probabilities. The average number of comparisons is reduced as the split rule is located closer to the first rule (surface decreases as m approaches one). Furthermore, splitting yields

better results when the general rule has a high probability. However as illustrated in Figure 8B, the closer the specific rule is to the location of the original rule the average number of comparisons increases, which is the penalty of adding one more rule to the policy.

The effect of splitting a single rule can be described mathematically as follows. Consider n rules where rule r_n can be split into rules $r_{n,l}$ and $r_{n,r}$ (whose union is the original rule). In addition, assume the split rule $r_{n,l}$ will be located at the mth position ($1 \leq m < n$), while rule $r_{n,r}$ will remain at the nth location. The goal is to determine the best location m, which yields a lower average number of comparisons as compared to the original rule set. This can be defined mathematically in the following formula.

$$\sum_{i=1}^{n} i \cdot p_i > \sum_{i=1}^{m-1} i \cdot p_i + m \cdot p_{n,l} + \sum_{i=m}^{n-1} (i+1) \cdot p_i + (n+1) \cdot p_{n,r}$$

The left side of the inequality is the average number of comparisons for the original rule set. The right hand side of the inequality is the average number of comparisons with the specific rule at location m. If it is assumed that the rules located between m and n have an equal probability (denoted as p) the previous equation can be solved for m.

$$m < \frac{n \cdot p - n \cdot p_n + (n+1) \cdot p_{n,r}}{p - p_{n,l}}$$

The new rule must be located between the first and m^{th}; however, its final location will depend on the relationship with the other rules (cannot be placed before any rule for which it is a superset). This result can be applied iteratively to multiple rules and repeatedly to the same rule.

Rule Optimization for QoS

In the preceding sections, optimizing the entire security policy has been discussed. However, it may be desirable to optimize the rules for a certain type of traffic, in order to reduce the average number of comparisons this traffic encounters. This can be done by organizing the policy trie via traffic

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classification, then optimizing the sub-tries. The result is an ordering where the rules for the most important traffic are tested first.

Network Firewall Optimization Using Rule Compression

Another method for network firewall optimization is referred to as rule compression. Given a security policy R, one objective in optimizing firewall performance is to reduce number of rules in the policy while maintaining the original integrity. A method for reducing the number of rules called *rule compression*, which combines and replaces two rules in the policy will now be described. Although compression does reduce the number of rules, it can only be done if the integrity of the original policy is maintained.

Consider two rules r_i and r_j in policy R, where r_i appears before r_j. The two rules can be compressed if and only if the following conditions are true

1. The two rules intersect, $r_i \cap r_j \neq \emptyset$ (an edge between r_i and r_j exists in the policy DAG) (Tuples that are proper subsets and supersets are considered. Compression may still occur if the rules do not intersect or are adjacent in the set space, the resulting rule may contain ranges.)
2. The action of r_i and r_j is the same.
3. Rule r_i is not dependent on any rule r_k that is directly or indirectly dependent on r_j (only one path from r_i to r_j exists in the policy DAG).

The result of compression is a new rule, $r_{i,j}$ whose tuples are the union of the corresponding tuples of rules r_i and r_j. The new rule $r_{i,j}$ replaces both r_i and r_j in R; however, the location of $r_{i,j}$ in R may require the relocation of other rules. Let D_j be the ordered set of rules that appear after r_i that directly or indirectly depend upon r_j. The new rule is placed at the original location of r_i in R and the rules D_j are placed before $r_{i,j}$.

For example, consider the policy given in Table 2. It is possible to compress rules r_1 and r_5, creating the new rule $r_{1,5}$ =[TCP, *, *, 2.*, *, accept]. The ordered set D_j in this example consists of the rules r_3 and r_4. As a result, the new rule $r_{1,5}$ is placed at the original location of r_1 while the rules in D_j are placed before the new rule. Figures 9A and 9B respectively illustrate the

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original policy DAG for Table 2 and the policy DAG after rules r_1 and r_5 are compressed.

No.	Proto.	Source IP	Source Port	Destination IP	Destination Port	Action
1	TCP	1.1.*	*	2.2.*	*	accept
2	TCP	1.*	*	*	80	deny
3	TCP	3.3.*	*	*	80	accept
4	TCP	3.*	*	*	*	deny
5	TCP	*	*	2.*	90	accept

Table 2: Example Policy Consisting of Multiple Ordered Rules

Theorem *Compressing rules r_i and r_j of policy R will maintain integrity if the three conditions are met and method described is used.*

Proof Before r_i and r_j are compressed, relocate the rules D_j immediately before r_i and D_i. This relocation will maintain integrity due to the third requirement for compression (no rule in D_i can be dependent on any rule in D_j). Now place r_j directly after r_i. This relocation will not affect integrity since no rule in D_i can have an edge to r_j (again, due to the third condition). Compressing the neighboring rules r_i and r_j creates $r_{i,j}$. This does not affect integrity since the resulting rule only matches the packets that match r_i or r_j in the original policy. Therefore, the result is the compression of rule r_i and r_j, and the integrity of the policy is maintained.

Determining if Compression Should Occur

Although compression may be possible, it may not improve the performance of the policy due to the relocation of rules. Compression should only occur if the average number of comparisons required for the new policy R_c is less than the original policy R; therefore, $E[R_c] < E[R]$.

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Firewall Rule Sub-Trie and Sub-List Ordering

Policy Sub-Trie Ordering

Additional methods for firewall optimization are referred to as firewall sub-trie and sub-list ordering. Given a policy trie T, it may be desirable to order all sub-tries such that the average number of tuple comparisons is reduced and policy integrity is maintained. Consider a policy trie T that contains sub-tries T_i and T_j having the same parent node, as seen in Figures 10A-10C. Let P_i denote the sum of the probabilities of the rules contained in sub-trie i, while C_i denotes the number of comparisons required to completely traverse sub-trie i (which is equal to the number of branches). In order to reduce the average number of tuple comparisons, sub-tries that share the same parent node should be ordered such that the following two conditions are observed.

1. Sub-tries that share a parent node are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-tries that share a parent node have the same probability (P_i equals P_j), then order the sub-tries such that the C_i values are non-descending (sub-tries consisting of fewer comparisons occur first, from left to right).

These conditions are recursively applied throughout the policy trie as seen in Figures 11A-11D. However, these conditions do not necessarily maintain policy integrity.

Consider a group of n sub-tries that share the same parent node that are numbered sequentially from left to right. Consider any two non-intersecting sub-tries T_i and T_{i+k} in this group that are out of order. If two sub-tries do not intersect, denoted as $T_i \pitchfork T_j$, then no rule in one sub-trie will intersect with any rule in the other sub-trie, $r_k \pitchfork r_l$, $\forall r_k \in T_i$, $\forall r_l \in T_j$. The following *integrity condition* must be observed when reordering the sub-tries. The two sub-tries can be exchanged (rotated about the parent) if and only the sub-tries T_i through T_{i+k-1} do not intersect with T_{i+k} and the sub-tries T_{i+1} through T_{i+k} do not intersect with T_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. This is observed in Figure 10A,

where no edge exists between any rule in T_1 and T_2. More particularly, Figure 10A is a policy DAG of a six-rule firewall list. Figure 10B is a policy trie representation of the firewall rule list represented by Figure 10A. In Figure 10B, the average number of tuple compares required per packet is 5.5. Figure 10C illustrates the policy trie after rotating sub-tries T_1 and T_2. In Figure 10C, the average number of tuple compares required is 4.5. In Figures 10A-10C, the following probabilities are assumed:

$P_1 = 0.5$

$C_1 = 4$

$P_2 = 0.5$; and

$C_2 = 2$.

The average number of tuple comparisons is an estimate based on the longest trie path.

Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-tries that share the same parent node.

```
m = a parent node in T
done = false
while(!done)
    done = true
    for each sub-trie Ti having parent m AND a right neighboring sub-trie
        if((Pi < Pi+1 AND (Pi == Pi+1 AND Ci > Ci+1)) AND Ti ⋔ Ti+1) then
        interchange Ti and Ti+1
        done = false
        endif
    endfor
endwhile
```

Figures 11A-11D illustrate policy trie rotation for an eight-rule firewall policy. More particularly, Figure 11A illustrates the policy DAG representation of an eight-rule firewall policy. Figure 11B is a policy trie representation of the original firewall policy. In this example, ordering occurs in three stages, starting at the bottom level and moving towards the top level of the trie. In Figure 11C, the leaves are ordered at the lowest level. More particularly, nodes r_1 and r_2 are exchanged with nodes r_7 and r_8. The average number of tuple compares for the ordering represented by Figure 11C is 10.45. In Figure 11D, the sub-

tries on the second lowest level (T_3, T_4, T_5, and T_6) are ordered. More particularly, Figure 11D illustrates the policy trie after exchanging sub-tries T_3 and T_4. The average number of tuple compares for the representation in Figure 11D is 10.275. In Figure 11E, the sub-tries on the second highest level, (T_1 and T_2) are ordered. Figure 11E illustrates the final ordering after exchanging T_1 and T_2. In the policy trie of Figure 11E, the average number of tuple compares required is 6.775. The average number of tuple comparisons is an estimate based on the longest trie path.

Policy Sub-List Ordering

The preceding section describes conditions for sorting policy sub-tries, which allow the exchange of groups of rules (sub-tries). The same conditions can be applied to list based policies, where sub-lists are ordered to improve the average number of rule comparisons.

In the sections above relating to rule sorting, a method is described to exchange neighboring rules in a list-based security policy, as seen in Figure 12B. However, it was observed that when ordering rules in this fashion it is possible that one rule can block the exchange of another. If groups of rules were allowed to be exchanged the average number of rule comparisons could be further reduced.

Given a policy list L, it may be desirable to order all sub-lists such that the average number of rule comparisons is reduced and policy integrity is maintained. Consider a policy list L that contains sub-tries L_i and L_j. Let P_i denote the sum of the probabilities of the rules contained in sub-list i, while C_i denotes the number of rules in sub-list i. In order to reduce the average number of rule comparisons, sub-lists should be ordered such that the following two conditions are observed.

1. Sub-lists are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-lists have the same probability (P_i equals P_j), then order the sub-lists such that the C_i values are non-descending (sub-lists consisting of fewer comparisons occur first, from left to right).

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These conditions are applied throughout the policy list; however as with policy tries, these conditions do not necessarily maintain policy integrity.

Consider a group of n sub-lists that are numbered sequentially from left to right. Consider any two non-intersecting sub-lists L_i and L_{i+k} in this group that are out of order. If two sub-lists do not intersect, denoted as $L_i \pitchfork L_j$, then no rule in one sub-list will intersect with any rule in the other sub-list, $r_k \pitchfork r_l$, $\forall r_k \in L_i$, $\forall r_l \in L_j$. The following *integrity condition* must be observed when reordering the sub-lists. The two sub-lists can be exchanged if and only if the sub-lists L_i through L_{i+k-1} do not intersect with any rule in L_{i+k} and sub-lists L_{i+1} through L_{i+k} do not intersect with L_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. For example, consider the sub-lists $L_1 = \{r_1, r_3\}$ and $L_2 = \{r_2, r_4\}$ given in Figure 12B. No edge exists between any rule in L_1 and L_2. The two sub-lists are out of order with respect to P and should be exchanged. The resulting list is given in Figure 12C. Figure 12A illustrates the original policy order and results in an average number of rule comparisons of 3.4. In the sorted version in Figure 12B, the average number of rule comparisons is 3.3. In Figure 12C, the average number of rule comparisons has been reduced to 2.7. Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-lists.

```
done = false
while(!done)
    done = true
    for each sub-list Li having a right neighboring sub-list
        if ((Pi < Pi+1 OR (Pi == Pi+1 AND Ci > Ci+1)) AND Li ⋔ Li+1)then
            interchange rules and probabilities
            done = false
        endif
    endfor
endwhile
```

Summary of Firewall Policy Optimization Techniques and Methods

As stated above, the methods and systems described herein for a network firewall policy optimization can be implemented using any combination of hardware, software, and/or firmware. Alternatively, the steps for firewall policy optimization can be performed manually with the number of rules being optimized is small enough. Figure 13 is a flow chart illustrating an exemplary process for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 13, in block **1300**, a firewall policy including an ordered list of firewall rules is defined. In block **1302**, for each rule, a probability indicating a likelihood of receiving a packet that matches each rule is specified. In block **1304**, neighboring rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. In block **1306**, groups of rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. For example, any of the policy-trie-based methods described above may be used. In block **1308**, one or more rules are split to reduce the number of average packet comparisons. In block **1310**, intersecting rules having common actions are identified and collapsed into single rules.

As described above, the subject matter described herein may be implemented in hardware, software, and/or firmware. In one implementation, the subject matter described herein for firewall policy optimization may be implemented on a general purpose computing platform. Figure 14 is a block diagram of a general purpose computing platform including software for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 14, computing platform **1400** may be a general purpose computer, such as a personal computer, that includes a microprocessor **1402**, memory **1404**, and I/O interfaces **1406**. Microprocessor **1400** may be any suitable microprocessor, such as any of the Intel or AMD families of microprocessors. Memory **1404** may include volatile memory for running programs and persistent memory, such as one or more disk storage devices. I/O interface **1406** may include interfaces with I/O devices, such as user input devices and output devices.

In the illustrated example, software that may be resident in memory **1404** includes a firewall policy editor **1408** and a firewall policy optimizer **1410**. Firewall policy editor **1408** may allow a user to define a firewall policy. For example, firewall policy editor **1408** may allow a user to define a firewall policy by specifying different rules. The rules may be specified in a graphical manner, for example using policy DAGs as described above. Alternatively, firewall policy editor **1408** may allow a user to input rules in a tabular manner, as illustrated in any of the tables described herein. Firewall policy optimizer **1410** may implement any or all of the firewall policy optimization techniques to order rules entered via firewall policy editor **1408** in a manner that preserves policy integrity and that enhances firewall performance.

A firewall rule set that is optimized using the subject matter described herein may be implemented on any firewall system that includes one or more firewalls. For example, an optimized firewall rule set according to embodiments of the subject matter described herein may be implemented using any of the hierarchical, multi-node firewall systems described in commonly assigned, co-pending U.S. patent application no. 11/316,331, filed December 22, 2005, the disclosure of which is incorporated herein by reference in its entirety. Figure 15 illustrates an example of a multi-node firewall system suitable for implementing the firewall rules according to an embodiment of the subject matter described herein. Referring to Figure 15, a plurality of firewall nodes **1500**, **1502**, **1504**,and **1506** may collectively implement any of the optimized firewall policies described herein. For example, the firewall nodes may collectively implement different portions of a firewall policy data structure including an ordered list of firewall rules. A firewall policy engine **1508** resident on each firewall node may filter packets using its local portion **1510** of the firewall policy data structure. A control node **1512** may include a firewall policy optimizer **1514** that measures the average number of comparisons per packets for the current rule configuration and may dynamically reorder the rules to reduce the average number of comparisons per packet. For example, firewall policy optimizer **1514** may utilize any of the methods described herein to rearrange rules and improve firewall performance. Rules may be tested for rearrangement at user-specified

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intervals or when average number of packet comparisons increases by a user-specified amount.

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The disclosure of each of the following references is hereby incorporated herein by reference in its entirety.

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It will be understood that various details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

CLAIMS

What is claimed is:

1. A computer-implemented method for producing a performance optimized firewall policy, the method comprising:

(a) defining a firewall policy including an ordered list of firewall rules;

(b) for each rule, defining a probability indicating the likelihood of receiving a packet matching each rule;

(c) sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy; and

(d) sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy.

2. The method of claim 1, wherein sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes, for each pair of neighboring rules, rearranging the rules if a first rule of the pair has a lower probability than a second rule of the pair and the first rule of the pair is not a subset of the second rule of the pair with a different action.

3. The method of claim 1, wherein sorting groups of two or more rules in a manner that preserves firewall policy includes assigning each group of rules to a sub-trie in a policy trie, computing a sum of packet matching probabilities for rules in each sub-trie, and, in response to determining that a first sub-trie has a lower sum than a second sub-trie, rotating the first and second sub-tries about a common parent so that rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

4. The method of claim 3, comprising, in response to determining that the first and second sub-tries have equal sums, determining whether the second sub-trie has a lower number of branches than the first sub-trie, and, in response to determining that the second sub-trie has a lower number of branches than the first sub-trie, rotating

the first and second sub-tries about a common parent so that the rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

5. The method of claim 1, wherein sorting groups of two or more rules in a manner that preserves the firewall policy includes:

(a) identifying first and second sub-lists of rules in the ordered list of firewall rules, the first sub-list preceding the second sub-list in the ordered list of firewall rules;

(b) determining a sum of packet matching probabilities for each of the first and second sub-lists;

(c) determining whether the first and second sub-lists intersect; and

(d) in response to determining that the sum of the packet matching probabilities for the second sub-list is greater than the sum of the packet matching probabilities for the first sub-list and that the first and second sub-lists do not intersect, switching the order of the first and second sub-lists in the ordered list of firewall rules.

6. The method of claim 5, comprising, in response to determining that the sums of the packet matching probabilities for the first and sub-lists are equal, determining whether the second sub-list has a lower number of rules than the first sub-list, and, in response to determining that the second sub-list has a lower number of rules than the first sub-list, switching the order of the first and second sub-lists in the ordered list of firewall rules.

7. The method of claim 1, comprising splitting at least one of the firewall rules to reduce an average number of comparisons required per received packet.

8. The method of claim 1, comprising identifying intersecting rules having a common action and collapsing the rules into a single rule representing a union of the intersecting rules.

9. The method of claim 1, wherein sorting neighboring rules includes sorting rules such that comparisons for a particular class of packets are reduced.

10. The method of claim 1, comprising assigning the rules to vertices in a directed acyclical graph (DAG). determining precedence relationships between the rules,

assigning the precedence relationships to edges that connect the vertices in the DAG, and wherein sorting the neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes sorting the neighboring rules in a manner that preserves the precedence relationships represented by the DAG.

11. The method of claim 1, wherein the rules comprise intrusion detection rules.

12. The method of claim 1, wherein the rules comprise intrusion protection rules.

13. A system for firewall policy optimization, for implementing the steps of any one of claims 1-12.

14. A network firewall comprising:

(a) a firewall policy data structure for storing an ordered list of firewall rules;

(b) a firewall policy engine for implementing a firewall policy by comparing packets to the rules in the order specified by the firewall policy data structure; and

(c) a firewall policy optimizer for optimizing performance of the network firewall by reordering the rules in a manner that reduces an average number of rule comparisons per packet and that preserves the firewall policy, the firewall policy optimizer sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy.

15. The network firewall of claim 14, wherein the firewall policy optimizer is adapted to measure average number of comparisons per packet for a rule ordering specified by the firewall policy data structure and to dynamically re-order to rules to reduce the average number of comparisons per packet

16. A computer program product comprising computer executable instructions embodied in a computer readable medium for performing steps comprising:

(a) defining a firewall policy including an ordered list of firewall rules;

(b) for each rule, defining a probability indicating the likelihood of receiving a packet matching each rule;

(c) sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy; and

(d) sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy.

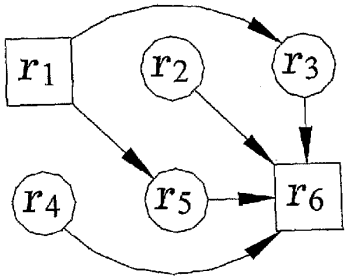


FIG. 1A

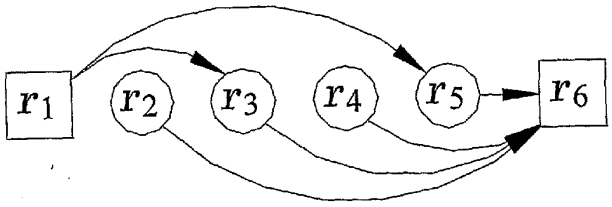


FIG. 1B

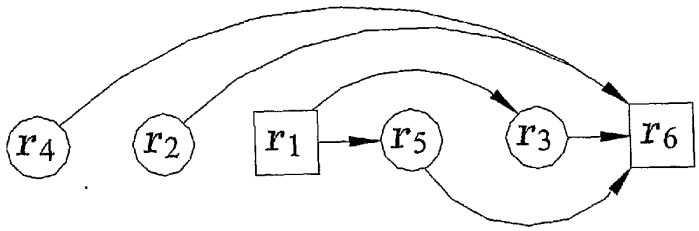


FIG. 2A

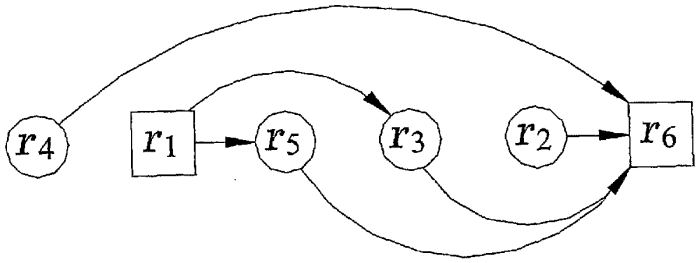


FIG. 2B

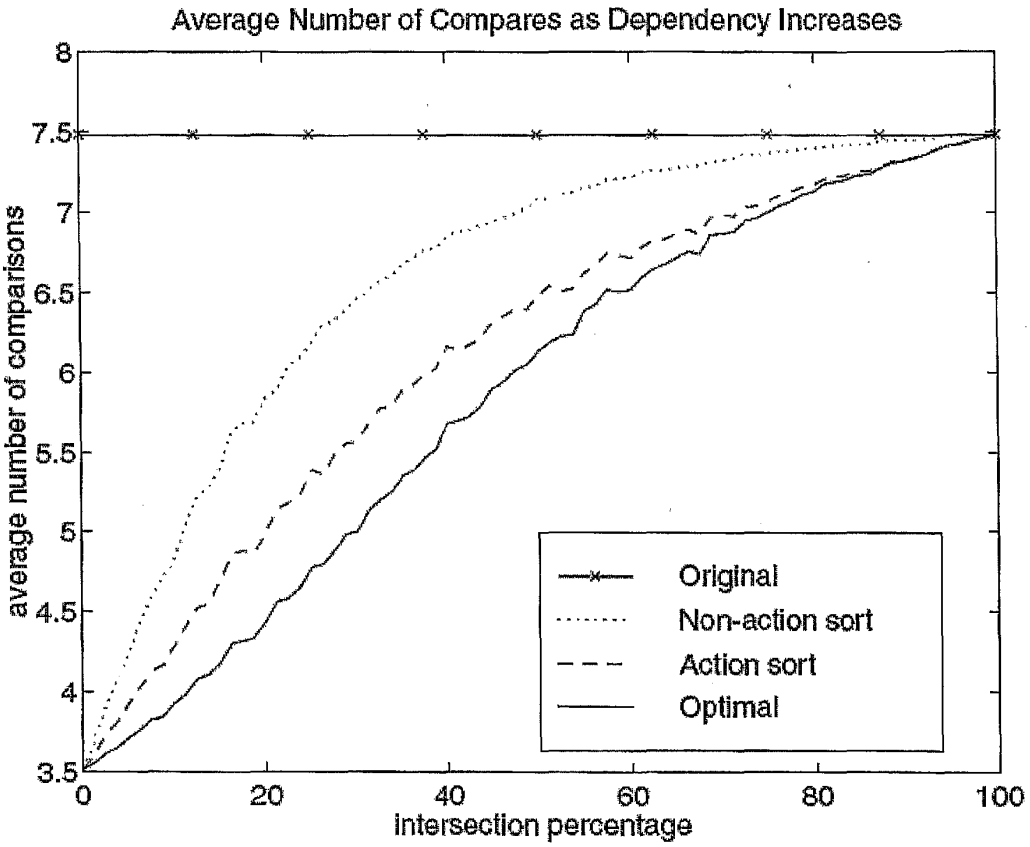

Average Number of Compares as Dependency Increases
average number of comparisons
intersection percentage
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
0
20
40
60
80
100
Original
Non-action sort
Action sort
Optimal

FIG. 3A

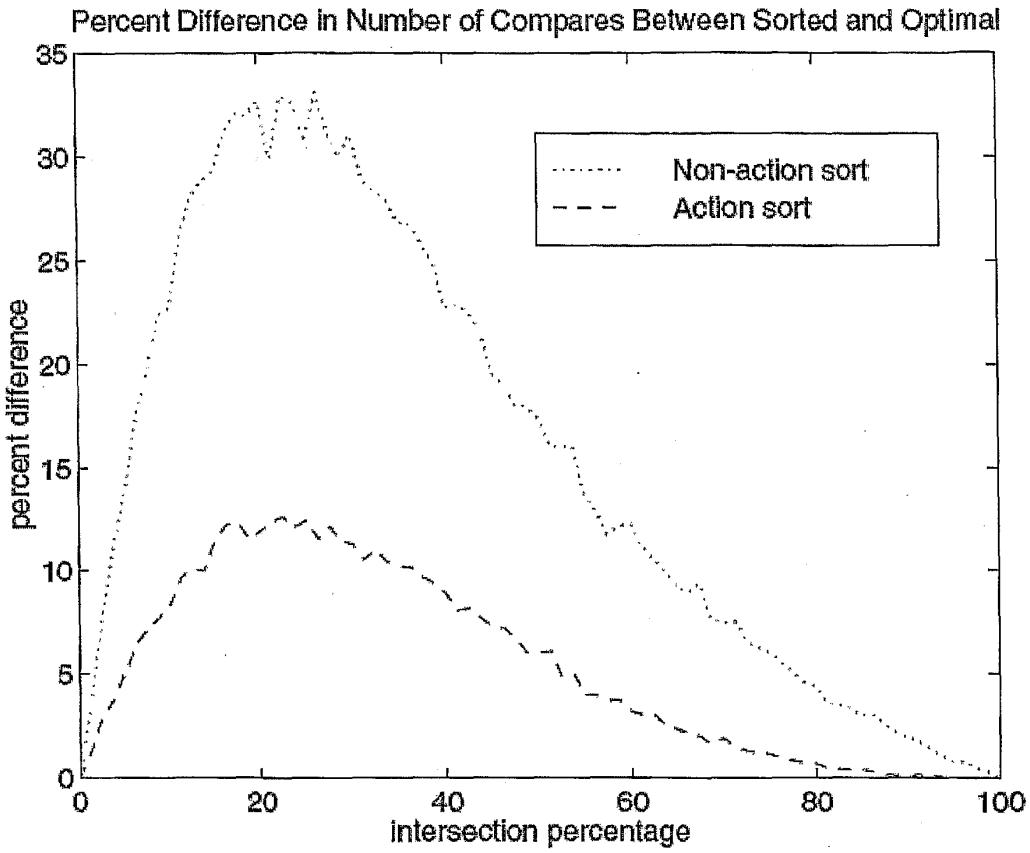

Percent Difference in Number of Compares Between Sorted and Optimal
percent difference
intersection percentage
Non-action sort
Action sort
0
5
10
15
20
25
30
35
0
20
40
60
80
100

FIG. 3B

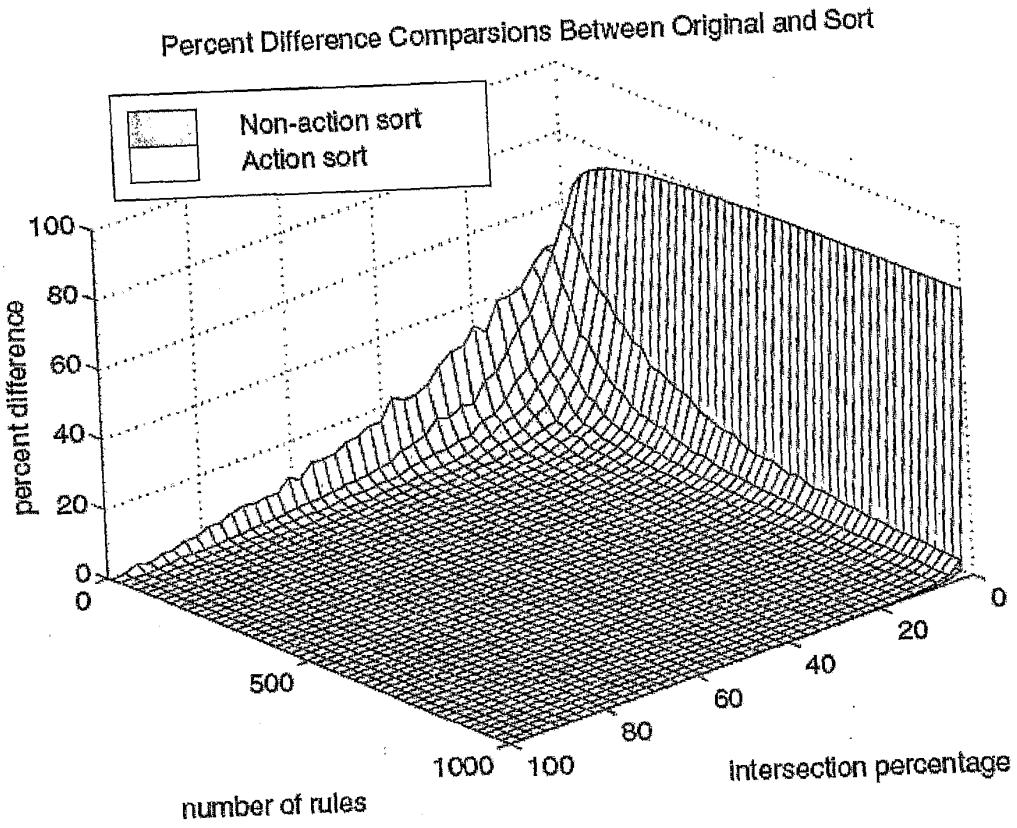

Percent Difference Comparsions Between Original and Sort
Non-action sort
Action sort
percent difference
100
80
60
40
20
0
0
500
1000
number of rules
0
20
40
60
80
100
intersection percentage

FIG. 4A

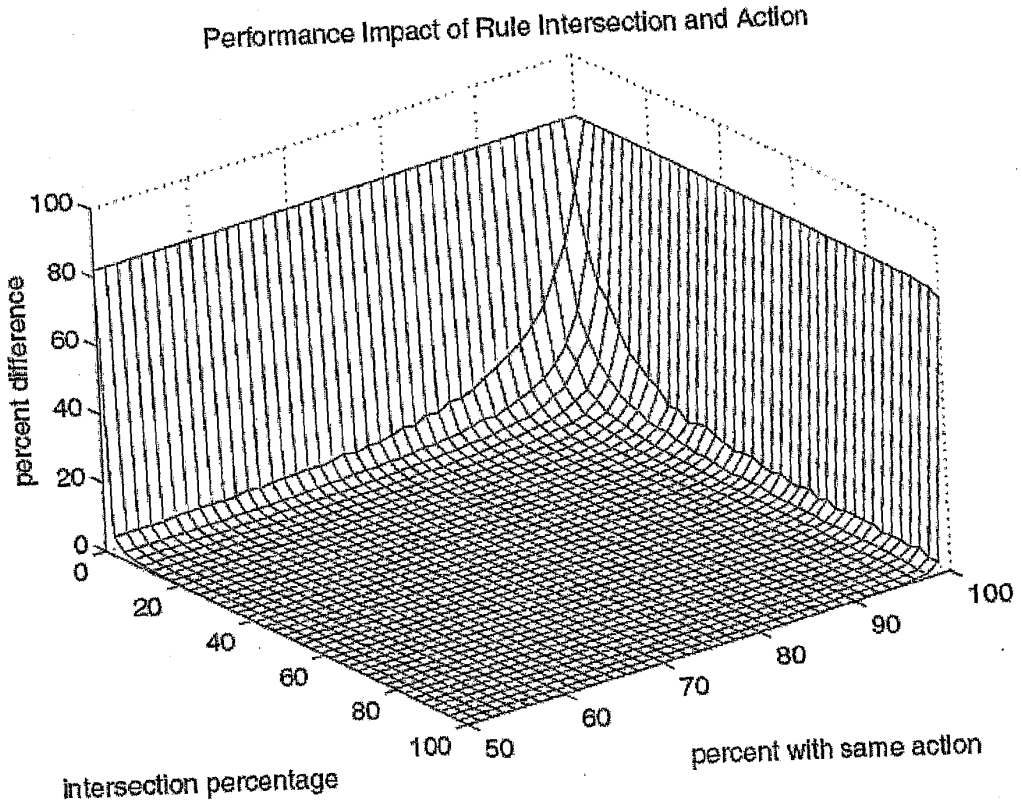

Performance Impact of Rule Intersection and Action
percent difference
0
20
40
60
80
100
intersection percentage
0
20
40
60
80
100
percent with same action
50
60
70
80
90
100

FIG. 4B

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5A

r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5B

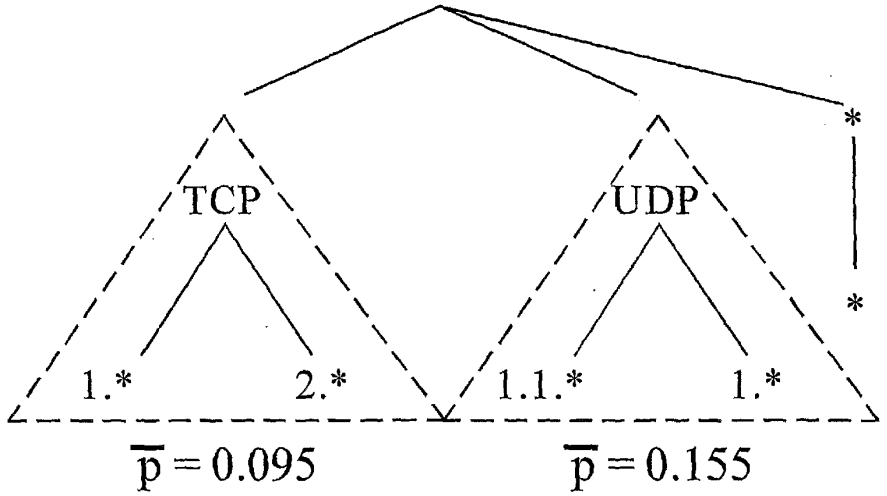


FIG. 6A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 6B

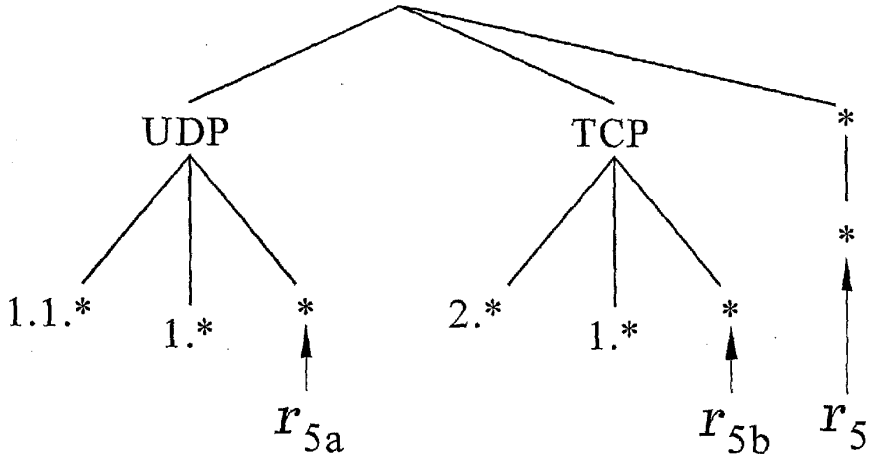


FIG. 7A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	ACCEPT)	$p_4 = 0.30$
r_{5a}	(UDP,	*,	DENY)	$p_{5a} = 0.47$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_{5b}	(TCP,	*,	DENY)	$p_{5b} = 0.03$

FIG. 7B

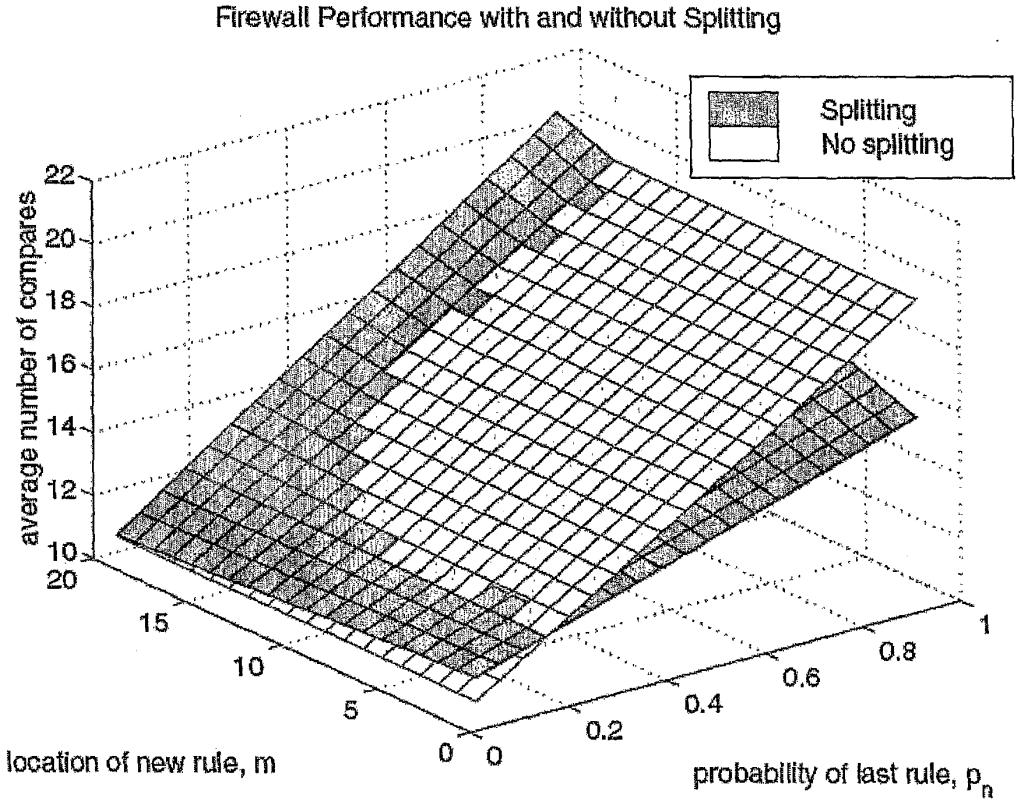

Firewall Performance with and without Splitting
Splitting
No splitting
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8A

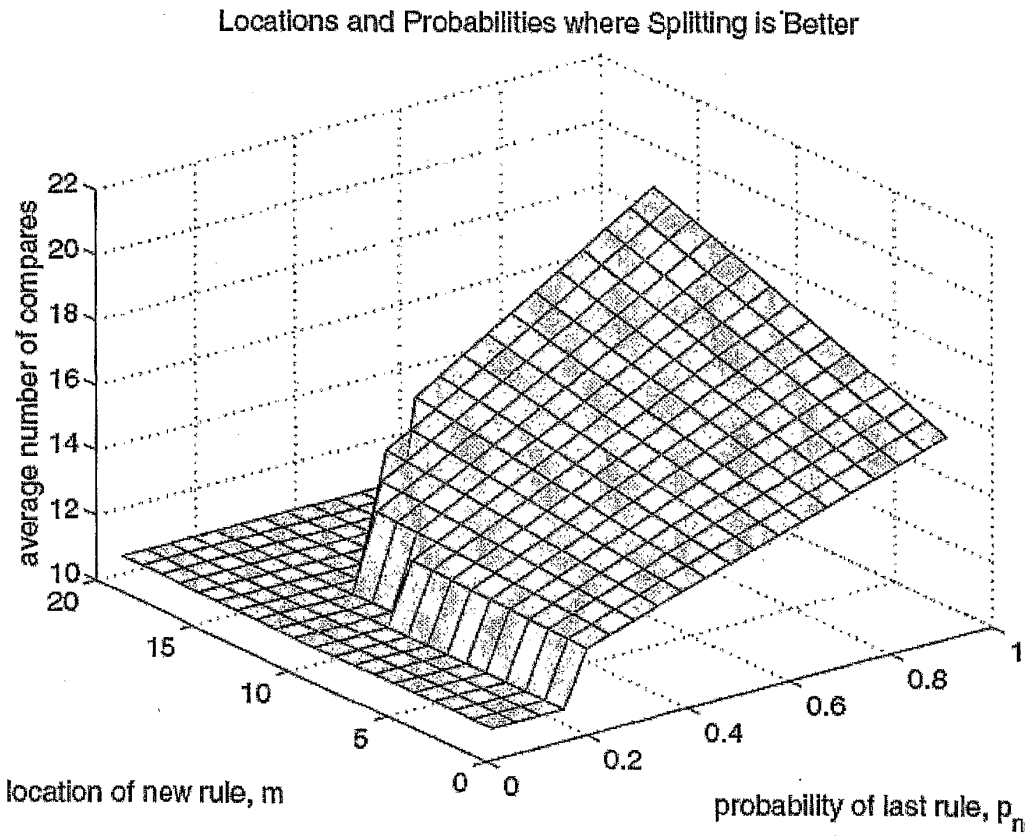

Locations and Probabilities where Splitting is Better
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8B

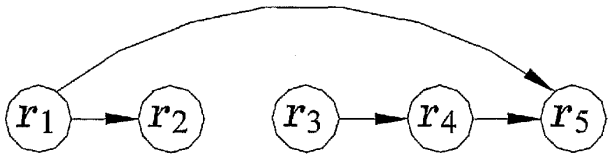


FIG. 9A

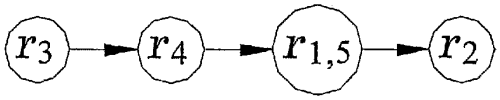


FIG. 9B

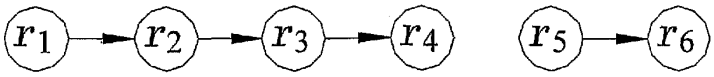


FIG. 10A

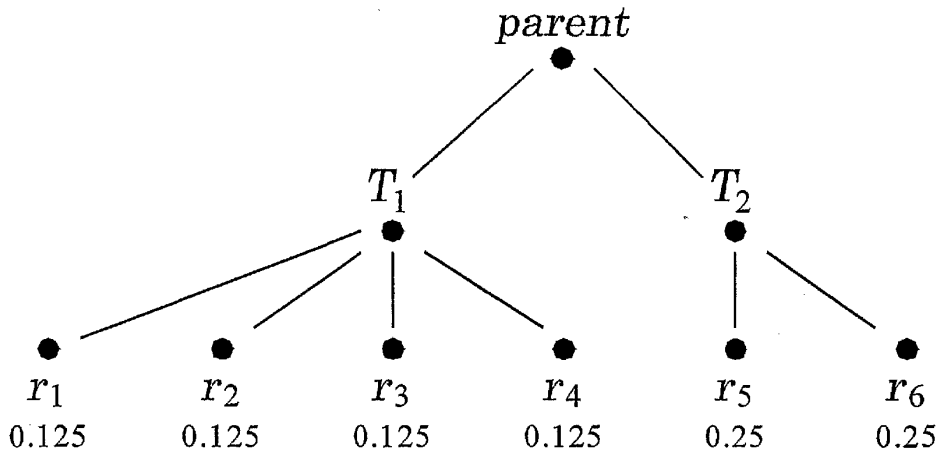


FIG. 10B

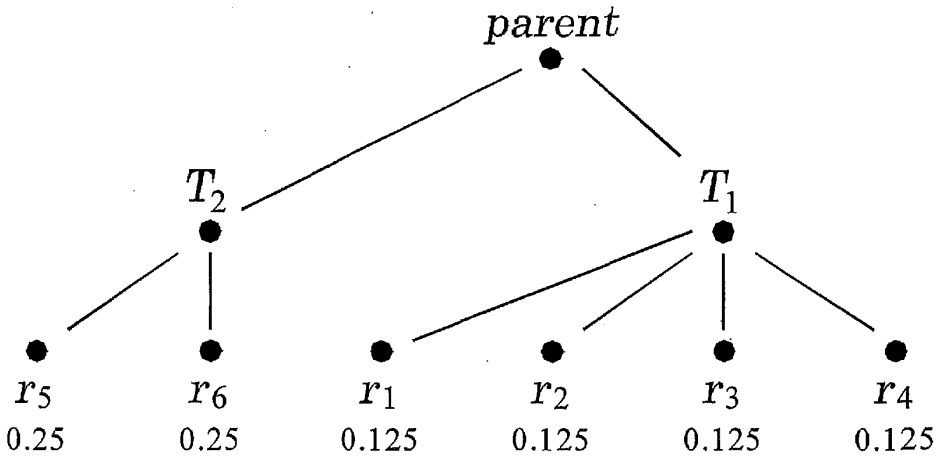


FIG. 10C

FIG. 11A

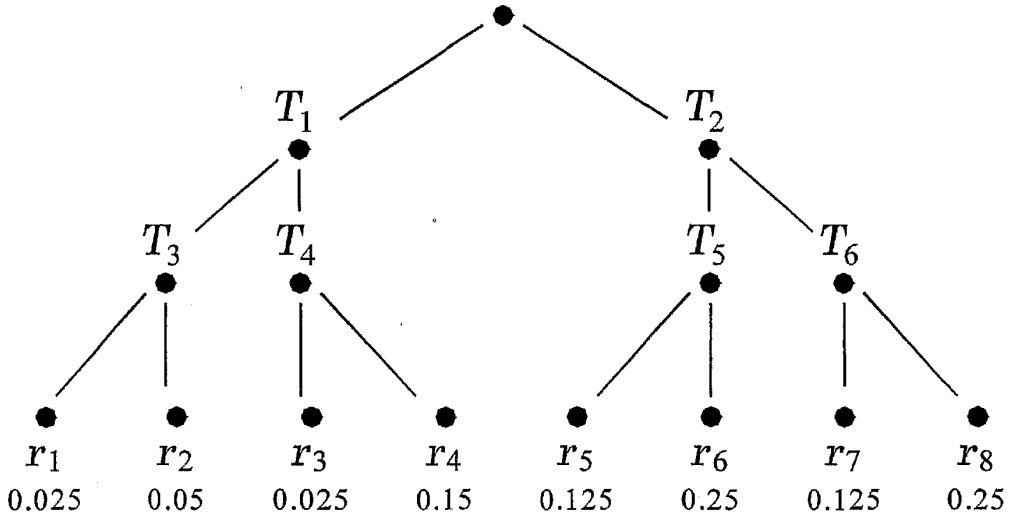


FIG. 11B

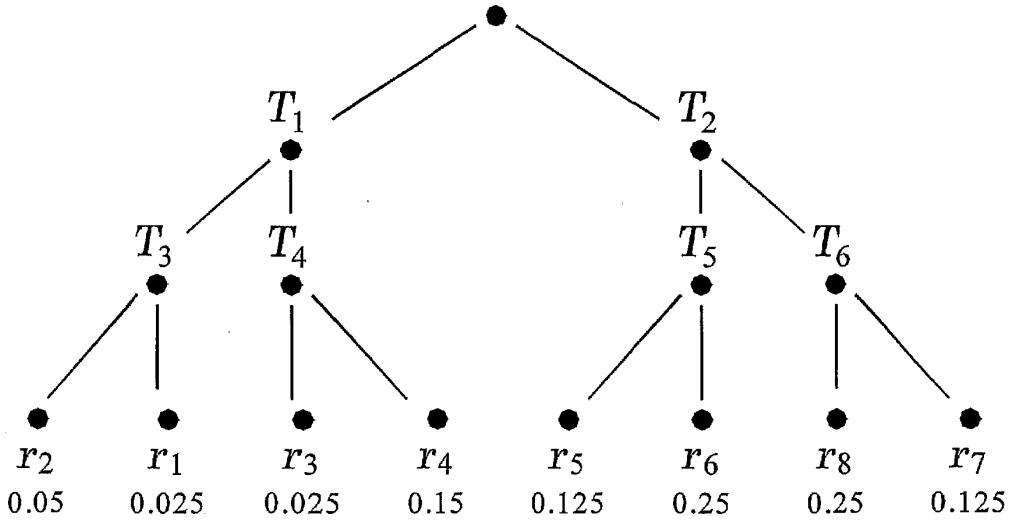


FIG. 11C

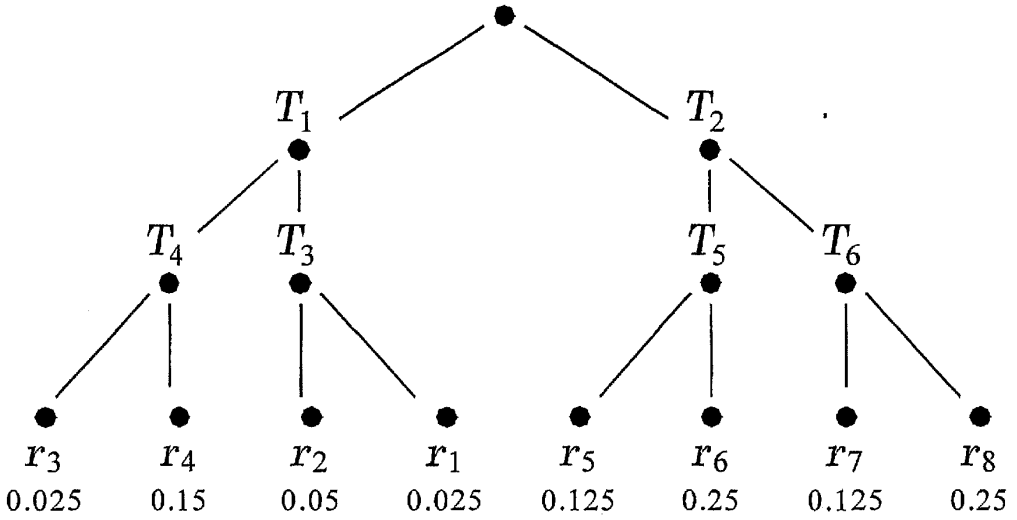


FIG. 11D

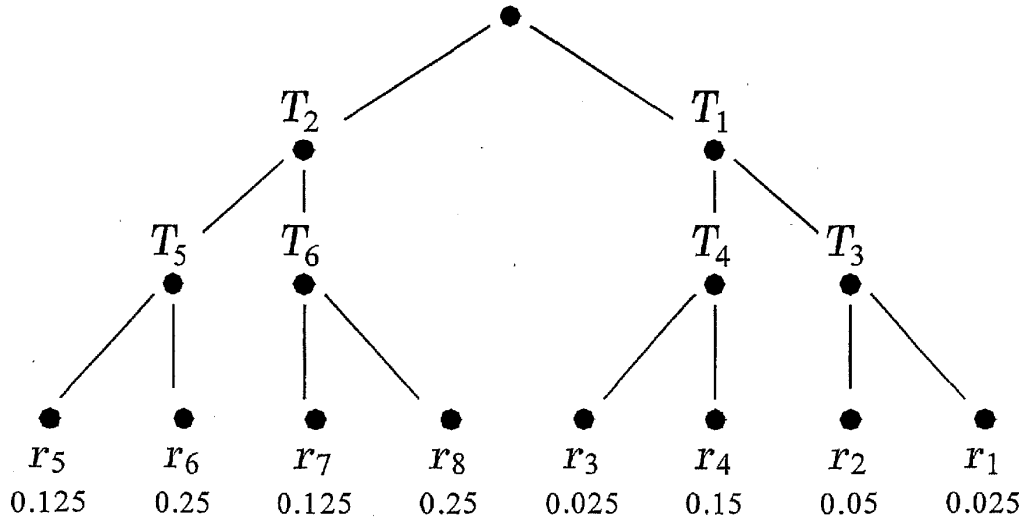


FIG. 11E

16/19

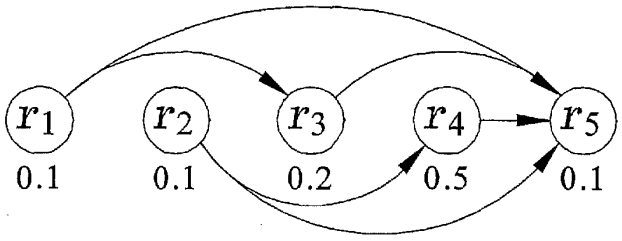


FIG. 12A

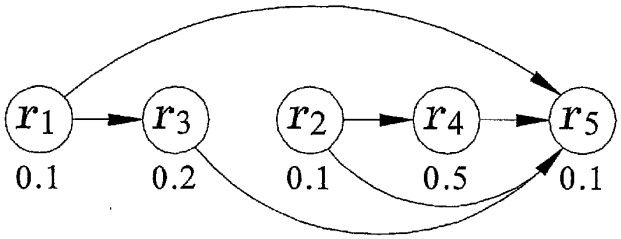


FIG. 12B

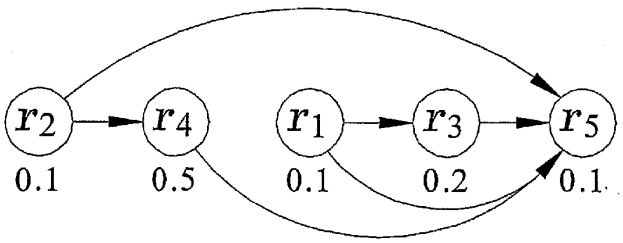


FIG. 12C

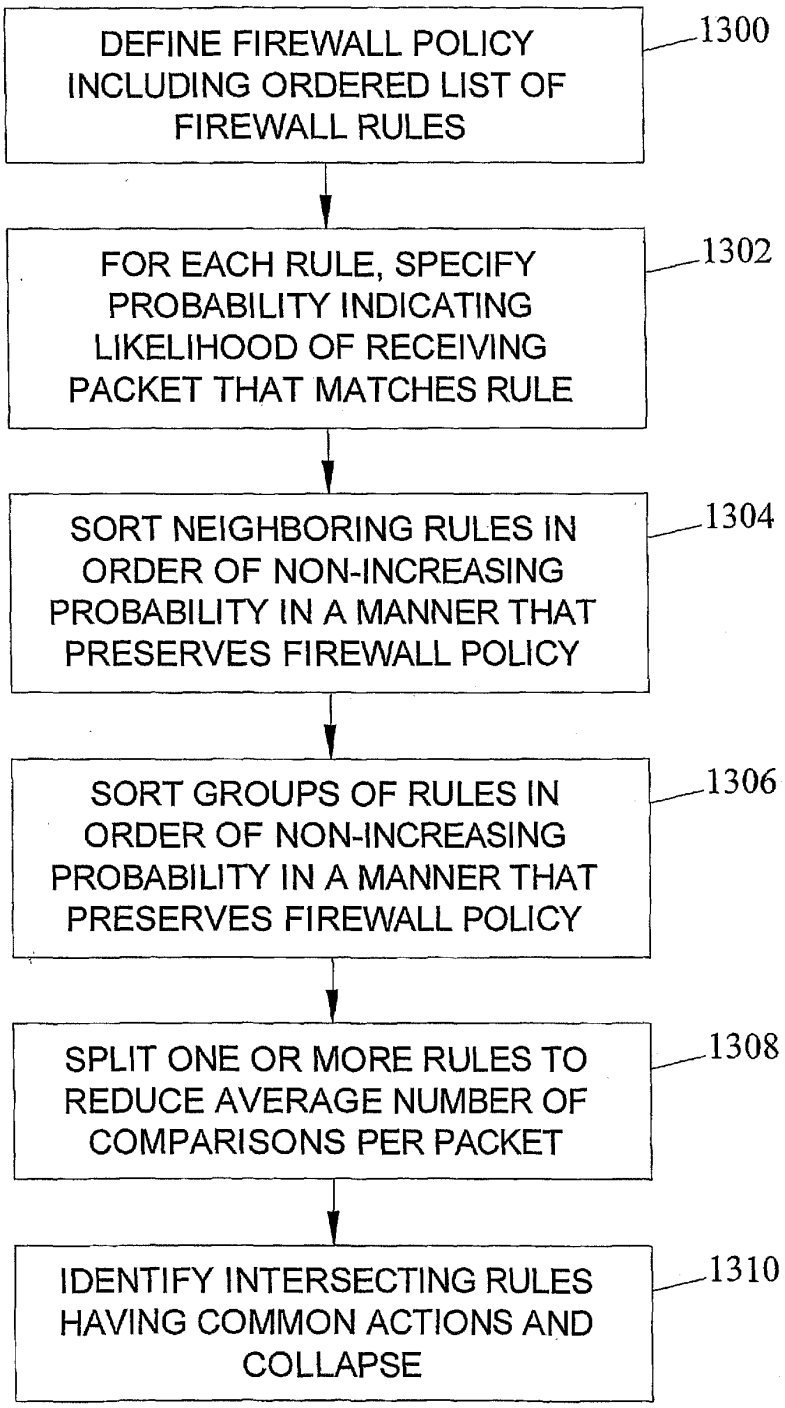

DEFINE FIREWALL POLICY INCLUDING ORDERED LIST OF FIREWALL RULES
1300
FOR EACH RULE, SPECIFY PROBABILITY INDICATING LIKELIHOOD OF RECEIVING PACKET THAT MATCHES RULE
1302
SORT NEIGHBORING RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1304
SORT GROUPS OF RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1306
SPLIT ONE OR MORE RULES TO REDUCE AVERAGE NUMBER OF COMPARISONS PER PACKET
1308
IDENTIFY INTERSECTING RULES HAVING COMMON ACTIONS AND COLLAPSE
1310

FIG. 13

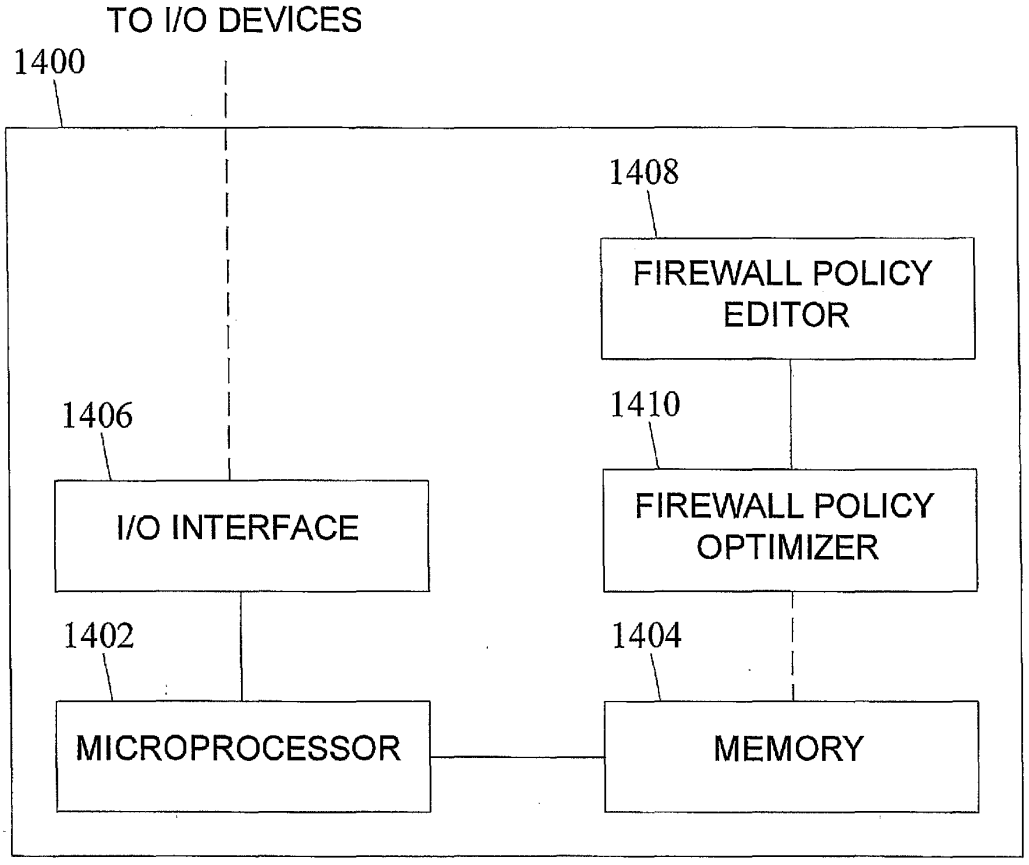

TO I/O DEVICES
1400
1408
FIREWALL POLICY EDITOR
1406
1410
I/O INTERFACE
FIREWALL POLICY OPTIMIZER
1402
1404
MICROPROCESSOR
MEMORY

FIG. 14

19/19

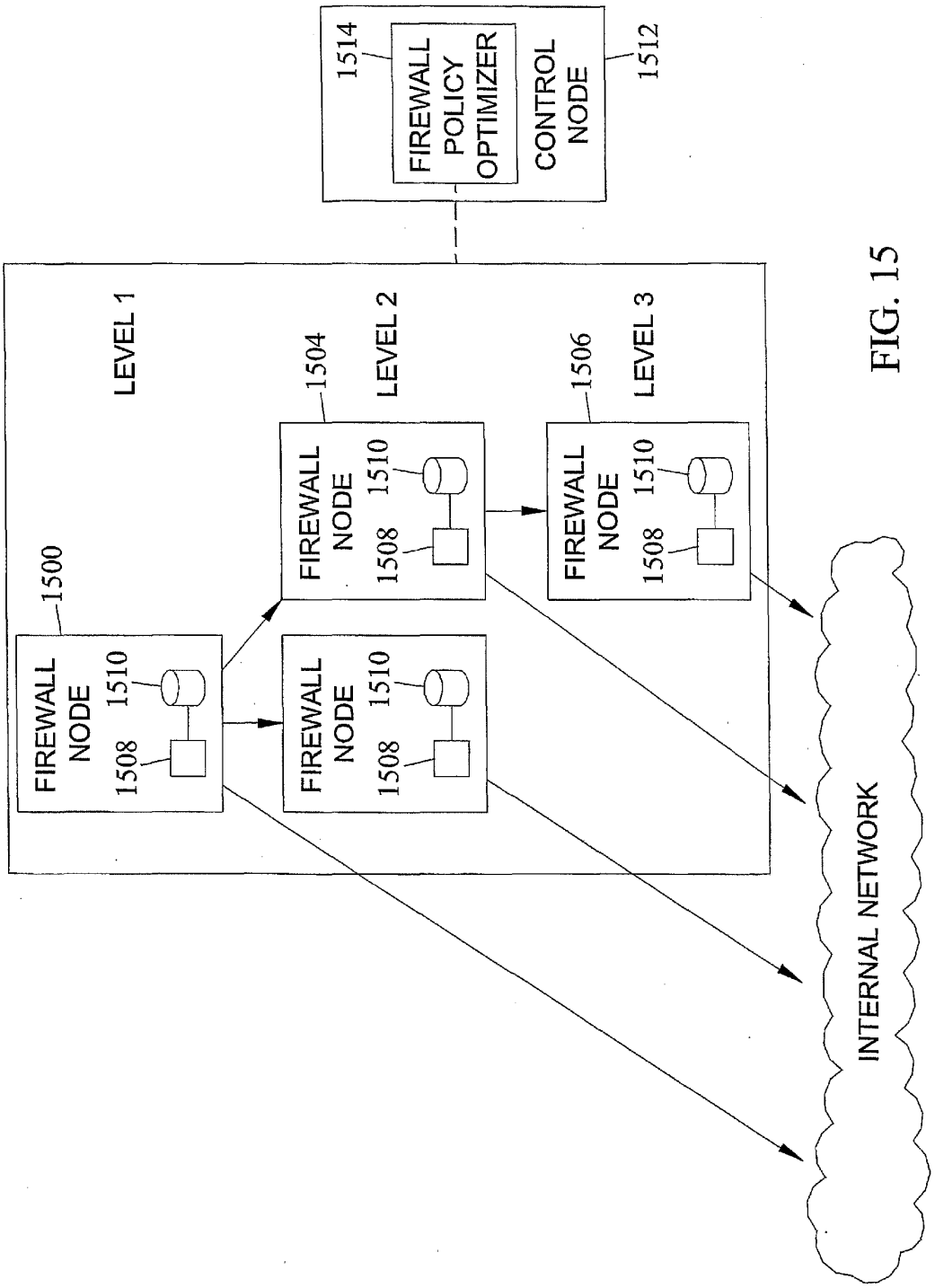

1514
FIREWALL POLICY OPTIMIZER
CONTROL NODE
1512
LEVEL 1
LEVEL 2
LEVEL 3
1500
1504
1506
FIREWALL NODE
1508
1510
INTERNAL NETWORK

FIG. 15

Espacenet

Bibliographic data: WO2012146265 (A1) — 2012-11-01

CORRELATION OF MEDIA PLANE AND SIGNALING PLANE OF MEDIA SERVICES IN A PACKET-SWITCHED NETWORK

Inventor(s): SCHOLZ HENDRIK [DE]; WALLBAUM MICHAEL [DE]; KRUEGER MICHAEL [DE]; BASTIAN JAN [DE] ± (SCHOLZ, HENDRIK, ; WALLBAUM, MICHAEL, ; KRUEGER, MICHAEL, ; BASTIAN, JAN)

Applicant(s): VOIPFUTURE GMBH [DE]; SCHOLZ HENDRIK [DE]; WALLBAUM MICHAEL [DE]; KRUEGER MICHAEL [DE]; BASTIAN JAN [DE] ± (VOIPFUTURE GMBH, ; SCHOLZ, HENDRIK, ; WALLBAUM, MICHAEL, ; KRUEGER, MICHAEL, ; BASTIAN, JAN)

Classification: **- international:** ***H04L12/24; H04L29/06;*** *H04L12/26*
- cooperative: **H04L41/5032**; **H04L43/062**; **H04L43/12**; **H04L65/1006**; **H04L65/1009**; **H04L65/1069**; **H04L65/607**; **H04L65/80**

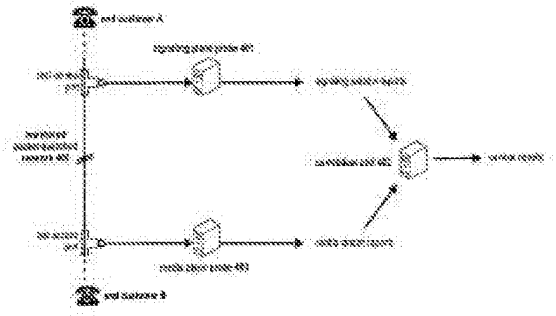
Application number: WO2011EP02145 20110428

Priority number(s): WO2011EP02145 20110428

Also published as: US2014089504 (A1) EP2702740 (A1) CA2834168 (A1)

Abstract of WO2012146265 (A1)

This invention relates to methods for correlating media streams and signaling sessions of services, for example, in a passive monitoring system of a packet-switched network. Furthermore, the invention also relates to an implementation of these methods in hardware and software, and provides a signaling plane probe, a media plane probe and a correlation unit. Moreover, a passive monitoring system comprising one or more of these hardware devices is provided. To correlate media streams and



signaling sessions of services, the invention proposes to independently generate correlation keys in a media plane probe for monitored media streams and correlation keys for signaling sessions that are monitored by a signaling plane probe in a fashion that matching correlation keys are generated for a respective service. By identifying reports on the media streams and reports on the signaling session that contain matching correlation keys respectively, the media streams and the signaling streams are correlated in a correlation unit.

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H04L 12/24 (2006.01)

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(71) Applicant *(for all designated States except US)*: **VOIPFUTURE GMBH** [DE/DE]; Wendenstrasse 4, 20097 Hamburg (DE).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **SCHOLZ, Hendrik** [DE/DE]; C/o Voipfuture Gmbh, Wendenstrasse 4, 20097 Hamburg (DE). **WALLBAUM, Michael** [DE/DE]; C/o Voipfuture Gmbh, Wendenstrasse 4, 20097 Hamburg (DE). **KRUEGER, Michael** [DE/DE]; C/o Voipfuture Gmbh, Wendenstrasse 4, 20097 Hamburg (DE). **BASTIAN, Jan** [DE/DE]; C/o Voipfuture Gmbh, Wendenstrasse 4, 20097 Hamburg (DE).

(74) Agent: **BOEHMERT & BOEHMERT**; Felix Hermann, Hollerallee 32, 28209 Bremen (DE).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
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(54) **Title**: CORRELATION OF MEDIA PLANE AND SIGNALING PLANE OF MEDIA SERVICES IN A PACKET-SWITCHED NETWORK

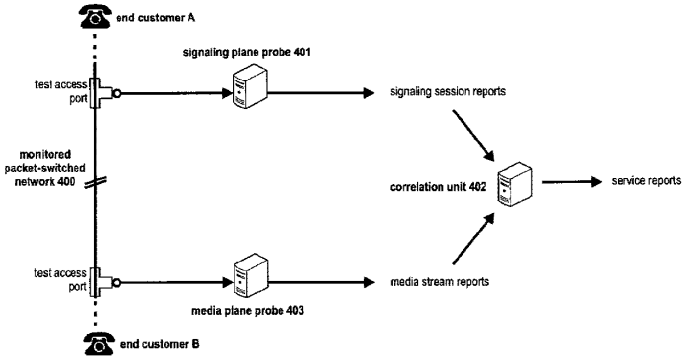


Fig. 4

(57) **Abstract**: This invention relates to methods for correlating media streams and signaling sessions of services, for example, in a passive monitoring system of a packet-switched network. Furthermore, the invention also relates to an implementation of these methods in hardware and software, and provides a signaling plane probe, a media plane probe and a correlation unit. Moreover, a passive monitoring system comprising one or more of these hardware devices is provided. To correlate media streams and signaling sessions of services, the invention proposes to independently generate correlation keys in a media plane probe for monitored media streams and correlation keys for signaling sessions that are monitored by a signaling plane probe in a fashion that matching correlation keys are generated for a respective service. By identifying reports on the media streams and reports on the signaling session that contain matching correlation keys respectively, the media streams and the signaling streams are correlated in a correlation unit.

WO 2012/146265 A1

Correlation of Media Plane and Signaling Plane of Media Services in a Packet-Switched Network

FIELD OF THE INVENTION

This invention relates to methods for correlating media streams and signaling sessions of services, for example, in a passive monitoring system of a packet-switched network. Furthermore, the invention also relates to an implementation of these methods in hardware and software, and provides a signaling plane probe, a media plane probe and a correlation unit. Moreover, a passive monitoring system comprising one or more of these hardware devices is provided.

TECHNICAL BACKGROUND

VoIP Services

VoIP ("Voice over IP" – IP denoting the Internet Protocol) services may be considered to consist of a signaling plane and a media plane. On the signaling plane various protocols describe the session (call) flow in terms of involved parties, intermediary VoIP entities (i.e. VoIP proxies, routers) and the characteristics of the VoIP service (call).The media plane typically carries the media information (i.e. audio and/or video data) between the involved parties. Neither the media plane nor the signaling plane alone is sufficient to carry a VoIP service. On the signaling plane protocols like SIP (see IETF RFC 3261, "SIP: Session Initiation Protocol", available at http://www.ietf.org) or ITU-T recommendation H.323 (see H.323, "Packet-based multimedia communications systems", Edition 7, 2009, available at http://www.itu.int) are commonly used, whereas protocols like RTP (Real-time Transport Protocol, see IETF RFC 3550, "RTP: A Transport Protocol for Real-Time Applications", available at http://www.ietf.org), MSRP (see IETF RFC 4975, "The Message Session Relay Protocol (MSRP)", available at http://www.ietf.org) or ITU recommendation T.38 (see T.38, "Procedures for real-time Group 3 facsimile communication over IP networks", Edition 5 (2007) or Edition 6 (2010), available at http://www.itu.int) may be present on the media plane.

In contrast to the traditional PSTN (Public Switched Telephone Network) network both planes may be on different infrastructure using different protocols and even take different routes through a network.

Correlation Information

The property of disjunct signaling stream(s) and media stream(s) of a VoIP service within packet-switched networks may necessitate a correlation mechanism. This correlation may only be based on the common parameters carried on both planes of the session. Monitoring equipment used in VoIP networks may be limited to either the signaling or media plane due to the network structure. A correlation of signaling stream(s) and media stream(s) is thus needed outside the VoIP network in between the monitoring components.

In RTP-based VoIP networks the data basis is rather limited as defined by the RTP protocol and the underlying transport and Internet layer protocols. An RTP stream which typically carries voice or video information from one party to another of a VoIP service is made up of plural RTP packets. The header of each RTP packet does not contain an identifier which can be used to distinctively associate single RTP packets or the entire RTP stream to a VoIP service (defined by the VoIP signaling). The same way the VoIP signaling protocol does not carry information to relate a signaling session (signaling plane of the VoIP service) to RTP protocol header information.

The parties originating or receiving a VoIP service actively dictate the transport and Internet layer address (IP address and port) on which they want to receive media streams. This configuration is done on the signaling plane. Using SIP as a signaling protocol, the address tuple(s) to be used on the media plane is/are defined in a so-called SDP body (see IETF RFC 3264, "An Offer/Answer Model with the Session Description Protocol (SDP)", available at http://www.ietf.org). The address tuple(s) - usually consisting of an IP address and port – is/are the sole information to correlate media plane of a VoIP service with the signaling plane of the VoIP service, and vice versa.

Challenges in Correlation of Signaling Plane and Media Plane

Beside the limited information available for correlation, the correlation of the signaling plane and media plane imposes also numerous further challenges, especially in passive mid-point monitoring scenarios. While an address tuple (IP address and port) may be enough information to identify a single RTP stream at a given point in time, multiple streams

identified by different address tuples may exist in a regular VoIP call. In fact at least two media streams are needed to allow two-way communication between the caller and callee.

It will be outlined in further detail in the following how multiple media streams may occur in a single VoIP service and how they are communicated between the parties involved (which may not always be the case).

Mid-point monitoring equipment (i.e. the signaling and media probes) is introduced into the network path which active components (e.g. VoIP phones and servers) use to communicate with each other. This passive equipment is not involved in the communication itself and has to derive all information from the network packets it observes on said network path. The correlation challenge increases as the passive equipment lacks information the active components internally have. A VoIP phone may internally assign a media port to a signaling session but never send out this information combined so that a mid-point monitoring probe could benefit from this information.

Time Constraints due to Port Reuse

The IP address and port combination transmitted inside the signaling plane of a VoIP service as well as the IP address and port observed on the media plane of the VoIP service may be reused. For exemplary purposes it can be assumed that each VoIP device has a single IP address. The port range from which the client can draw is limited to roughly 65000 ports by the underlying transport layer protocol UDP (see RFC 768, "User Datagram Protocol", available at http://www.ietf.org). In practice additional specifications and configuration parameters significantly further limit this port range. RFC 3550 which defines the Real-Time Transport Protocol mandates that only even port numbers may be used to transport media streams. The odd ports are reserved for Real-Time Transport Control Protocol (RTCP) packets. This standardization alone effectively halves the number of ports available for VoIP communication.

As a result a VoIP device has to re-use a certain IP address and port combination, thus eliminating a unique identification criterion. Essentially the IP address and port combination can only be assumed to be unique for a limited amount of time. The time-frame depends on the utilization of the VoIP device as well as the number of IP addresses required in an Internet Service Provider's network. If a correlation of the signaling and media plane takes place without a time criteria, it would therefore produce so-called false positives: Multiple media streams would match the requested IP address and port combination, since the signaling plane may have caused re-use of the very same IP address and/or port for another VoIP service.

Media Streams

Multiple streams may exist per direction of each VoIP service. The caller sends data to the callee and vice versa resulting in at least one media stream per direction. Desirable features, such as for example codec changes, may trigger additional streams. On the network multiple streams may use the same IP address and port tuple depending on the media protocol. For example, each RTP stream is additionally identified by a unique identifier - the Sender Synchronization Source (SSRC) – which is used to distinguish between multiple streams.

Fig. 1 shows exemplary situations where multiple media streams may be triggered. The focus is on the media plane traffic and its timing. The x-axis denotes the time basis, starting on the left side. The vertical lines in Fig. 1 denote signaling events and the bold horizontal lines are RTP streams present in the respective exemplified VoIP service example (please note that the different VoIP service examples are separated by broken horizontal lines). Only the RTP stream direction from the callee to the caller is shown per VoIP service example. The RTP stream from the caller to the callee can be assumed to be less complex (e.g. as shown in the "normal" VoIP service example).

The three vertical lines denote important events in the phase of a call. The leftmost line denotes the start timestamp. This is the time at which the caller submitted the call setup request to the network. The connected point is the timestamp at which a callee or his endpoint/handset picked up and moved the service into a fully established state. The service ends when one of the parties sends a termination request.

The most common VoIP services will be the trivial session examples where there is only one RTP stream per direction (see "normal" or "early media"). In a "normal" VoIP service flow both parties only start sending once the session is fully established on the signaling plane. More often the callee would start sending early media, i.e. when sending ring-tones or (pre-call) announcements. In "session forking" VoIP service example there may be multiple concurrent or sequential RTP streams at the beginning of a service e.g. due ring-tones being sent to multiple VoIP devices of the callee, while one is answered at the connect event

During a service media codecs may be changed (see "code change" VOIP service example) which is commonly resulting in a new media stream. Another service scenario may be the VoIP call being put on hold and picked up at a later time essentially generating multiple media streams (see "call on hold" VoIP service example). Silence suppression and other RTP features may cause multiple streams sporadically during a service (see "silence suppression" VoIP service example). Also retransmissions on the signaling plane may

desynchronize the signaling plane and media plane (see "SIP retransmissions" VoIP service examples).

Geographic Distribution or Media Plane and Signaling Plane

As indicated above, signaling plane data and media plane data of VoIP services may take different routes. In examples, where SIP is used for session setup, this is indeed the case as those sessions usually contain signaling-only components (i.e. SIP proxies, REGISTRARs). As a result passive mid-point monitoring solutions may be split geographically along the routes of the VoIP traffic.

An exemplary passive mid-point monitoring scenario for this case is shown in Fig. 2. Fig. 2 shows three geographically distributed POPs (Point of Presence) which are linked over the carrier's internal network. The signaling data flows on the signaling plane between POP A and B via the signaling-only POP C. POP C would typically host a centralized routing entity which reduces the complexity in the POPs A and B. To prevent back-hauling traffic from POP A to POP C before sending it to POP B the VoIP system is configured in a way that would allow the media to flow directly on the media plane between POPs A and B.

Typical mid-point monitoring locations would be inside each POP. Due to the layout of the network no media traffic would be visible in POP C. To allow for successful correlation of signaling and media streams by the correlation mechanism it is therefore desirable to support distributed networks. If the same session traverses multiple POPs it would be desirable for the correlation mechanism to identify this and support correlation of the session legs across multiple sites.

Limitations/Challenges in Correlation of Signaling Plane and Media Plane

The correlation may be solely based on the IP address and port used on the transport and Internet layer. On the media plane each RTP stream is destined to exactly one IP address and port on the transport layer. On the signaling plane one IP address and port is typically exchanged inside the Session Description Body of the SDP protocol during the VoIP service setup. However this IP address and port combination may not be the combination used throughout the VoIP service. In this case the above mentioned correlation mechanism fails: It fails upon searching a media stream for a specific signaling session of the VoIP service. The same way it fails to locate a signaling session of the VoIP service for a specific media stream on the media plane. The reasons for using another IP address port combination than advertised upon session setup are manifold.

Network Address Translation (NAT)

Network Address Translation (NAT, RFC 1631) was developed to solve Internet address space depletion and routing problems. In today's Internet one may distinguish between internal addresses which are often only unique locally (i.e. typically used inside company or home networks), and external addresses of global validity and uniqueness as used on the public Internet.

Fig. 3 shows an exemplary network using internal and external addresses. The internal network on the left side uses IP addresses from the so-called private space, as for example defined in IETF RFC 1918, "Address Allocation for Private Internets", available at http://www.ietf.org. The external network on the right side is the public Internet with globally reachable addresses. A router with embedded Network Address Translation (NAT) functionality is located in between the two networks. The router does not directly route packets in between the two connected networks, but "translates" (i.e. replaces) IP source and destination addresses within the routed IP packets on demand.

Essentially, the NAT functionality of the router hides the entire internal network (10.0.0.0/8 in this example) behind one public IP address (192.0.2.1). Every IP connection from within the internal network to the Internet will seem to originate from the sole public IP address (192.0.2.1) of the entire network.

For each node inside the internal network this imposes some limitations. Although Internet access works in general, a node in the internal network may not be reachable from the outside. This is due to the fact that IP traffic from an outside node (i.e. a node in the external network) would be destined to the public IP address (192.0.2.1), but the router with this IP address does not know at this point in time where to forward the traffic to on the internal network, given that there was no prior communication from an node inside of the internal network and the external node.

Additionally the internal node may not be aware that it is behind a router which performs the NAT. As required by the transport protocols, the internal node will use the internal IP address for communication purposes. On the VoIP signaling and media layer (i.e. session layer or application layer), the application will also use the internal IP address (i.e. 10.0.0.123) instead of the public IP address. VoIP signaling protocols (e.g. SIP or H.323) contain various IP addresses on the application layer. An intermediary NAT device (i.e. the router in Fig. 3) will not perform translation of the addresses on the session layer or application layer, but only translates IP addresses in the network layer. The internal IP addresses inside the VoIP

signaling (i.e. SIP or H.323 messages) impose a problem to the application as internal IP addresses are most likely not reachable from the public Internet.

VoIP devices involved in the processing of a certain call may detect this problem by comparing the IP addresses seen on the Internet and transport layers with the IP addresses set on the application layer. The following message is an exemplary SIP message as seen on the network and transport layer, which means that both the Internet and transport layer information (IP addresses and ports) are visible:

```
U 2010/09/09 13:57:31.925226 192.0.2.99:37682 -> 10.0.0.1:5060
```

The Internet and transport layers show that the UDP packet (U) was received from the external address 192.0.2.99 (port 37682).

The following message represents the same exemplary SIP message as seen on the application layer, which means that both the Internet and transport layer information (IP addresses and ports) as well as the application layer (SIP message contents) are visible:

```
INVITE sip:echo@example.com SIP/2.0
Via: SIP/2.0/UDP
192.168.1.216;branch=z9hG4bK3BB64874;rport=37682;received=192.0
.2.99
CSeq: 7726 INVITE
To: <sip:echo@example.com>
Content-Type: application/sdp
From: "John Doe" <sip:jdoe@example.com>;tag=693C7725
Call-ID: 1341723561@192.168.1.216
Subject: sip:jdoe@example.com
Content-Length: 230
User-Agent: kphone/4.2
Contact: "John Doe" <sip:jdoe@192.168.1.216;transport=udp>
v=0
o=username 0 0 IN IP4 192.168.1.216
s=The Funky Flow
c=IN IP4 192.168.1.216
t=0 0
m=audio 60942 RTP/AVP 0 97 8 3
a=rtpmap:0 PCMU/8000
a=rtpmap:3 GSM/8000
a=rtpmap:8 PCMA/8000
a=rtpmap:97 iLBC/8000
a=fmtp:97 mode=30
```

In contrast to the information available at the network and transport layers claiming that the message was received from the external address 192.0.2.99 (port 37682), the application claims that the source was the internal address 192.168.1.216 (port 5060 - the port 5060 is not viewed for the source address as it is the default port).

In general the translation of the network (IP) address also applies to the port numbers which are used on the transport layer. This feature is named Port Address Translation (PAT). NAT and PAT commonly happen at the same time in the same device.

PAT becomes necessary if multiple devices attempt to use the same port. Since different devices have different IP addresses their IP address and port tuple is unique. If packet streams from both devices traverse the same NAT device, the NAT device has to translate the port of one of the two packet streams. Otherwise there would be two distinct packet streams sharing the same external IP address of the NAT device and the same port. While this may not be a problem if the destination IP address and port tuple of the destination device are different for the two packet streams, it adds overhead which the NAT device wants to prevent. By rewriting the source port of one of the packet streams the address tuples of the external IP address and ports become unique again.

However, in networks where NAT (and PAT) is performed to for example hide private networks from the outside Internet, the correlation of signaling sessions of VoIP services and the associated media plane streams is becoming complex.

Multiple Communication Paths

Numerous solutions have been developed to allow traffic of VoIP services to operate in networks with Network Address Translation (NAT). These mechanisms require the involved caller and callee to exchange information, for instance on additional transport protocols or addresses which can be used to reach the remote party. These include – but are not limited to - IPv6 (Internet Protocol Version 6, see IETF RFC 2460, "Internet Protocol, Version 6 (IPv6), Specification"), TURN (Traversal Using Relays around NAT, see IETF RFC 5766, "Traversal Using Relays around NAT (TURN):Relay Extensions to Session Traversal Utilities for NAT (STUN)") addresses or ICE (Interactive Connection Establishment, see IETF RFC 5245, "Interactive Connectivity Establishment (ICE): A Protocol for Network Address Translator (NAT) Traversal for Offer/Answer Protocols") candidates (all RFCs available at http://www.ietf.org).

These additional tuples of IP addresses and ports communicated in these solutions establish different data paths in media plane and signaling plane of a VoIP service and thereby break

up the previous one-to-one relation of signaling session to media stream to a given VoIP device. Previously one media stream to the given VoIP device could be distinctively identified by exactly one IP address and port. In the new scenario on the signaling plane a list of IP address and port tuples is transported on which the VoIP device may receive media thereby increasing the complexity of correlation between media plane and signaling plane of a VoIP service.

SUMMARY OF THE INVENTION

One object of the invention is to suggest correlation mechanisms that allow overcoming one or more of the limitations and challenges on the correlation of signaling plane and media plane of services.

The object is solved by the subject matter of the independent claims. Advantageous embodiments of the invention are subject to the dependent claims.

One of the various aspects of the invention is to suggest a definition of correlation keys that allow the correlation of media streams of services and the associated signaling session of the respective services based on data records (reports) that provide information on the media plane and signaling plane of the respective services. These correlation keys may be for example provided in form of hash keys. A correlation key may be associated to a given direction of the media data paths of the media streams belonging to a given service (e.g. caller-to-callee or callee-to-caller for a simple bi-directional service, e.g. VoIP call). Hence, assuming that the service comprises at least two media streams of different directions, at least two correlation keys are provided on the signaling plane for later correlation of the media plane and signaling plane of the service. On the media plane one correlation key is provided per media stream.

The correlation keys for use in correlation are generated by a media plane probe and a signaling plane probe independently from each other, but the two probes generate matching correlation keys for a given media service (i.e. the signaling plane probe and the media plane probe independently each generate the same correlation key for a given direction/media data path of the media service, given that there are not any exceptional situations preventing the match of the correlation keys).

In response to the detection of the end of a signaling session, the signaling plane probe generates for this signaling session at least one correlation key for each "direction" of the service to which the signaling session belongs. Each correlation key (e.g. hash key) is generated by the signaling plane probe based on a timestamp indicative of the point in time

at which the end of the respective signaling session has been detected by the signaling plane probe and using information on respective direction of the media plane data flow (e.g. caller-to-callee or callee-to-caller for a simple bi-directional service, e.g. VoIP call). The correlation keys generated for the different directions of the service corresponding to the signaling session the end of which has been detected are then collated in a signaling session report, which may be for example stored in a database or a flat file.

For the media plane, the media plane probe generates a correlation key (e.g. hash key) for each media stream. The correlation keys for the media steams are generated upon the media plane probe detecting the end of the respective media stream. The correlation key for a respective terminated media stream is generated by the media plane probe based on the direction of the respective media stream, e.g. based on the media data path of a media stream, and on a timestamp indicative of the point in time at which the respective media stream has ended. The timestamp at which the respective media stream has ended is for example the time at which the last packet of the media stream has been received by the media plane probe. The media plane probe stores the correlation key (e.g. hash key) for the media stream in a media stream report, which may be for example stored in a database or exported as a flat file.

Another aspect of the invention is the use of the correlation keys comprised in the signaling session reports and the media stream reports to identify the media streams and signaling session belonging to a single media service. As indicated above, the correlation keys generated by the signaling plane probe and the media plane probe should be matching each other (i.e. the correlation keys of a given signaling session report should be found in the media stream reports, respectively, the correlation key of a media stream report should be found in one of the signaling session reports), provided that signaling session and related media streams are terminated nearly at the same point in time, i.e. within a given timeframe. Hence, a correlation unit can identify which media streams belong to which signaling session (or vice versa) and may therefore generate a service record that summarizes a service based on information contained in the media stream reports and information contained in the signaling session report of the respective service.

According to one exemplary embodiment of the invention, a method for correlating media streams and signaling sessions of services in a passive monitoring system of a packet-switched network is provided. It is assumed for exemplary purposes that one service has one signaling session.

In this method a signaling plane probe generates at least one correlation key for each direction of a service based on the information of the signaling session of the respective

service monitored at the signaling plane probe. As noted above the direction may be equivalent to a respective media data path of a media stream belonging to a given service. The correlation keys for a respective service may be generated using a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the signaling plane probe and using information on the direction of the respective service. Furthermore, the signaling plane probe stores a signaling session report for each signaling session in a database. Each of the signaling session reports comprises at least two correlation keys generated for the respective directions of the service.

Moreover, in this method a media plane probe also generates a correlation key for each media stream monitored by the media plane probe. The media plane probe generates the correlation key using a timestamp indicative of the point in time of the end of the respective media stream as detected by the media plane probe and using information on the media data path of the respective media stream. The media plane probe stores a media stream report for each media stream in a database, wherein each media stream report comprises at least the correlation key generated for the respective media.

A correlation unit further correlates the media streams and the signaling sessions based on the correlation keys comprised within media stream reports and signaling session reports.

In a more detailed exemplary embodiment of the invention, the generation of the respective correlation keys for the respective media streams by the media plane probe is based on the media data path information of the respective media stream and the timestamp indicative of the point in time at which the respective media stream ended.

According to another exemplary embodiment of the invention, information on the direction of the respective service – based on which the correlation keys are generated by signaling plane probe for a respective service – is information on one or more media data paths of media streams of the service learned from messages of the signaling session of the service. In other words, the direction of the service may be for example given by the media data path which is yielding a given direction. For example in a simple VoIP call between two peer devices, there are two directions: caller-to-callee and callee-to-caller as noted above.

In a further embodiment of the invention, the signaling plane probe monitors signaling messages of the respective signaling sessions of the services, and detects media streams belonging to each service associated to a respective monitored signaling session based on the signaling messages of the respective signaling sessions. The correlation keys for a respective one of the signaling sessions may be generated by the signaling plane probe

based on information on the media data path of the media streams belonging to the service associated to the respective one of the signaling sessions and the timestamp indicative of the point in time at which the end of the respective signaling session has been detected by the signaling plane probe. For example, in one possible implementation information on a media data path of a media stream is a destination IP address and port number of the media stream.

In another embodiment, the timestamps used for the generation of the correlation keys by the signaling plane probe and the media plane probe could be for example rounded (e.g. in a configurable or fixed interval) before the generation of the correlation keys, in order to ensure that timing differences in the events monitored in the media plane and signaling plane of the services do not lead to generation of non-matching correlation keys for a given service. Alternatively, in another exemplary implementation, the timestamps – by default – have a granularity that is higher than one second, e.g. a granularity in the range of one to ten seconds.

In a further embodiment, instead of storing a single correlation key per direction of a signaling session or per media stream, additional correlation keys may be generated and stored. The input for these additional correlation keys are the same IP address and port information, but a different timestamp. For example, the signaling plane probe could calculate an additional correlation key using a timestamp earlier than the timestamp indicative of the end of the respective signaling session.

In case of using a rounded timestamp this earlier timestamp may be the next earlier rounded timestamp before the rounded timestamp indicative of the end of the respective signaling session. In one exemplary implementation, the signaling plane probe could generate two timestamps from a (non-rounded) timestamp indicative of the end of the respective signaling session which are each used together with the same IP address and port information to generate two respective correlation keys for a given direction: One of these two generated timestamps used for calculation of the correlation keys may be the timestamp indicative of the end of the respective signaling session rounded to the nearest lower value according to the rounding interval, while the other of these two generated timestamps may be the timestamp indicative of the end of the respective signaling session rounded to the nearest higher value according to the rounding interval.

All correlation keys that are generated by the signaling plane probe for a given direction may be stored as part of the signaling session records.

In a similar fashion as described above for the signaling plane probe and the directions indicated in the signaling, also the media plane probe may optionally generate more than one correlation key for a given media data path/media stream. In case of using rounded timestamps also the media plane probe could generate two timestamps from a (non-rounded) timestamp indicative of the end of the respective media stream which are each used together with the same IP address and port information of the media stream to generate two respective correlation keys. One of the two timestamps generated by the media plane probe may be the timestamp indicative of the end of the respective media stream rounded to the nearest lower value according to the rounding interval, while the other of these two generated timestamps may be the timestamp indicative of the end of the respective media stream rounded to the nearest higher value according to the rounding interval. All correlation keys that are generated by the media plane probe for a given media stream may be stored as part of the media stream records.

In case of rounding timestamps in the media plane probe and the signaling plane probe, the rounding interval in both probes should be identical. The gain of having both probes generating additional correlation keys and correlating a multitude of correlation keys may not reflect in the increased processing needs.

In a further exemplary embodiment of the invention, the correlation of the media streams and the signaling session of the respective services is performed by a correlation unit periodically or in response to a query.

Another exemplary embodiment of the invention is related to a method for correlating media streams and signaling sessions of services. According to this method a correlation unit correlates the media streams and the signaling sessions of one or more services based on the correlation keys comprised within media stream reports of the media streams and signaling session reports of the signaling sessions to thereby identify the media stream reports and signaling session report belonging to a respective one of said one or more services. For correlating media streams and the signaling sessions, the correlation unit identifies one or more media streams of a respective service and the corresponding signaling session of the respective service based on the correlation keys comprised in the media stream reports and signaling session reports. Further, the correlation unit generates a service record for a respective one of said at least one service based on information contained in the media stream reports and information contained in the signaling session report of said at least one service.

In one exemplary implementation, these steps are performed by a correlation unit periodically for all signaling session reports and media stream reports generated within a configurable time interval, or in response to a request.

In case the correlation unit is unable to match one or more media streams to said signaling session report, the correlation unit may optionally generate a service record without quality information of the media streams of the service or may optionally generate a corresponding indication of the user/operator of the correlation unit.

A service report generated for a service by the correlation unit may comprise – according to one exemplary implementation – information on the service and the quality information of the media streams of the service.

In one exemplary implementation, the correlation keys provided in a respective signaling session report may have been generated using a timestamp indicative of the point in time at which the end of the respective signaling session of the corresponding service has been detected and using information on the media streams of the service. Similarly, the correlation keys provided in a respective media stream report may have been generated using a timestamp indicative of the point in time at which the respective media stream ended and using information on the media data path of the media stream.

In one further exemplary implementation, the correlation unit first attempts a correlation of media stream reports and signaling session reports using the correlation keys that have been generated based on the timestamps indicative of the end of the signaling session, respectively, the end of the media stream(s). In case the correlation is unsuccessful, the correlation unit may further use optionally available additional correlation keys contained in the signaling session reports and/or media plane reports which are based on other timestamps, e.g. before and after the actual end of the respective signaling session or media stream(s), respectively. This layered approach allows to first conduct the correlation using the correlation keys which are more likely to yield a result and as a fallback conduct the correlation using a wider timeframe.

According to a more detailed exemplary embodiment of the invention, the correlation of the media streams and the signaling sessions of one or more services based on the correlation keys comprised within media stream reports of the media streams and signaling session reports of the signaling sessions by the correlation unit comprises matching the respective correlation keys of the media stream reports of media streams are to the respective correlation keys of the signaling session reports, or vice versa. A match of the correlation keys of a one of the media stream reports and one of the signaling session reports (i.e. the

two correlation keys are identical) yields that the media stream of said one media stream report belongs to the same (media) service to which the signaling session of said one signaling session report belongs.

In another exemplary embodiment of the invention, for correlating the media streams and the signaling sessions of one or more services by the correlation unit, same may obtain from a signaling session report correlation keys identifying the media streams belonging to the same service as the signaling session. Further the correlation unit could then identify those media stream reports which include one of the correlation keys obtained from the signaling session report.

Alternatively, in another exemplary embodiment, the correlation of the media streams and the signaling sessions of one or more services could also be implemented by the correlation unit obtaining from a media stream report a correlation key identifying the media stream, and further the correlation unit identifying a signaling session report among the signaling session reports which includes the same correlation key obtained from the signaling session report.

According to one exemplary embodiment of the invention, a method for correlating media streams and signaling sessions of services in a passive monitoring system of a packet-switched network is provided. It is assumed for exemplary purposes that one service has one signaling session.

Another embodiment of the invention is related to a passive monitoring system for correlating media streams and signaling sessions of services in a packet-switched network. The passive monitoring system comprises a signaling plane probe that generates at least one correlation key for each direction of a service based on the information of the signaling session of the respective service monitored at the signaling plane probe. As noted above, there may be one or more correlation keys for each direction of the service. The correlation keys for a respective service are generated by the signaling plane probe using a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the signaling plane probe and further using information on the direction of the respective service (e.g. information on the media data path of the given direction, such as a destination IP address and UDP port number). The signaling plane probe stores a signaling session report for each signaling session in a database, wherein each signaling session report comprises the at least two correlation keys generated for the respective directions of the service.

Furthermore, the passive monitoring system also comprises a media plane probe for generating a correlation key for each media stream monitored by the media plane probe. The

correlation key is generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream. The media plane probe stores a media stream report for each media stream in a database. Each media stream report comprises at least the correlation key generated for the respective media.

The passive monitoring system further comprises a correlation unit for correlating the media streams and the signaling sessions based on the correlation keys comprised within media stream reports and signaling session reports. The correlation unit may for example use one of the different correlation methods described herein for this purpose.

Another embodiment of the invention is related to the design of the signaling plane probe. According to this embodiment of the invention, the signaling plane probe comprises a network interface card for receiving packets of signaling sessions of multiple media services and a monitoring unit for monitoring the signaling sessions based on the packets of the signaling sessions received by the signaling plane probe to thereby obtain information on a respective one of the signaling sessions. The monitoring unit of the signaling plane probe is further capable of detecting the point in time at which a respective signaling session of the respective service terminates.

The signaling plane probe also comprises a processing unit for generating at least one correlation key for each direction of a service based on a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the monitoring unit and based on information on the direction of the respective service. Moreover, the monitoring unit stores a signaling session report for each signaling session in a database, wherein each signaling session report comprises at least two correlation keys generated for the respective directions of the service.

Another embodiment of the invention is related to a media plane probe which comprises a network interface card for receiving packets of media streams of multiple media services, and a monitoring unit for monitoring the media streams based on the packets of the media streams received by the media plane probe. Thereby the media plane probe obtains information on a media data path a respective one of the media stream. Further, the monitoring unit detects the point in time at which a respective media stream of the respective service terminates, and a processing unit of the media plane probe generates a correlation key for each media stream monitored by the monitoring unit. This correlation key may be for example generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream.

The media plane probe's monitoring unit further stores a media stream report for each media stream in a database, wherein each media stream report comprises at least the correlation key generated for the respective media.

The invention according to another embodiment is related to a correlation unit capable of correlating media streams and signaling sessions of services in a passive monitoring system of a packet-switched network. The correlation unit comprises a database access unit for accessing a database comprising signaling session reports for signaling sessions of services and a database comprising media stream reports of media streams of the services. The signaling session reports each comprise at least one correlation key for each direction of a respective service, and the media stream reports each comprise one correlation key indicating the direction of the media stream. A processing unit of the correlation unit is used to correlate the media streams and the signaling sessions of the services based on the correlation keys comprised within media stream reports and signaling session reports to thereby identify the media stream reports and signaling session report belonging to a respective one of said one or more services. The processing unit identifies one or more media streams of a respective service and the corresponding signaling session of the respective service based on the correlation keys comprised in the media stream reports and signaling session reports. The correlation unit may further comprise a service record generation unit (e.g. implemented by a processing unit) for generating a service record for a respective service based on information comprised in the media stream reports and information comprised the signaling session report of said at least one service.

In a further embodiment of the invention, the correlation unit is further adapted, e.g. by comprised respective configured means, to perform the steps of the correlation methods according to one of the different embodiments described herein. Furthermore, also the signaling plane probe and the media plane probe may be adapted, e.g. by comprised respective configured means, to implement the different functions thereof as described herein.

Further embodiments of the invention relate to the implementation of the different functions of media plane probe, signaling plane probe and correlation unit in software. In this context, another embodiment of the invention provides a computer-readable medium storing instructions that, when executed by a processor of a signaling plane probe, cause the signaling plane probe to receive packets of signaling sessions of multiple media services, and to monitor the signaling sessions based on the packets of the signaling sessions received by the signaling plane probe to thereby obtain information on a respective one of the signaling sessions. The execution of the instructions further cause the signaling plane probe to detect the point in time at which a respective signaling session of the respective

service terminates, and to generate at least one correlation key for each direction of a service based a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected and based on information on the direction of the respective service. Moreover, the executed instructions may further cause the signaling plane probe to store a signaling session report for each signaling session in a database, wherein each signaling session report comprises the at least two correlation keys generated for the respective directions of the service.

Another exemplary embodiment of the invention is providing a computer-readable medium storing instructions that, when executed by a processor of a media plane probe, cause the media plane probe to receive packets of media streams of multiple media services, and to monitor the media streams based on the packets of the media streams received by the media plane probe to thereby obtain information on a media data path a respective one of the media streams. Moreover, the execution of the instructions cause the media plane probe to detect the point in time at which a respective media stream of the respective service terminates, and to generate a correlation key for each media stream monitored by the monitoring unit, wherein the correlation key is generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream. Furthermore, the execution of the instructions may further cause the media plane probe to store a media stream report for each media stream in a database, wherein each media stream report comprises at least the correlation key generated for the respective media.

Another embodiment of the invention is providing a computer-readable medium storing instructions that, when executed by a correlation unit, cause the correlation unit to correlate media streams and signaling sessions of services in a passive monitoring system of a packet-switched network. The execution of the instructions cause the correlation unit to access a database comprising signaling session reports for signaling sessions of services and a database comprising media stream reports of media streams of the services. The signaling session reports each comprise at least one correlation key for each direction of a respective service, and the media stream reports each comprise one correlation key indication the direction of the media stream. The execution of the instructions further cause the correlation unit to correlate the media streams and the signaling sessions of the services based on the correlation keys comprised within media stream reports and signaling session reports to thereby identify the media stream reports and signaling session report belonging to a respective one of said one or more services and to identify one or more media streams of a respective service and the corresponding signaling session of the respective service based on the correlation keys comprised in the media stream reports and signaling session reports.

The execution of the instructions also cause the correlation unit to generate a service record for a respective one of said at least one service based on information comprised in the media stream reports and information comprised the signaling session report of said at least one service.

Another embodiment is providing a computer readable medium storing instruction that, when executed by the processor of the correlation unit, cause the correlation unit to perform the steps of the method for correlating media streams and signaling sessions of services according to one of the different embodiments described herein.

BRIEF DESCRIPTION OF THE FIGURES

In the following the invention is described in more detail in reference to the attached figures and drawings. Similar or corresponding details in the figures are marked with the same reference numerals.

Fig. 1 shows exemplary situations where multiple media streams may be triggered in a media service,

Fig. 2 shows three geographically distributed POPs (Point of Presence) which are linked over the carrier's internal network,

Fig. 3 shows an exemplary network using internal and external addresses,

Fig. 4 shows an exemplary overview on a system according to an embodiment of the invention comprising signaling plane probe, a correlation unit and a media plane probe in a packet-switched network,

Fig. 5 shows a flow chart of the operation of the correlation unit according to an exemplary embodiment of the invention,

Fig. 6 shows the structure of a correlation unit according to an exemplary embodiment of the invention,

Figs. 7 & 8 shows two exemplary flow charts of the operation of a signaling plane probe according to different exemplary embodiments of the invention,

Fig. 9 shows the structure of a signaling plane probe according to an embodiment of the invention,

Fig 10 shows the structure of a media plane probe according to an embodiment of the invention,

Fig. 11 shows a flow chart of the operation of a media plane probe according to an embodiment of the invention,

Fig. 12 shows a network in which locations are indicated, where signaling and media plane probes of the invention may be advantageously located according to an embodiment of the invention,

Fig. 13 illustrates the use of rounded timestamps within a signaling plane probe and a media plane probe to highlight potential sources of error in correlation, and

Fig. 14 illustrates the use of two rounded timestamps for generating respective correlation keys according to an exemplary embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The following paragraphs will describe various embodiments of the invention. For exemplary purposes only, most of the embodiments are outlined in relation mainly to VoIP services as an example for a media service, but the invention is not limited to VoIP services. For example, the invention may also be used for other types of media services provided in packet-switched networks. The invention may be advantageously used in media services which have signaling plane and media plane separated and/or taking different routes through the packet-switched network.

The explanations given in the Technical Background section above are intended to better understand the often VoIP call-related exemplary embodiments described herein and should not be understood as limiting the invention to the described specific implementations of processes and functions in a packet-switched communication network.

As indicated above, the invention generally relates to methods for correlating at least one media data path and a signaling session of a service in a passive monitoring system that is monitoring a packet-switched network. Furthermore, the invention also relates to an implementation of these methods in hardware and software, and provides a signaling plane probe, a media plane probe and a correlation unit, as well as passive monitoring system comprising same. Based on the assumption of disjunctive signaling and media components of a service, the correlation mechanism suggested herein supports correlation across

multiple hosts connected via a network (e.g. a Local Area Network (LAN), Wide Area Network (WAN) or the Internet).

One of the various aspects of the invention is to suggest a definition of correlation keys that allow the correlation of media streams of services and the associated signaling session of the respective services based on data records (reports) that provide information on the media plane and signaling plane of the respective services. In the following these correlation keys are implemented as in form of hash keys for exemplary purposes. The correlation keys may be used to query database(s) to correlate media stream reports for media streams monitored by a media plane probe and a signaling session report on the signaling session provided by a signaling plane probe that belongs to the same service – it should be noted that for the proper functioning of the invention, it is not decisive whether media stream reports and signaling session reports are stored in the same or different databases, or whether there are even multiple database partitions provided. The media stream reports and signaling session reports may even be stored in files.

The correlation keys are generated by one or more media plane probes and one or more signaling plane probes that monitor a packet-switched network independently from each other. This independent calculation of the correlation keys facilitates distributed correlation spanning across multiple geographically distributed components or even across multiple vendors of software components. Furthermore, as will become more apparent from the following, for a given media data path – respectively a corresponding given direction –, the parameters that are used for generating correlation keys at the signaling plane probe(s) and the media plane probe(s) ensure that the identical correlation keys are generated for the given media data path by the signaling plane probe(s) and the media plane probe(s) to facilitate correlation. A respective correlation key may be associated to a given direction of the media data paths of the media streams belonging to a given service. For example, assuming for exemplary purposes a simple bi-directional service, e.g. VoIP call, there are two directions: caller-to-callee and callee-to-caller.

The signaling plane probe may generate a correlation key for each direction of the service. For example, the signaling plane probe generates one correlation key for the caller-to-callee direction and another correlation key for the callee-to-caller direction. However, the signaling plane probe may also generate multiple correlation keys per direction, as will be outlined below in further detail. Consequently, in case it is assumed that a service comprises at least two media streams of different directions, then at least two correlation keys are calculated by the signaling plane probe for later correlation of the media plane and signaling plane of the service. The correlation key for a given direction or media data path may be generated based on information on the direction or media data path, such as for example a tuple comprising

the destination IP address and UDP port for a media stream in the service's media plane corresponding to the given direction or media data path. In addition, the generation of the correlation key is further based on a timestamp. With respect to the generation of the correlation key by the signaling plane probe, the timestamp may for example indicate the point in time at which the signaling plane probe has detected the end of the signaling session (and thus the service). In another exemplary implementation, the timestamp used in the generation of a correlation key for a media data path of a media stream in the media plane of the service could also be the point in time of the termination (end) of the media stream in the media plane detected by the signaling plane probe.

The signaling plane probe may generate the correlation keys for the different endpoints (the endpoint indicate a direction of the related media data flow) of a service upon detection of the end of a signaling session and additionally or alternatively, upon detection of the end of a media stream in the service's media plane. Typically but not limited thereto, there is one endpoint per direction, e.g. the caller and callee. The callee may be represented by multiple endpoints in case of more complex media service scenarios, e.g. when session forking is used (see Fig. 1).

The end of a signaling session may be for example detected in the signaling plane probe by detecting a signaling protocol specific hang-up message, a terminal failure to connect the involved endpoints or a session timeout. Each correlation key (e.g. hash key) is then generated by the signaling plane probe based on a timestamp indicative of the point in time at which the end of the respective signaling session has been detected by the signaling plane probe and using information on respective direction of the media plane data flow (e.g. caller-to-callee or callee-to-caller for a simple bi-directional service, e.g. VoIP call).

The direction may be for example given by a media data path of a media stream of the respective service. A media data path could be for example indicated by a tuple comprising the destination IP address and UDP port number for transmitting the media packets of a media stream of the service. The signaling plane probe may thereby generate only one single correlation key per direction or multiple correlation keys per direction. In one exemplary embodiment of the invention, the signaling plane probe generates one correlation key per direction, where the correlation key for a respective direction is based on a media data path of a media stream. This media stream of which the media data path information is used to generate the correlation key should be existent at the end of the signaling session (according to the session signaling monitored by the signaling plane probe), in order to be able to match the correlation key to a corresponding correlation key in a media stream report generated by a media plane probe. The media data path(s) of a service and optionally their

existence (e.g. start time and termination time) could be for example learned by the signaling plane probe from the messages of the signaling session of the service.

The correlation keys generated for the different directions of the service corresponding to the signaling session the end of which has been detected are then comprised in a signaling session report, which may be for example stored in a database or (flat) file.

Alternatively, the signaling plane probe may also generate a correlation key for each media stream in the media plane of the service. In this case it may be assumed that the signaling plane traffic, i.e. the packets of the signaling protocol of the signaling plane, allow the signaling plane probe to detect the termination (i.e. end) of respective media streams in the media plane. In this case, the detection of the end of a media stream could trigger the generation of a correlation key for the respective media stream based on information on its media data path and a timestamp indicating the point in time at which the signaling plane probe detected the termination of the media stream.

Further, in another alternative implementation, the detection of the end of a signaling session, respectively, service as well as the end of a media stream as detected by a signaling plane probe could be used to trigger the generation of correlation keys in the signaling plane probe. For example, during the ongoing service the detection of the termination of a media stream in the media plane as learned from the signaling plane traffic could trigger the signaling plane probe to generate and include respective correlation keys for the media streams terminated during the ongoing session into the signaling session report of the service, while the detection of the end of the signaling session, and thus the service, could be used as a trigger for generating correlation keys for the respective media streams being "alive" in the media plane of the service at the signaling plane probe and their inclusion into the signaling session report of the service.

In the media plane, the media plane probe generates a correlation key (e.g. hash key) for each media stream. The correlation keys for the media steams are generated upon the media plane probe detecting the end of the respective media stream. The correlation key for a respective terminated media stream is calculated by the media plane probe based on the direction of the respective media stream, e.g. based on the media data path of a media stream, and on a timestamp indicative of the point in time at which the respective media stream ended. This point in time is for example the point in time at which the last packet of the media stream has been received at the media plane probe. In this latter case, the media plane probe may thus maintain a timestamp indicating the time of reception of the last packet of the media stream at the media plane probe.

The timestamp used for the generation of the correlation key may indicate another point in time than the point in time at which the media plane probe detects the end of the media stream. For example, in a packet switched network, there may be interruption in the packet stream of the media stream so that there may be a timer that measures the time since the last reception of a packet of the media stream. In case the time since the last reception of a packet of the media stream is exceeding a threshold (e.g. the timer "expires") – for example after 15 or 30 seconds, or the like – then the media plane probe detects the end of the media stream. The timestamp used in the correlation key generation may nevertheless be the point in time at which the last packet of the media stream has been received. The media plane probe stores the correlation key (e.g. hash key) for the media stream in a media stream report, which may be for example stored in a database or exported as a flat file.

Furthermore the timestamp used for the generation of a correlation key may be rounded. This counters differences in the time basis (local time) of multiple signaling and media probes as slightly different timestamps still yield the same rounded timestamp. Additional correlation keys may be generated with different timestamps, e.g. indicative of the – optionally rounded – end of a respective signaling session and/or media stream or a timeframe before or thereafter. These additional correlation keys may be stored in the respective signaling session reports and/or media session reports.

A media stream may also be interrupted due to codec features such as Voice Activity Detection (VAD). If a sender of a media stream is mute the codec may not encode any data resulting in an interruption of the media stream. This is typically indicated in the packet stream transporting the media and should not be considered by the media plane probe as an indication of the end of the media stream itself. In case a timer mechanism is used to detect terminated media streams, the timer should be configured such that codec features that lead to a temporary interruption of the media stream are not triggering the termination of the media stream (according to the detection mechanism for detecting terminated media streams in the media plane probe).

Furthermore, in another exemplary embodiment, the correlation of media streams of services and the signaling sessions of the services may also be based on a compound keys used as a correlation keys. This exemplary alternative implementation may however require a more complex database structure of the media stream reports and signaling session reports, as will be outlined below.

Another further aspect of the invention is the use of the correlation keys comprised in the signaling session reports and the media stream reports to identify the media streams and signaling session belonging to the respective services. This correlation of media streams and

signaling session could be done for example periodically or on request. The correlation keys generated by the signaling plane probe and the media plane probe should be matching each other (i.e. the correlation keys of a given signaling session report should be found in the media stream reports, respectively, the correlation key of a media stream report should be found in one of the signaling session reports). Hence, a correlation unit can identify which media streams belong to which signaling session (or vice versa) based on the correlation keys contained in the media stream reports and the signaling session reports and may therefore generate a service record for a respective service based on information contained in the media stream reports and information contained the signaling session report of the service.

The correlation methods according to the different embodiments of the invention proposed herein are based on a probe monitoring the signaling plane traffic of services (i.e. the signaling plane probe) identifying new services and associated media data paths of the media plane by detecting their corresponding signaling sessions and determining for each service correlation keys allowing to identify at least the media streams of the media plane existent upon termination of the service. It should be noted that "at least the media streams" means that it is optionally possible to generate a correlation key for each media data path of the media plane learned from the signaling plane traffic of the service, in case it is possible to detect the termination of the media data paths of the media plane in the signaling plane traffic. In this case the correlation key for a respective media stream may be based on the information on the media data path of the respective media stream visible in the signaling plane of the service and the point in time at which the signaling plane probe detects the termination of the media stream in the signaling plane.

Regarding the use of the point in time of the termination of the signaling session (e.g. a signaling message in the signaling plane indicating "hang up") for the generation of correlation keys it should be noted that the termination of the signaling session also means that all existent media data paths, respectively, the corresponding media streams of the media plane are terminated. Hence, in case it is not possible to detect the termination of the media data paths of the media plane in the signaling plane traffic, it is assumed to be possible to detect at least the end of the signaling session and to thereby conclude on the termination of the respective media data paths of the media plane and to thereby facilitate correlation of the media streams that have been "alive" at the end of the service and the corresponding signaling session of the service.

As noted above, another possibility may be to use compound keys as correlation keys. A compound key is defining a set of information comprised e.g. in a given set of fields of a database entry of a signaling session report and media stream report that – together with

additional criteria on the point in time of the termination of a media stream or the service – allows to correlate media streams and signaling sessions of the services. In one exemplary embodiment, the one or more databases that are used to store the signaling session reports and the media stream reports are partitioned into partitions covering only a given amount of time (i.e. time interval) of signaling session reports and/or media stream reports, respectively. The "size", i.e. the time interval covered by the partitions may be for example determined based on the average time interval in which port reuse occurs in the target monitored packet-switched network (e.g. the partition could cover ½ of the average time interval in which port reuse occurs). In the given partitions it may thus be assumed that the media data path information, such as destination IP address and UDP port number are unique. In this case, the signaling session reports and media stream reports may not include separate correlation keys, but the correlation key can be generated on-demand as a compound key from the information on the media data paths contained in the signaling session reports and media stream reports.

Hence, it would be sufficient that the signaling session reports and media stream reports store information on the media data paths of the service (e.g. destination IP address and UDP port number) and a timestamp that indicates the point in time of termination of the respective media data path in the media plane, as detected by the signaling plane probe from the monitored signaling sessions and the media plane probe from the monitored media streams. As noted above, the signaling plane probe can also detect the point in time of termination of the media data path(s) in the media plane by detecting the point in time of termination of the signaling session, which is – in most practical cases – coinciding with the termination of all media streams of the service in the media plane as well.

In this case, the correlation could be realized by first selecting the database partition of the media plane reports according to a timestamp of the termination of a media data path/signaling session within a given signaling session report, and by then determining the media stream reports that comprise media stream information matching those indicated in the given signaling session report.

Fig. 4 shows a packet switched network 400 according to an exemplary embodiment of the invention that comprises a signaling plane probe 401, a correlation unit 402 and a media plane probe 403. Please note that more than one signaling plane probe 401 and media plane probe 403 may be provided. Optionally, there may be multiple correlation units 402 present, working independent of each other and not impacting the performance or correlation accuracy of any other component.

The signaling monitoring probe 401 and the media plane probe 402 are monitoring the traffic on a packet-switched network 400, which may be for example an IP based packet switched network. It is assumed for exemplary purposes that the signaling plane probe 401 and the media plane probe 403 monitor the traffic of the packet-switched network 400 at different locations of the packet-switched network 400, but observe the same network traffic.

In one exemplary implementation, the signaling plane probe 401 and the media plane probe 403 are probes of a minimal non-intrusive, passive monitoring system. The respective monitoring probes 401, 403 are connected to the packet-switched network 400 via respective test access ports (TAPs). A TAP is a passive network device that mirrors network traffic of the packet-switched network without interference of the original network traffic. It provides a copy of every packet sent or received on the network, by duplicating the data packets observed on the physical layer of the network. Instead of a TAP a Switch Port Analyzer (SPAN) port may be used to monitor the traffic of the packet-switched network.

In packet-switched environments, the signaling data of the signaling plane and media data of the media plane is packaged into packets on the transmitter side. Packets are transported over the packet-switched network independent of each other. The receiver of the packets – identified by the destination IP address and port – may have to regroup and sometimes reorder packets in order to compile streams from single packets.

On the signaling plane multiple packets belong to one signaling session. The first packet of a signaling session – usually containing a "call setup" message – starts a new signaling session (respectively a new service). At this point, the signaling plane probe 401 generates a session entry along with auxiliary data, i.e. a unique correlation key identifying the session internally (signaling session identifier). Packets following the initial signaling packet are matched to one of the currently ongoing signaling sessions (respectively services) and signaling sessions managed by the signaling plane probe. Packets which do not start a new signaling session and do not belong to existing sessions may be discarded.

Matching single signaling packets to existing signaling sessions is specified in the standards which define the signaling protocol itself. Transport layer information like IP addresses and protocol-specific information (e.g. SIP Call-IDs and tags) may be used.

A signaling session may be torn down upon reception of a special packet – a "call hang-up" message. This message again is specific to the signaling protocol used. Upon reception of this message the signaling plane probe 401 can conclude on the termination (end) of the signaling session and generates the correlation keys for use in correlation of media plane and signaling plane of the services. Furthermore, the signaling session may be removed

from its internal storage. Additionally the signaling monitoring component may remove sessions from its internal storage, if it identifies stale sessions.

The media plane 403 of the service may for example identify the media plane data in form of RTP streams. RTP streams are – analog to the signaling sessions – made up from individual RTP packets. The transmitter of an RTP stream generates RTP packets by splitting the media data into smaller pieces. In general these packets are relatively small to reduce the delay between sender and receiver. As a result many packets are created and form a single RTP stream – typically 50 packets per second. Single RTP packets can be grouped into an RTP stream by media plane probe 403. When using RTP, the media plane probe 403 has transport layer information as well as the RTP protocol header which contains a so called Synchronization source (SSRC). The SSRC is a 32-bit numeric identifier which is contained in every single packet and deemed mandatory by the RTP. When media plane probe 403 first receives a packet which does not match an existing RTP stream in its internal storage it creates an RTP stream. Consecutive RTP packets can then be matched to the existing streams by comparing the transport layer information and SSRC value. If no packets are received for a single RTP stream for a certain time the stream is considered ended and can be removed from the internal storage. A short interruption in the packet stream should not trigger the media plane probe 403 to mark an RTP stream as ended, thus the time before a media plane probe 403 can consider an RTP stream as ended is multiple seconds and has to take features like voice activity detection into account.

The signaling plane probe 401 and the media plane probe 403 generate information about the signaling session and media streams, respectively. This generated information is comprised in signaling session reports and media stream reports, respectively. In order to track running sessions and media streams the entities 401, 403 store information internally while the signaling sessions and media streams are in progress. When a signaling session or media stream is terminated the respective monitoring component 401, 403 may generate a signaling session report with signaling information, respectively media stream report with information on the media stream. As will be outlined below in further detail, the signaling session report provides a summary of the signaling session (service) and includes the correlation keys (e.g. hash keys) for correlation. Similarly, the media stream reports summarize the media stream and also include a respective correlation key (e.g. hash key) to facilitate correlation.

Each signaling session report for a signaling session may be for example written by the signaling plane probe 401 upon completion of a signaling session and contains data which describes the signaling session it monitored. For example, in one embodiment of the invention, the data stored in the signaling session report and describing the signaling session

include – but are not limited to – a set of caller and callee specific properties which will be available per endpoint (caller or callee). These endpoint-specific properties may for example include at least one of the following:

- endpoint address/name (e.g. SIP URI),
- phone number,
- User-Agent (endpoint software and version),
- capabilities/features,
- supported media types,
- IP addresses and ports for signaling and media streams (from SDP body), and
- hash key of the media path (for example described by the destination IP address and UDP port of the expected media stream)
- signaling routing information.

Additionally, one or more of the following signaling session properties which are not endpoint-specific may also be included in the signaling plane report:

- timestamps: e.g. session start, Post-Dial-Delay (PDD), connect time, session end;
- information on the session flow (e.g. signaling message(s) with timestamps),
- session state (e.g. successful, unsuccessful, timed out, reason for failure), and
- events during session (media on hold, codec renegotiation, session forking, authentication)

In one exemplary embodiment of the invention, the signaling session report comprises all of the above noted endpoint-specific properties, and – optionally – all signaling session properties listed above, as far as they are available from the signaling protocol messages.

Depending on the specific implementation and capabilities of the signaling plane probe, the signaling session reports may contain information about multiple endpoints and/or multiple media streams per endpoint. In this case the session end timestamp may be available per involved endpoint, and not per session.

For example, the most trivial VoIP service is a phone call between two parties (including two media streams, one in each direction). In this case, the signaling session report could store each party as one endpoint with the above mentioned information and the media stream's destination IP address and port information. If the VoIP service would contain a video call (i.e. one audio and video stream per direction) the endpoint information may be extended to contain the destination IP address(es) and port numbers of the two media streams per direction (one IP address & port tuple for audio, one IP address & port tuple pair for video). Considering a VoIP service, the respective tuples of destination IP address and UDP port number of the media streams of the session may be for example learned by the signaling plane probe from the SDP body of SIP signaling.

Likewise, the signaling plane probe may extend the signaling session report to include additional endpoints, if multiple endpoints were part of the VoIP service. Multiple endpoints could be for example involved in a VoIP service, in case a caller tries to reach a callee which has call forwarding configured. The caller may then hear a ring-tone from the callee's landline, followed by a ring-tone from the callee's mobile phone. Finally a voicemail box picks up the session generating a third endpoint on the callee's side.

The media plane probe 403 monitors the media traffic, i.e. the individual media streams that convey the media information of the different services. The media plane probe 403 identifies a new media stream of a media service based on the network traffic it observes on the monitored packet switched network 400. The identification of a new media stream for a given service may happen shortly after this service is set up on the signaling plane. Throughout the duration of the media stream information on the media stream may be stored in an internal data record on the media steam. The media plane probe 403 may note for each stream the last RTP packet received for the respective media stream in an internal data record on the media stream in order to allow detecting the media stream's termination.

The media plane probe 403 may optionally perform a real-time analysis of the media streams monitored on the packet switched network and may generate a fine-grained media stream quality report with media stream related information. Fine-grained media stream quality reports could be for example written in predetermined time intervals, e.g. every five seconds, and could provide a summary of the media stream in the respective interval as well as quality information of the media stream in the respective interval. The information of the fine-grained media stream quality reports of a media stream could be used by the media plane probe 403 to generate a single media stream report on the media stream upon the end of the media stream is detected by the media plane probe 403. The media stream report and optionally also the fine-grained media stream quality reports of a media stream may be stored in individual databases.

The media stream report generated by the media plane probe 403 upon detecting the end of the media stream may contain data which describes the unidirectional media stream it monitored as well as correlation key that can be for example generated based on the destination IP address and UDP port number of the media stream and a timestamp that indicates the point in time at which the media stream ended/terminated. The media plane probe 403 could for example learn the destination IP address and UDP port number from the IP header encapsulating the RTP packets on the network layer. The characteristics of each media stream can be grouped into two categories. The transport and RTP header information characterize the media stream, e.g. for correlation purposes, whereas the quality information enable quality related processing of the media stream. In general the transport information is the same for all media packets processed as part of a single media stream. The stream quality information includes information covering all media packets and may be aggregated or stored on a per-packet basis.

In one exemplary embodiment of the invention, the media stream report generated by the media plane probe 403 for a given media stream may for example include one or more of the following transport media information:

- source and destination IP address,
- source and destination UDP port,
- RTP header Synchronization source (SSRC) value,
- RTP payload type, and
- correlation key(s) (e.g. hash value(s)) calculated based on destination IP address, destination UDP port and a timestamp indicating the point in time at which the of the media stream terminated (e.g. the timestamp of the last packet received for the media stream) or timestamp indicative of the timeframe before or after the termination timestamp.

The stream quality information that may be added to the media stream report by the media plane probe 403 may for example include/indicate one or more of the following:

- timestamp information (e.g. start and/or end time),
- RTP format violations,
- protocol conformance (e.g. sequence errors and/or DSCP errors),

- transport information (e.g. packet interval and jitter statistics, information on packet loss, information on duplicate packets, etc.), and

- MOS values (e.g. per time-slice (e.g. every 5 seconds), minimum/average/maximum value for entire stream duration, etc.),

- events (e.g. comfort noise, silence suppression, DTMF tones, codec changes, marker bits).

In one exemplary embodiment of the invention, the media stream report comprises all of the above noted transport media information and optionally further all stream quality information listed above, as far as they are available to the media plane probe from the packets of the media streams.

In addition to "measured values" (e.g. jitter between multiple media packets) the media stream report may also contain calculated information like MOS (Mean Opinion Score) values and information about impairments experienced by the receiver of the stream.

As further shown in Fig. 4, a correlation unit 402 correlates the media stream reports and signaling session reports generated by the signaling plane probe 401 and the media plane probe 403 in order to identify the media streams and the signaling session that belong to a respective service. It should be noted that each service is assumed to have one signaling session, but may have one or more media streams.

Generation of Correlation Key

The correlation key that is used for correlation may be built from:

- the timestamp that indicates the end of the signaling session, respectively the end of a given media stream, and

- information on a media stream, such as for example the destination IP address and UDP port of the media stream.

The correlation of signaling plane and media plane by the correlation unit 402 is based on this compound correlation key.

As noted earlier, the correlation key may be for example a hash key generated based on the before-mentioned parameters. The hash function to calculate the hash key (sometimes also called hash value) from the given data should be known to all parties involved (i.e. signaling plane probe 401, and media plane probe 403 and optionally also correlation unit 402) so that

the result for a given input is the same for all parties. Therefore, the hash keys are determined by the signaling plane probe 401 and media plane probe 403 using media data path information in addition to a timestamp that indicates point in time when the signaling session, respectively, the media stream ended/terminated. The correlation unit 402 may generate additional correlation keys based on the timestamps indicative of the timeframe before or after the timestamp that indicates the point in time when the respective session ended.

The hash function to determine the hash key may be a simple concatenation of one or more of the input parameters. For example, a concatenation of a destination IP address, destination UDP port number and a timestamp may (optionally including a delimiter character in between the parameters) be used for defining the hash keys. Of course more complex mechanisms may also be used to calculate a hash key representing the signaling session identifiers and/or the media path identifiers. For example the MD5 message digest function (see IETF RFC 1321, "The MD5 Message-Digest Algorithm", 1992, available at http://www.ietf.org) could be used to create a valid hash key. The MD5 message digest function may be fed with a concatenation of a destination IP address, destination UDP port number and the timestamp indicating the time of termination of the signaling session, respectively, the media stream and the resulting string can be used as a correlation key. Another hash function that could be used may be selected from the SHA cryptographic hash function family (see FIPS PUB-180, "Secure Hash Standard (SHS)", 2008 available at http://www.itl.nist.gov/fipspubs/). Furthermore, in another embodiment, a linear hash function may be used.

As outlined with respect to Fig. 1 earlier herein, ephemeral media streams may exist at any point during a service, such as a VoIP service. The ephemeral media streams may be generated by early media streams, service forking and codec changes. As a result the start and end timestamps of media streams may not necessarily concur with the start and end time of the VoIP service itself. Yet the timestamps of the start or end of a signaling session or media stream are an important piece of information for a successful correlation, as it significantly reduces the search window and amount of data to search. In typical scenarios, it can be expected that the start time of signaling and media streams deviate significantly and are thus not ideal candidates for a correlation mechanism.

At the end of a VoIP service both caller and callee have an established signaling session and send each other media on the media plane. Once a party hangs up the session a hang-up signal is send on the signaling plane and at the same time stops sending media packets. Once the remote party receives the hang-up signal it also stops transmitting media. The timestamps of the end of the signaling session of a service and the end of the corresponding

media streams in the media plane of the service are commonly very close to each other compared to the start of a media service in signaling plane and media plane. All these events will be subject to the same network- and application-imposed delays. Still the time-frame in which these happen is typically in the few milliseconds range or in the sub-second-range on long-distance or low bandwidth networks. This makes the timestamps of the end of the signaling session and the end of the media streams a good choice for calculating a correlation key.

Nevertheless, since signaling plane probe 401 and media plane probe 403 independently determine the correlation keys based on timestamps (and even minor deviations of the timestamps in the millisecond-range could lead non-matching correlation keys), the granularity of the timestamps used for the generation of the correlation keys may be chosen to account for those deviations of events in signaling plane and media plane events (i.e. deviations in the end of the signaling session in the signaling plane and the end of the corresponding media streams in the media plane of a service). Therefore the timestamps could have a granularity for example in the range of one or more seconds or at least 250 milliseconds or 500 milliseconds. In one exemplary embodiment, UNIX timestamps (which is indicating the seconds passed since January 1, 1970, 00:00:00) are used for the calculation of the correlation keys. Alternatively, also timestamps with a high resolution (e.g. resolution of one or ten or hundred milliseconds) could be used, but the timestamps may be rounded for the calculation of the correlation keys. It should be noted that the choice of the granularity or rounding interval may also impact the performance of a database or databases storing the media stream reports and signaling session reports for correlation. The larger the granularity, respectively the rounding interval and thus the search window the more data have to be processed to match signaling sessions and media streams.

Rounding timestamps could be for example implemented by rounding the timestamp to the nearest n second interval. Assuming for example that the interval is 5 seconds the following UNIX timestamps would be rounded as exemplified in Table 1.

Unix timestamp value	rounded value (5 sec)	description
1283936131	1283936130	rounded down
1283936133	1283936135	rounded up
1283936135	1283936135	unchanged
1283936136	1283936135	rounded down
1283936139	1283936140	rounded up

Table 1

The rounding interval can be any time interval in seconds or even milliseconds whereas the specific value is a trade-off between speed and accuracy. As noted above, the larger the interval the more data may have to be processed to match signaling sessions and media streams. The smaller the search window is the more likely it is to miss a match due to misaligned timestamps or derivations due to the delays outlined above.

The best rounding interval depends on the network monitored. Reasons for increased time differences are possible derivations from a shared time source (NTP) or differences seen in signaling and media events, i.e. the delay between a call being terminated and the endpoints stopping to send media.

For a smaller search window of three seconds the rounded values are different, as for example shown in Table 2.

Unix timestamp value	rounded value (3 sec)	description
1283936131	1283936130	rounded down
1283936133	1283936133	unchanged
1283936135	1283936136	rounded up
1283936136	1283936136	unchanged
1283936139	1283936139	unchanged

Table 2

Using normalized "session end" timestamp (i.e. timestamps of low granularity or timestamps that have been rounded) may be advantageous to counter the effects (e.g. false positive hash key matches) of the re-used port numbers. Since the end of a service (and/or end of media streams) becomes part of the correlation criteria only the port numbers that are used and valid at this point in time are considered in the correlation.

Another issue that could complicate the correlation processing is that deviations in detecting the end of a media stream, respectively a signaling session at the media plane probe 403 and the signaling plane probe 401 leads to the two entities rounding the timestamps to different values. For example, the signaling plane probe 401 could round the timestamp up, while the media plane probe 403 rounds the timestamp down to the next rounding interval value due to (minor) deviations in the timestamps at the signaling plane probe 401 and media plane probe 403. In another exemplary embodiment, additional correlation keys may be therefore generated by either one or both, the signaling plane probe 401 and media plane probe 403.

The signaling plane probe 401 and/or media plane probe 403 may use timestamps indicative of the rounding intervals before or after the timestamp indicative of the point in time where a

particular signaling session or media steam ended. For example a session ended at a point in time identified by the Unix timestamp value 1283936135. The correlation unit applies the rounding mechanism based on 3 second intervals. The rounded value thus is 1283936136. The correlation unit may generate additional keys with the timeframes before or after the mentioned rounded value. In this case the timestamps used for generation of the additional keys are 1283936133 (1283936136 – 3 seconds) and 1283936139 (1283936136 + 3 seconds). Of course, especially in cases where the rounding interval is short, it may also be desirable to more rounded timestamps rounded to the next and subsequent rounding interval(s) based on which correlation keys are calculated.

As noted above, the inclusion of multiple correlation keys calculated based on different timestamps for a given direction of a signaling session and/or media stream may for example be useful to counter correlation failures due to applying different rounding of timestamps in the signaling plane probe 401 and media plane probe 403 as will be outlined in further detail based on Fig. 13 and Fig. 14 in the following. The end of the signaling session $t_{signaling}$ of a service as observed by the signaling plane probe 401 and the end of the one or more media streams t_{stream} of the service as observed in the media plane probe 403 may not perfectly match each other as shown in Fig. 13. Even in case signaling plane probe 401 and media plane probe 403 calculate correlation keys based on the same IP address and UDP port tuple, the use of different timestamps $t_{signaling}$ and t_{stream} for the calculation of the correlation key will result in the correlation keys generated by signaling plane probe 401 and media plane probe 403 not matching each other. Additionally the use of rounded timestamps may not necessarily resolve this problem, as it cannot always be assured that the timestamps $t_{signaling}$ and t_{stream} are rounded to the same value. As also highlighted in Fig. 13 it could well happen that signaling plane probe 401 rounds the timestamp $t_{signaling}$ to the next lower rounded value T_1 in accordance with the rounding interval R, while the media plane probe 403 rounds the timestamp t_{stream} to the next higher rounded value T_2 in accordance with the rounding interval R. Again, correlation keys calculated on the different rounded timestamps T_1 and T_2 would not match each other.

As noted above, one possible solution to this problem is to include additional correlation keys at least to one of the signaling session reports and media stream reports. For example, in one exemplary embodiment, the media plane probe 403 could include two correlation keys per direction to the signaling session report. For a given media data path of a media stream (e.g. IP address and UDP port tuple) observed by the signaling plane probe, the signaling

plane probe could calculate one correlation key $C_{stream,1}$ on the media data path information and a rounded timestamp T_1, i.e. using the timestamp indicative of the end of the signaling session $t_{signaling}$ rounded to the next lower value according to the rounding interval, and the signaling plane probe could further calculate one correlation key $C_{stream,2}$ on the media data path information and a rounded timestamp T_2, i.e. using the timestamp indicative of the end of the signaling session $t_{signaling}$ rounded to the next higher value according to the rounding interval. Both correlation keys could then be included for the direction/media data path to the signaling session report.

A further implementation may include even further correlation keys, e.g. a third correlation key that is based on the rounded timestamp T_0, indicative of the next lower timestamp to T_1 according to the rounding interval.

The media plane probe 403 may calculate only one correlation key C_{stream} based on a rounded timestamp T_1 or T_2, i.e. based on the timestamp indicative of the end of the media stream (media data path) t_{stream} rounded to the next lower or higher value according to the rounding interval (and rounding rules). This correlation key for the media stream would then be included to the media stream report.

The correlation of the signaling session to the media stream(s) of the service would be successful in this embodiment, since either the correlation key $C_{stream,1}$ or the correlation key $C_{stream,2}$ within the signaling session report for the given direction/media stream would correspond to the correlation key C_{stream} included in the media stream's media stream report.

Optionally, in another embodiment of the invention, also the media plane probe 403 may calculate two or more correlation keys for each media stream, one correlation key based on the rounded timestamp T_1, i.e. based on the timestamp indicative of the end of the media stream (media data path) t_{stream} rounded to the next lower value according to the rounding interval, and the other correlation key based on the rounded timestamp T_2, i.e. based on the timestamp indicative of the end of the media stream (media data path) t_{stream} rounded to the next higher value according to the rounding interval. Both timestamps would then be included in the media stream report for the media stream by the media plane probe. In this exemplary implementation, the correlation may check whether the two correlation keys of the service's signaling session report for the direction/media stream match the two correlation keys within

the media stream report of the service's media stream to confirm the signaling session report and media stream report belonging to the same service.

Please note that instead of or in addition to the media plane probe 403 including two or more correlation keys to the media stream reports, also the signaling plane probe 401 could calculate two or more correlation keys per direction/media data path that is to be indicated in the signaling session report. Including multiple correlation keys per direction/media data path in the signaling session reports may be advantageous as it reduces the overhead information, since there are commonly less signaling session reports than media stream reports generated in the passive monitoring system.

Furthermore, in another exemplary implementation, the database(s) for signaling session reports and media stream reports may be further partitioned to reduce the search space for correlation. For example, the (respective) database could be partitioned in chunks of multiple hours, e.g. 4 or 6 hours or the like. The signaling session reports and media stream reports may further include as a separate element the timestamps of the end of the signaling session, respectively, the end of the media streams, based on which the database(s) can be partitioned and based on which the correct partition could be chosen for correlation later. Hence, in a more advanced implementation, besides the correlation keys a service end timestamp can be used as a search criteria to limit the amount of data that are to be searched in a database significantly.

In another exemplary implementation, the signaling plane probe may also generate a respective correlation key for all media streams of a service, in case the end of media streams is detectable within the session signaling, as noted previously. In this case the signaling session reports could further include a timestamp that indicates the end of each media stream, in order to allow choosing the correct partition of media stream reports in the database for correlation.

Correlation Mechanisms

For correlation of the media streams and the signaling sessions, different possibilities exist how the correlation by the correlation unit can be implemented. For example, according to exemplary embodiments of the invention, the correlation unit may correlate the media streams and the signaling session of the respective services periodically (or proactive) or in response to a query (i.e. on demand).

For example, a proactive correlation process could be utilized by a third party entity which has access to both signaling session reports and media stream reports. Their data may be

present in one or more databases to ease access to the raw data. As noted above, the correlation aims at correlating signaling and media information of the services and at merging them into combined service reports that may be then accessed by a third party, e.g. for evaluation of the services.

The proactive correlation process periodically takes all new signaling session reports which outline – but not fully describe – the media services, e.g. the monitored VoIP sessions. For each signaling session report the correlation process draws the calculated correlation keys from the signaling session report. There are at least two correlation keys in each signaling session report, at least one per direction. Additional correlation keys may optionally exist in the signaling session report, for instance if it describes a video call or a session with multiple endpoints. For each correlation key contained in a respective signaling session report the correlation process searches the media stream report database for the media streams with the same correlation key. If the correlation keys in the signaling session report are generated based on a timestamp indicating the end of the signaling session, every media stream of the service that existed at the end of the service in the media plane should have the same correlation key and will be in the result set of the search. If the correlation keys in the signaling session report also contain correlation keys for media streams that have been terminated during the ongoing service, the search may also further detect those media streams in the media stream report database based on the correlation key.

If a search returned two or more media stream reports, the correlation process encountered one of two scenarios. Either both media streams belong to the signaling session (i.e. service) or one of them was returned due to a correlation key collision. Both cases may be recovered by comparing the contents of the media stream report against the signaling session report. If a media stream in the result set starts before or ends after a signaling session, it was added to the result set due to a correlation key collision. Due to time information it cannot match the signaling session and is deleted from the result set by the correlation unit. If the media stream result set still contains multiple entries after the previous correlation key collision check, all remaining media streams (i.e. their media stream reports) belong to the media service (e.g. the VoIP session).

If a search returned no usable entry, i.e. no signaling session reports and media stream reports comprising matching correlation keys have been found, the correlation unit may optionally use additional correlation keys contained in either the signaling session reports and/or media stream reports to run another search, as explained with respect to Fig. 13 and Fig. 14 above.

The correlation process may optionally select only the most significant media stream for each direction for inclusion to the service report on the media service. The parameters to define the significance of the media streams may be for example configurable by the user/administrator. One parameter for deciding the significance of a media stream in the result set could be the duration of a media stream. For example, the service report generated for a given media service by the correlation unit could include the media stream with the longest duration, in case multiple media stream reports match a correlation key of a signaling session report. Another option would be to include in the service report the last media stream that has been alive in the media service, in case multiple media stream reports match a correlation key of a signaling session report. The correlation process may optionally add information from multiple media streams to the service report, e.g. when the service consisted of an audio and video part.

For a given signaling session (i.e. service), the correlation process may run at least twice, one time for each correlation key in a signaling session report. For example, in case the media service is a VoIP service, the correlation process may be for example performed by the correlation unit once for the caller's media stream and once for the callee's media stream, both identified by their respective correlation keys in the signaling session report.

The correlation unit combines the information contained in the media stream reports that are correlated to a respective signaling session report and the information contained in the signaling session report to provide a service report, providing an outline of the service. The content of this combined service report may be for example the sum or a subset of information of the signaling and media stream reports of a given service. Furthermore, the content of the service reports for the respective services may be configurable and/or depending on the application.

In another exemplary embodiment of the invention, the correlation unit may perform the correlation based on the media stream reports as starting points which are matched to their corresponding signaling session report. Ideally, each media stream of a media stream report should match to one signaling session report based on its correlation key. This implementation may optimize the search time in the correlation processing. The above correlation mechanism starting from the signaling session reports searches the rather large media stream report database at least twice for each signaling session. If the correlation process is based on the correlation keys within the media stream reports entries as starting point, the correlation would periodically take all new media stream reports, obtain the correlation keys thereof and search the signaling session reports for matching signaling sessions. At this point the same steps are taken as outlined above.

Another option may be to correlate media stream reports and signaling session reports on demand. An on-demand correlation employs the same mechanism as the proactive correlation mechanism described above, but instead of running periodically, e.g. when introducing new signaling session reports or media stream reports into the database(s), the on-demand correlation process runs when a user requests particular data.

In an exemplary implementation, the database may contain independent sets of signaling session reports and media stream reports. An operator could request service reports of services linked to some given search criteria, e.g. a specific user, a specific source and/destination IP address, a certain service type, services using a particular software application, codec, etc. The user could be for example specified by providing a username, phone number, the user's SIP URI, etc. or another identifier of the user that can be found in a signaling session report. The correlation unit would then search for the signaling session reports for all signaling sessions matching the particular search criteria. The search criteria may be for example provided to the correlation unit through a web application running on a browser.

For each signaling session report matching the search criteria, the correlation unit subsequently searches for the matching media stream reports as described above for the proactive correlation process. The input for this on-demand correlation is a set of signaling session reports matching the search criteria and not all signaling session reports as in the proactive correlation procedure described above. The on-demand correlation process generates for each signaling session report matching the search criteria a service report, for example by enriching the information of the signaling session report with the matching media stream report information and returns the service report for each matching signaling session report. The returned data may be for example viewed by the web application as individual service reports. Optionally the on-demand correlation process may also store the generated service reports in a database. This would save the on-demand correlation processing time in case an operator requests the same information multiple times.

Correlation Unit

Next, the correlation unit 402 as shown in Fig. 4 is discussed in further detail with respect to Fig. 5 and Fig. 6. Fig. 6 shows the structure of a correlation unit 402 according to an exemplary embodiment of the invention.

The correlation unit 402 may be reachable via the packet-switched network, e.g. through a web based application. For this purpose, the correlation unit 402 may comprise one or more network interface cards 601. The correlation unit 402 has a receiving unit 602 and a

transmitter unit 603, for example for receiving correlation related messages, such as for example on-demand correlation requests, and for responding thereto. Furthermore, the receiving unit 602 and a transmitter unit 603 may transmit and receive messages for accessing remote database(s) that contain(s) the signaling session reports and the media stream reports. The receiving unit 602 and transmitter unit 603 may receive and transmit the correlation related messages from its network interface card(s) 601.

The correlation unit 402 may also have a processing unit 604. The processing unit 604 may be used to determine correlation respective signaling sessions to their corresponding media streams. Furthermore, the processing unit 604 may be used to generate services reports. The service reports may for example comprise information on the respective services and the quality information of the media streams of the respective services. This information may be obtained from the signaling session report and media stream reports belonging to a given service. For correlation, it may be necessary to query one or more databases that comprise the signaling session reports and the media stream reports as provided by one or more signaling plane probes 401 and media plane probes 403. The correlation unit 402 may therefore comprise a database access unit 605 which provides functionality to access these one or more databases. In one exemplary implementation, the database(s) may be located remote from the correlation unit 403.

The correlation unit 402 may also have a storage unit 606, e.g. a RAM, for (temporarily) storing information and data related to the correlation processing. For example, the result set of media stream reports for correlation process, the data of the signaling session reports, and the service report generated for a respective service may be stored in the storage unit 606.

Fig. 5 shows a flow chart of the operation of the correlation unit 402 according to an exemplary embodiment of the invention. Exemplarily, the correlation processing for determining the media streams belonging to one given signaling session report is illustrated in Fig. 5. In case a correlation should be performed for more than one signaling session (report), the procedure of Fig. 5 is repeated for each signaling session report. For example, when using a proactive correlation mechanism, the correlation unit 402 could obtain all signaling session reports that have been generated since the previous correlation process from a signaling session database and process each of the signaling session reports according to Fig. 5. In another embodiment related to an on-demand correlation process, the correlation unit 402 could also receive a correlation request that is indicating one or more search criteria, and may first – not shown in Fig. 5 – query a signaling session database for all signaling session reports that match the search criteria. The signaling session reports matching the search one or more criteria may then be each processed according to Fig. 5 and the service report(s) are returned to the querying party.

The correlation unit 402 obtains 501 a signaling session report to be processed and generates 502 a service report for the service corresponding to the given signaling session. This service report may include information contained in the signaling session report and will be further supplemented with additional information as described below. Furthermore, the correlation unit 402 obtains 503 a correlation key contained in the signaling session report – as noted previously there should be at least two correlation keys contained in the signaling session report. Using the obtained correlation key, the correlation unit 402 queries 504 a media report database to receive all media stream reports that match the correlation key i.e. that contain the same correlation key.

As noted above, it may happen that the query results in the database returning more than one media stream report for the given correlation key, for example due to a hash collision of the correlation key. Therefore, the correlation unit 402 checks 505 whether the returned result set of the database query comprises more than one media stream report. If not (no), the correlation unit 402 can immediately enrich 508 the service report with information on the media stream as contained in the one media stream report returned from the media stream database.

In case the result set returned by the database comprises multiple media stream reports, the correlation unit 402 may try to detect 506 and resolve a hash collision. For example, the hash collision could be resolved by checking further information in the media stream reports of the result set for parameters that identify the media stream (report) that belongs to the correlation key that has been queried. For example, in case the media stream reports contain timestamps of the beginning and/or end of the media stream, same could be compared to respective timestamps contained in the signaling session report, which yield the beginning and/or end of the signaling session. The media stream report(s) of media stream(s) that start before or end after the signaling session may be obtained from the database due to a hash collision. Accordingly, the correlation unit 402 may select 507 only the most relevant media stream report, i.e. the media stream report that is most likely corresponding to the service of the signaling session report from the result set and may add 508 at least a part of its information to the service report. Further, the correlation unit checks 509 whether there is a further correlation key contained in the signaling session report and, if so (yes), repeats steps 503 to 508. These steps are repeated for each further correlation key(s) comprised in the signaling session report.

Once all correlation keys contained in the signaling session report have been processed, the service report for the signaling session is complete, and may be optionally stored 510 by the correlation unit 402 in a service report database.

Depending on the correlation type or application, the procedure of Fig. 5 could be supplemented with additional steps. For example, in case of a proactive/periodic correlation, the correlation unit 402 may check whether there is another signaling session report to be matched to its corresponding media stream reports, and if so the procedure of Fig. 5 would be executed for each signaling session report to be processed. In case of performing a correlation on demand, the correlation unit 402 may likewise check whether there is another signaling session report to be matched to its corresponding media stream reports, and if so the procedure of Fig. 5 would be executed for each signaling session report to be processed. Once all signaling session reports have been processed the correlation unit 402 may generate a correlation response message comprising the service reports generated by the correlation unit 402 in response to the search criteria provided in a correlation request, and returns the correlation response message to the querying entity, e.g. another device/computer.

Signaling Plane Probe

Fig. 9 shows an exemplary implementation of a signaling plane probe 401 and Figs. 7 and 8 show two exemplary flow charts of the operation of same according to different embodiments of the invention. In general, the signaling plane probe 401 observes one or more network links to obtain a copy of all packets passing these network links/interfaces. For this purpose, the signaling plane probe 401 comprises a monitoring unit 901 that receives 701 packets of a service on the packet-switched network 400. For example, this monitoring unit 901 may receive the packets from a one or more specialized packet capture cards 906 (network interface card - NIC) which is capable of receiving and processing packets on the physical interface and to provide them to the application layer, nearly without requiring CPU processing time and operation system functionality. An optional filter in each packet capture card of the signaling plane probe 401 may be used to prevent unwanted packets from being copied from the network interfaces to the processing processes. These filters may be for example implemented as stateless or stateful Internet Protocol (IP) or payload filters. For example, this filter may check 702, whether the currently processed packet is a signaling packet or not. If the packet does not belong to a signaling session, i.e. is not packet of a signaling related protocol, the next packet may be processed.

Each signaling packet received at the signaling plane probe 401 will be processed by a detection unit 902 which analyzes the contents of the packets provided by the monitoring unit 901 so as to identify and process packets as signaling packets. Specifically, the detection unit 902 detects signaling packets and matches these to signaling sessions of the media service, and is capable of identifying one or more media data paths of a media plane of the

service based on signaling information of the service comprised in the received packets. Optionally, the detection unit 902 may be provided in one or more specialized packet capture cards.

For example, the detection unit 902 identifies packets containing signaling information (signaling packets) in a parsing process based on their header information. If parsed successfully as a signaling packet, the signaling packet is forwarded to a state engine. The state engine is designed to identify 703 and form signaling sessions from individual signaling packets.

The state engine (which may be considered an internal database with correlation related information maintained in the storage unit 903) of the detection unit 902 has a processing facility and a state table which holds information about signaling sessions (signaling session records). Based on the protocol-specific identifiers in the signaling packets the detection unit 902 can identify the start and end of a signaling session, respectively media service, or "append" a respective processed signaling packet to an existing signaling session. Signaling packets may also contain information on the start and termination of media streams in the media plane of the media service, which are events that may be tracked by the detection unit 902. Depending on whether the identified signaling session is already registered in the signaling plane probe 401 (step 704), the detection unit 902 registers 705 the new signaling session in the state table, including the generation of a new signaling session record for the signaling session.

The signaling session record may be supplemented with information on the signaling session while same is running to account – for example – for endpoint address/name (e.g. SIP URI); the phone number of the user; the user-agent (endpoint software and version); capabilities/features; supported media types; IP addresses and ports for signaling and media streams (from SDP body); signaling routing information; timestamps: e.g. session start, Post-Dial-Delay (PDD), connect time, session end; information on the session flow (e.g. signaling message(s) with timestamps); session state (e.g. successful, unsuccessful, timed out, reason for failure), and/or events during session (media on hold, codec renegotiation, session forking, authentication), etc.

Furthermore, by analyzing 706 the contents of the signaling packets, e.g. a SDP body of a SIP messages comprised in signaling packets, the detection unit 902 may further learn one or more media data paths of the media plane of the service belonging to the media service that is associated to a given signaling session. The signaling plane probe 401 may further comprise a storage unit 903, e.g. a volatile memory, to store the information describing the state of the respective signaling sessions in the state table. In case the signaling packet

indicates the start of a new media stream (step 706: yes), the detection unit 902 may add 707 information on the media data path (e.g. IP address and port number of the destination, and optionally the source of the media stream) of this media stream to the signaling session record. Likewise, in case the signaling packet indicates the end/termination of a new media stream (step 708: yes), the detection unit 902 may remove the information on the respective media stream from the signaling session record maintained in storage unit 903. In case the signaling packet indicates the termination of the signaling session (step 710: yes), the detection unit 902 may either itself or trigger the processing unit 904 to generate 711 a respective correlation key for each media data path indicated in the signaling session record. The correlation key for a respective media data path of a media stream may be generated for example based on information on the directivity of the media stream (e.g. as given by the tuple of destination IP address and UDP port number) and a timestamp indicating the point in time at which the signaling session was terminated. For example, this timestamp may indicate the point in time of reception of the signaling packet indicating the event of the termination of the signaling session at the signaling plane probe 401. For example, the network interface card(s) 906 of the signaling plane probe could generate a timestamp indicating the time of reception of the respective signaling plane packet and could make same available to the other components of the signaling plane probe 401. Furthermore, the detection unit 902 or the processing unit 904 may further generate 912 a signaling session report based on the information on the signaling session gathered in the signaling session record. Further, the signaling session report also included the correlation keys for the media data paths of the service that exist at the end of the service according to the signaling plane information. The signaling session report may then be stored in a signaling session report database, for example using the database access unit 907 of the signaling plane probe 401. Moreover, the signaling session is deregistered 713 from the state table.

Once a given signaling packet has been processed, it may be discarded. It should be also noted that the order of the checks in steps 706, 708 and 710 and the respective actions to be taken is only exemplary. It is only important that the information on the media streams of the service that exist in the media plane are tracked by the signaling plane probe 401, and that the signaling plane probe 401 is able to detect the termination of the signaling session.

Optionally (not shown in Fig. 7), in another exemplary embodiment, the detection unit 902 of the signaling plane probe 401 periodically (e.g. every 5, 10 or 15 seconds) traverses all entries in the state table in order to find and clean up stale signaling sessions. For this purpose, the signaling plane probe 401 may add a timestamp to each signaling session record in the state table that is updated each time a new signaling packet/message of the respective signaling session is received. Based on this timestamp allows to identify stale

signaling session by simply checking based on the signaling sessions' timestamps whether the last signaling packet/message for a given signaling session has been received longer than a threshold time period ago. For example, stale sessions might be those which did not receive new signaling packets/messages for 86400 seconds or signaling sessions may be defined stale and are terminated after a certain time. This clean-up removes unnecessary information from the state.

Fig. 8 shows another flow chart of the operation of a signaling plane probe 401 according to another embodiment of the invention. In the example discussed with respect to Fig. 7, the signaling plane probe 401 keeps track of the media streams currently existing in the media plane of the service, eliminating those media streams from the signaling session record that are terminated during the ongoing signaling session/service. In the flow chart of Fig. 8, which is corresponding to Fig. 7 to a large extent, the termination of one or more media streams in the media plane, as detected in step 708, causes the detection unit 902 or the processing unit 904 (triggered by the detection unit 902) to generate 801 a correlation key for each terminated media stream. Similar to the other correlation keys, the correlation key for a terminated media stream may be generated based on its media data path information (e.g. destination IP address and UDP port number) and a timestamp that indicates the point in time the media stream was terminated. This timestamp may indicate the point in time of reception of the signaling packet indicating the event of the termination of the media stream at the signaling plane probe 401. The correlation key generated is then added 802 to the signaling session record of the signaling session by the detection unit 902 or the processing unit 904 and is later then also stored in the signaling session report in step 712 together with the other correlation keys either generated in step 801 or step 711.

Media Plane Probe

Next, the media plane probe 403 according to an exemplary embodiment of the invention is described with respect to Fig. 10 and Fig. 11. Fig 10 shows an exemplary embodiment of a media plane probe 403, while Fig. 11 shows a flow chart of its exemplary operation according to an embodiment of the invention.

Similar to the signaling plane probe 401, the media plane probe 403 observes one or more network links to obtain a copy of all packets passing these interfaces. The media plane probe 403 may observe one or more network links to obtain a copy of all packets passing these interfaces. The media plane probe 403 comprises a monitoring unit 1001 that receives 1101 packets of a service on the packet-switched network 401. For example, this monitoring unit 1001 received the packets from one or more specialized packet capture cards 1006 (network interface card - NIC) which are capable of receiving and processing packets on the physical

interface and to provide them to the application layer, nearly without requiring CPU processing time and operation system functionality. An optional filter in the packet capture card of the media plane probe 403 may be used to prevent unwanted packets from being copied from the network interfaces to the processing processes. This filter may be for example implemented as stateless or stateful Internet Protocol (IP) or payload filter. For example, this filter may check 1102, whether the currently processed packet is a media plane packet (media packet) or is some other packet. If the packet does not belong to the media plane, i.e. is not packet of a media related protocol, such as for example RTP, the next packet may be processed.

Each media packet received will be processed by the media plane probe 403. The detection unit 1002 of the media plane probe 403 is designed to detect and form media streams from single media packets. The media plane probe 403 may further comprise a processing unit 1002 that may hold a state table which stores information about the media streams monitored by the media plane probe 403 in a local storage unit 1003, e.g. a volatile memory. Based on the protocol-specific identifiers in the media streams the media plane probe 403 (e.g. based on header information in the RTP packets and/or lower layer headers) the detection unit 1002 identifies 1103 the media data path, i.e. the media stream, the media packet belongs to. If the media data path has not been yet registered (step 1104: no), i.e. the processed media packet starts a new media stream (with the given media data path) the detection unit 1002 generates a new media data record in the state table to account for the new media data path observed by the media plane probe 403. This media stream record may contain information on the media stream such as for example the destination (and optionally the source) IP address and port combination of the media stream, the SSRC in the packet header (in case RTP is used for media transport), etc. If the media data path is already known (step 1104: yes), the media stream record already exists. In any case, the detection unit 1002 updates a timestamp 1106 in the media stream record to indicate the point in time at which the last media packet of the media stream has been received. This timestamp may be used for calculating the correlation key for the media stream. Furthermore, the detection unit 1002 may (re)start a timer 1108 for the media stream record, which when timing out is indicating the termination of the media stream as will be outlined below. Alternatively, no timer is used, but the media plane probe 403 periodically checks for media streams the last media packet of which was received more than a threshold time period ago, in order to determine terminated media streams.

The media stream records of the media streams may for example indicate the respective media data paths thereof by an IP address and port tuple of the destination device, i.e. the receiving device of the media stream. The media plane probe's detection unit 1002 stores

information describing the state of the detected media streams in the media stream records maintained in the state table. Optionally, the individual media streams (i.e. their media data paths) may be identified by a media path identifier (e.g. stream hash key) as unique key. Further optionally, upon detecting a new media stream, respectively media path (step 1104: no), the processing unit 1004 could generate 1105 a media path identifier (e.g. a media path identifier (e.g. stream hash key)) for the media stream, respectively media path and stores 1106 the media stream record in the state table as outlined above.

Optionally, the processing unit 1004 could analyze every received packet for quality information 1107 and – further optionally – store them in the storage unit 1003 for a given time period. Periodically the processing unit 1004 may aggregate or compress the quality information to form fine-grained media stream quality reports with media stream related information. Fine-grained media stream quality reports could be for example written in predetermined time intervals, e.g. every five seconds, and could provide a summary of the media stream in the respective interval and the aggregated quality information of the media stream in the respective interval. Upon generation of a respective fine-grained media stream quality report, the packets used for the generation of this fine-grained media stream quality report can be removed from the storage unit 1003.

The processing unit 1004 of the media plane probe may for example periodically check 1109 (e.g. every 5, 10 or 15 seconds); whether a timer set of a media stream (record) in step 1108 has expired. Alternatively, as noted above, the media plane probe 403 may also check timestamps indicating the last update (i.e. last reception of a media packet) of the respective media stream reports in the state table. A media stream may be for example considered terminated, if no new media packets have been received by the monitoring unit 1001 for the existing media stream for a given amount of time (e.g. 60 seconds). Accordingly, if using a timer to monitor the termination, the timer value could be set to this given amount of time. Further alternatively, instead of periodically checking the media stream records or expiry of their timers, the expiry of a timer for a media stream (record) could cause an interrupt invoking the processing unit 1004 to perform steps 1110 to 1112 as outlined below.

Upon detecting the termination of a media stream, the processing unit 1004 processes the respective information in the media stream record of this media stream the state table. The processing unit 1004 generates 1110 a correlation key for the media stream based on its media data path information (e.g. the destination IP address and UDP port number) and the timestamp in the media stream record that is indicating the point in time of receiving the last media packet of the media stream (see step 1106). Furthermore, the processing unit 1004 generates 1111 a media stream report for the media data path, respectively media stream, which includes the generated correlation key and further information on the media stream.

This further information may be for example transport media information and optionally stream quality information. For example, in case RTP is used for media transport, the transport media information could include the source and destination IP address of the RTP stream, the source and destination UDP port of the RTP stream, the RTP header Synchronization source (SSRC) value and the RTP payload type. Furthermore, the processing unit 1004 may also generate information on the media stream quality that is included to the media stream report as stream quality information. This stream quality information could for example include timestamp information (e.g. start and/or end time of the media stream), an indication of RTP format violations (e.g. the number thereof), information on the protocol conformance (e.g. sequence errors and/or DSCP errors), and transport information (e.g. packet interval and jitter statistics, information on packet loss, information on duplicate packets, etc.), MOS values (e.g. per time-slice (e.g. every 5 seconds), minimum/average/maximum value for entire stream duration, etc.), and/or events (e.g. comfort noise, silence suppression, DTMF tones, codec changes, marker bits). The contents of the media stream reports may be configurable by an operator and may be adapted to customers' needs.

The media stream record may be further stored in a media stream report database using the database access unit 1007 of the media plane probe 403. Finally, the processing unit 1004 of the media plane probe 403 deregisters 1112 the media data path from the state table, e.g. by deleting the corresponding media stream record.

Steps 1110 to 1112 are performed for every media stream that is considered terminated by the media plane probe.

Optimizations may be used to speed up processing of entries in the state tables inside the signaling plane probe 401, the correlation unit 402 and the media plane probe 403. A simple list would be sufficient to implement the features as outlined above. Add, modify, delete and search operations on simple lists may however be too slow. These operations may be implemented utilizing more complex but faster data structures, e.g. hash tables or data structures heavily dependent on CPU and Operating System specific behavior and functionality. The Intel Thread Building Block (TBB) library for instance can be used to implement in-memory databases used for the state tables in the signaling plane probe 401, the correlation unit 402 and the media plane probe 403. The Intel Thread Building Block (TBB) library may also be used to aid implementation of the processing queues inside and in between the components outlined above.

Please note that in case the signaling plane probe 401 and the media plane probe 403 should perform passive non-intrusive monitoring of the signaling plane traffic, respectively

media plane traffic, a separate network interface card is employed for the transmission of correlation related messages (i.e. the network interface card(s) for monitoring the traffic are only employed for packet reception but not for packet transmission).

Please also note that in the procedures described above the detection unit 902, 1002 and the processing unit 904, 1004 may use the database access unit 907, 1007 to access the database/state table in the storage unit 903, 1003.

Application

The correlation mechanism for signaling plane and media plane of a service may be used in manifold applications. For example, the correlation mechanism is useful in small networks but is more important in larger scale networks where the various signaling and media components are decomposed and present on different, sometimes geographically split, network entities. This is the case in IP Multimedia Subsystem (IMS) or Next Generation Network (NGN) setups.

Fig. 12 shows a simplified network in which locations are indicated where correlation may be desired and can be implemented using the correlation mechanism according to one of the various embodiments described herein. Possible monitoring locations are for example (and not limited thereto):

- The Access Session Border Controller (SBC) network interfaces with end customers (shown of the left side of Fig. 12),
- a decomposed gateways system, e.g. to the PSTN, is shown as Media Gateway (MGW) and a Media Gateway Controller (MGC) – see In the top right section of Fig. 12, and
- an Interconnection SBC interfaces to one or more interconnection or transit partners (see the lower right side of Fig. 12.

It should be noted that the location of the monitoring probes for signaling plane and media plane may also be subject to requirements on the monitoring solution.

In some cases, signaling plane and media plane may originate and/or terminate at the same endpoint (device). In case of an end customer this endpoint most likely uses the same IP address on the signaling and media plane. These streams may be for example observed, if the signaling plane probes 401 and the media plane probes 403 are placed close to the end customer devices. The Access Session Border Controller may be considered to be close to the carrier internal network's "border" towards end customer devices and to therefore receive

traffic from the end customers on one side and transmits this traffic on the other side towards the carrier internal network. Most commonly these Session Border Controllers (SBC) are used to separate the devices outside the own trust domain from the inside network. Although the traffic is in one geographic location the SBC may use different IP addresses to load balance traffic. In this case a simple IP address based correlation mechanism not using the principles and ideas outlined herein would already fail whereas the correlation mechanism described herein would succeed. The signaling plane probes 401 and media plane probes 403 may be for example placed in a way that they observe the signaling streams and media streams respectively.

In the upper right corner of the diagram shown in Fig. 12, a decomposed gateway is shown which uses different physical entities as media and signaling components (MGC and MGW, respectively). In between those devices a third party protocol may be used to synchronize the devices. For the sake of a minimum size network diagram only one of each component types is shown but in real life scenarios multiple media components are controlled by one signaling component (as it is the case in IMS, NGN). The media components may be co-located in the same location with the signaling component or spread across the internal network of the carrier. In either case the correlation task is rather complex as it involves multiple IP addresses on different physical network links and thus may require multiple signaling plane probes 401 as well as media plane probes 403.

In a third exemplary scenario the correlation has to correlate signaling and media streams from different locations. A media plane probe 403 component on the internal side of the interconnection point (lower right corner of the diagram – Interconnection SBC) observes a media stream from the Access SBC (middle left). The corresponding signaling session is observed next to the aforementioned Access SBC by a separate signaling plane probe 401.

The location of the correlation unit 402 does not impact what signaling sessions or media streams can be correlated. The correlation unit 402 should have access to the signaling session reports and media stream reports of the signaling plane probes 401 and media plane probes 403 and can be implemented as distinct physical machine or co-located on an existing signaling plane probe 401 or media plane probe 403.

The terms probe and correlation unit used herein can be considered to refer to dedicated hardware, a software program or a combination thereof to implement the desired functionality of the respective probe, respectively, correlation unit. Accordingly, another embodiment of the invention relates to the implementation of the above described various embodiments using hardware and software. It is recognized that probes and correlation unit of the invention may be implemented by having computing devices (processors) execute a software

program that causes the desired functionality being executed. A computing device or processor may for example be general purpose processors, digital signal processors (DSP), application specific integrated circuits (ASIC), field programmable gate arrays (FPGA) or other programmable logic devices, etc. Some of the computing devices may store the software program internally.

The various embodiments of the invention may also be performed or embodied by a combination of computing devices and software programs providing the desired functionality stored on any kind of computer readable storage media, for example RAM, EPROM, EEPROM, flash memory, registers, hard disks, CD-ROM, DVD, etc.

It should be further noted that the individual features of the different embodiments of the invention may individually or in arbitrary combination be subject matter to another invention.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A method for correlating media streams and signaling sessions of services in a passive monitoring system of a packet-switched network, the method comprising:

a) generating at least one correlation key for each direction of a service based on the information of the signaling session of the respective service monitored at the signaling plane probe, wherein the correlation keys for a respective service are generated using a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the signaling plane probe and using information on the direction of the respective service,

b) storing, by the signaling plane probe, a signaling session report for each signaling session in a database, wherein each signaling session report comprises the at least two correlation keys generated for the respective directions of the service,

c) generating a correlation key for each media stream monitored by the media plane probe, wherein the correlation key is generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream,

d) storing, by the media plane probe, a media stream report for each media stream in a database, wherein each media stream report comprises at least the correlation key generated for the respective media, and

e) correlating the media streams and the signaling sessions based on the correlation keys comprised within media stream reports and signaling session reports.

2. The method according to claim 1, wherein the generation of the respective correlation keys for the respective media streams by the media plane probe is based on the media data path information of the respective media stream and the timestamp indicative of the point in time at which the respective media stream ended.

3. The method according to claim 1 or 2, wherein information on the direction of the respective service, based on which the correlation keys are generated by

signaling plane probe for a respective service, is information on one or more media data paths of media streams of the service learned from messages of the signaling session of the service.

4. The method according to one of claims 1 to 3, further comprising the steps of:

f) monitoring, by the signaling plane probe, signaling messages of the respective signaling sessions of the services, and

g) detecting, by the signaling plane probe, media streams belonging to each service associated to a respective monitored signaling session based on the signaling messages of the respective signaling sessions,

wherein the correlation keys for a respective one of the signaling sessions are generated based on information on the media data path of the media streams belonging to the service associated to the respective one of the signaling sessions and the timestamp indicative of the point in time at which the end of the respective signaling session has been detected by the signaling plane probe.

5. The method according to one of claims 1 to 4, wherein information on a media data path of a media stream is a destination IP address and port number of the media stream.

6. The method according to one of claims 1 to 5, wherein the timestamps used for the generation of the correlation keys by the signaling plane probe and the media plane probe are rounded before the generation of the correlation keys or have a granularity in the range of one to ten seconds.

7. The method according to one of claims 1 to 6, wherein the signaling plane probe generates for each direction of the service at least one correlation key using a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the signaling plane probe and being rounded to the next lower timestamp value according to a rounding interval, and at least another correlation key using the timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the signaling plane probe and being rounded to the next higher timestamp value according to the rounding interval.

8. The method according to one of claims 1 to 7, wherein the media plane probe generates for each media stream at least one correlation key using a timestamp indicative of the point in time at which the respective media ended and being rounded to the next lower timestamp value according to a rounding interval, and at least another correlation key using the timestamp indicative of the point in time at which the respective media stream ended and being rounded to the next higher timestamp value according to the rounding interval.

9. The method according to one of claims 1 to 8, wherein the correlation of the media streams and the signaling session of the respective services is performed by a correlation unit periodically or in response to a query.

10. A method for correlating media streams and signaling sessions of services, the method comprising the steps of:

a) correlating the media streams and the signaling sessions of one or more services based on the correlation keys comprised within media stream reports of the media streams and signaling session reports of the signaling sessions to thereby identify the media stream reports and signaling session report belonging to a respective one of said one or more services, wherein correlating the media streams and the signaling sessions comprises identifying one or more media streams of a respective service and the corresponding signaling session of the respective service based on the correlation keys contained in the media stream reports and signaling session reports, and

b) generating a service record for a respective one of said at least one service based on information contained in the media stream reports and information contained the signaling session report of said at least one service.

11. The method according to claim 10, wherein correlation keys provided in a respective signaling session report have been generated using a timestamp indicative of the point in time at which the end of the respective signaling session of the corresponding service has been detected and using information on the media streams of the service.

12. The method according to claim 10 or 11, wherein correlation key provided in a respective media stream report has been generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the media stream.

13. The method according to one of claims 10 to 12, wherein correlating the media streams and the signaling sessions of one or more services based on the correlation keys comprised within media stream reports of the media streams and signaling session reports of the signaling sessions comprises:

matching the respective correlation keys of the media stream reports of media streams are to the respective correlation keys of the signaling session reports, or vice versa,

wherein a match of the correlation keys of a one of the media stream reports and one of the signaling session reports yields the media stream of said one media stream report belonging to the same service to which the signaling session of said one signaling session report belongs.

14. The method according to one of claims 10 to 13, wherein the service report comprises information on the service and the quality information of the media streams of the service.

15. The method according to one of claims 10 to 13, wherein correlating the media streams and the signaling sessions of one or more services based on the correlation keys comprised within media stream reports of the media streams and signaling session reports of the signaling sessions comprises:

obtaining from a signaling session report correlation keys identifying the media streams belonging to the same service as the signaling session, and

identifying those media stream reports which include one of the correlation keys obtained from the signaling session report.

16. The method according to one of claims 10 to 13, wherein correlating the media streams and the signaling sessions of one or more services based on the correlation keys comprised within media stream reports of the media streams and signaling session reports of the signaling sessions comprises:

obtaining from a media stream report a correlation key identifying the media stream, and

identifying a signaling session report among the signaling session reports which includes the same correlation key obtained from the signaling session report.

17. The method according to one of claims 10 to 16, wherein steps a) and b) are performed by a correlation unit periodically for all signaling session reports and media stream reports generated within a configurable time interval, or in response to a request.

18. The method according to one of claims 10 to 17, further comprising steps a) to d) of claim 1 or the steps of the method according to one of claims 2 to 9.

19. A passive monitoring system for correlating media streams and signaling sessions of services in a packet-switched network, the passive monitoring system comprising:

a signaling plane probe for generating at least one correlation key for each direction of a service based on the information of the signaling session of the respective service monitored at the signaling plane probe, wherein the correlation keys for a respective service are generated using a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the signaling plane probe and using information on the direction of the respective service,

wherein the signaling plane probe is further adapted to store a signaling session report for each signaling session in a database, wherein each signaling session report comprises the at least two correlation keys generated for the respective directions of the service,

a media plane probe for generating a correlation key for each media stream monitored by the media plane probe, wherein the correlation key is generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream,

wherein the media plane probe is adapted to store a media stream report for each media stream in a database, wherein each media stream report comprises at least the correlation key generated for the respective media, and

a correlation unit for correlating the media streams and the signaling sessions based on the correlation keys comprised within media stream reports and signaling session reports.

20. A signaling plane probe comprising:

a network interface card for receiving packets of signaling sessions of multiple media services,

monitoring unit for monitoring the signaling sessions based on the packets of the signaling sessions received by the signaling plane probe to thereby obtain information on a respective one of the signaling sessions, wherein the monitoring unit is further adapted to detect the point in time at which a respective signaling session of the respective service terminates, and

a processing unit for generating at least one correlation key for each direction of a service based on a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected by the monitoring unit and based on information on the direction of the respective service,

wherein the monitoring unit is adapted to store a signaling session report for each signaling session in a database, wherein each signaling session report comprises at least two correlation keys generated for the respective directions of the service.

21. A media plane probe comprising:

a network interface card for receiving packets of media streams of multiple media services,

monitoring unit for monitoring the media streams based on the packets of the media streams received by the media plane probe to thereby obtain information on a media data path a respective one of the media streams, wherein the monitoring unit is further adapted to detect the point in time at which a respective media stream of the respective service terminates, and

a processing unit for generating a correlation key for each media stream monitored by the monitoring unit, wherein the correlation key is generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream,

wherein the monitoring unit is adapted to store a media stream report for each media stream in a database, wherein each media stream report comprises at least the correlation key generated for the respective media.

22. A correlation unit for correlating media streams and signaling sessions of services in a passive monitoring system of a packet-switched network, the correlation unit comprising:

a database access unit for accessing a database containing signaling session reports for signaling sessions of services and a database comprising media stream reports of media streams of the services, wherein the signaling session reports each contain at least one correlation key for each direction of a respective service, and the media stream reports each contain one correlation key indication the direction of the media stream,

a processing unit for correlating the media streams and the signaling sessions of the services based on the correlation keys comprised within media stream reports and signaling session reports to thereby identify the media stream reports and signaling session report belonging to a respective one of said one or more services, wherein the processing unit is adapted to identify one or more media streams of a respective service and the corresponding signaling session of the respective service based on the correlation keys contained in the media stream reports and signaling session reports, and

a service record generation unit for generating a service record for a respective one of said at least one service based on information contained in the media stream reports and information contained the signaling session report of said at least one service.

23. The correlation unit according to claim 22, further comprising means to perform the steps of the method according to one of claims 10 to 17.

24. A computer-readable medium storing instructions that, when executed by a processor of a signaling plane probe, cause the signaling plane probe:

to receive packets of signaling sessions of multiple media services,

to monitor the signaling sessions based on the packets of the signaling sessions received by the signaling plane probe to thereby obtain information on a respective one of the signaling sessions,

to detect the point in time at which a respective signaling session of the respective service terminates,

to generate at least one correlation key for each direction of a service based a timestamp indicative of the point in time at which the end of the respective signaling session of the respective service has been detected and based on information on the direction of the respective service, and

to store a signaling session report for each signaling session in a database, wherein each signaling session report comprises the at least two correlation keys generated for the respective directions of the service.

25. A computer-readable medium storing instructions that, when executed by a processor of a media plane probe, cause the media plane probe:

to receive packets of media streams of multiple media services,

to monitor the media streams based on the packets of the media streams received by the signaling plane probe to thereby obtain information on a media data path a respective one of the media streams,

to detect the point in time at which a respective media stream of the respective service terminates, and

to generate a correlation key for each media stream monitored by the monitoring unit, wherein the correlation key is generated using a timestamp indicative of the point in time at which the respective media stream has ended and using information on the media data path of the respective media stream,

to store a media stream report for each media stream in a database, wherein each media stream report contains at least the correlation key generated for the respective media.

26. A computer-readable medium storing instructions that, when executed by a correlation unit, cause the correlation unit to correlate media streams and signaling sessions of services in a passive monitoring system of a packet-switched network, by:

accessing a database containing signaling session reports for signaling sessions of services and a database containing media stream reports of media streams of the services, wherein the signaling session reports each contain at least one correlation key for each direction of a respective service, and the media stream reports each contain one correlation key indication the direction of the media stream,

correlating the media streams and the signaling sessions of the services based on the correlation keys comprised within media stream reports and signaling session reports to thereby identify the media stream reports and signaling session report belonging to a respective one of said one or more services,

identifying one or more media streams of a respective service and the corresponding signaling session of the respective service based on the correlation keys comprised in the media stream reports and signaling session reports, and

generating a service record for a respective one of said at least one service based on information contained in the media stream reports and information contained the signaling session report of said at least one service.

27. The computer-readable medium according to claim 26, further storing instruction that, when executed by the processor of the correlation unit, cause the correlation unit to perform the steps of the method according to one of claims 10 to 17.

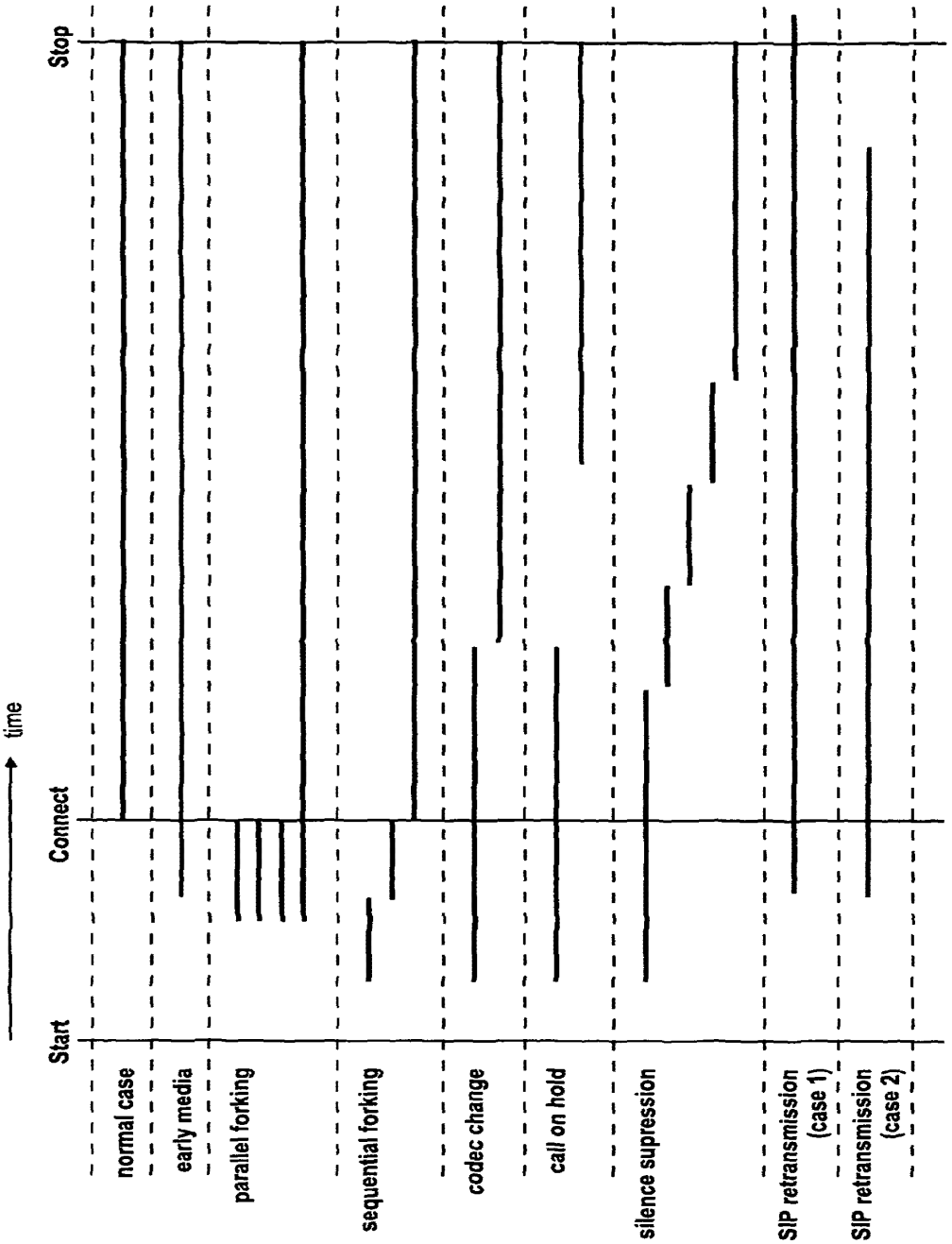

time
Start
Connect
Stop
normal case
early media
parallel forking
sequential forking
codec change
call on hold
silence supression
SIP retransmission (case 1)
SIP retransmission (case 2)

Fig. 1

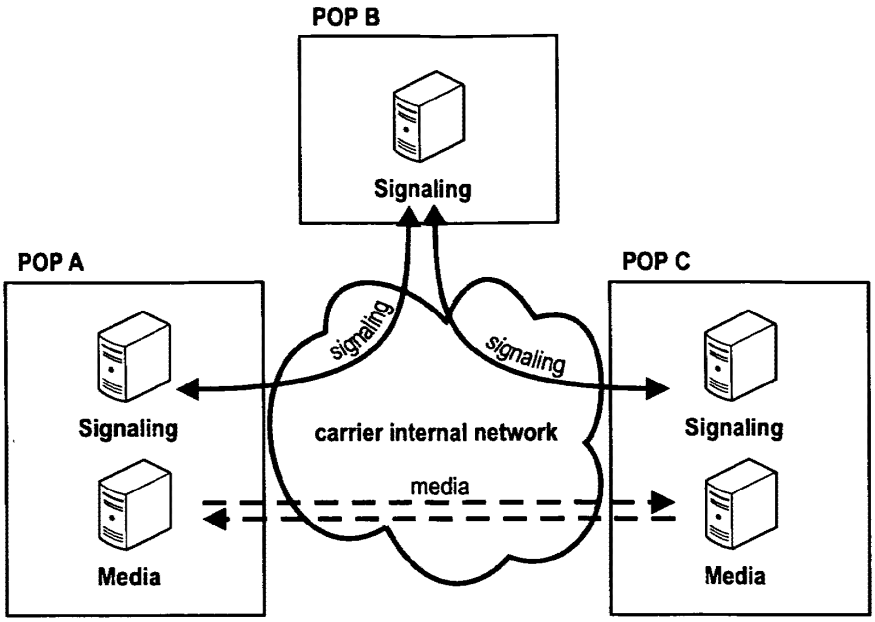

POP B
Signaling
POP A
POP C
signaling
signaling
Signaling
carrier internal network
Signaling
media
Media
Media

Fig. 2

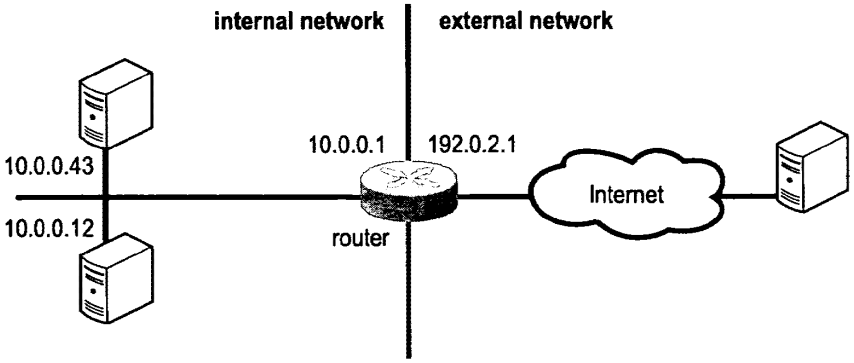

internal network
external network
10.0.0.43
10.0.0.12
10.0.0.1
192.0.2.1
router
Internet

Fig. 3

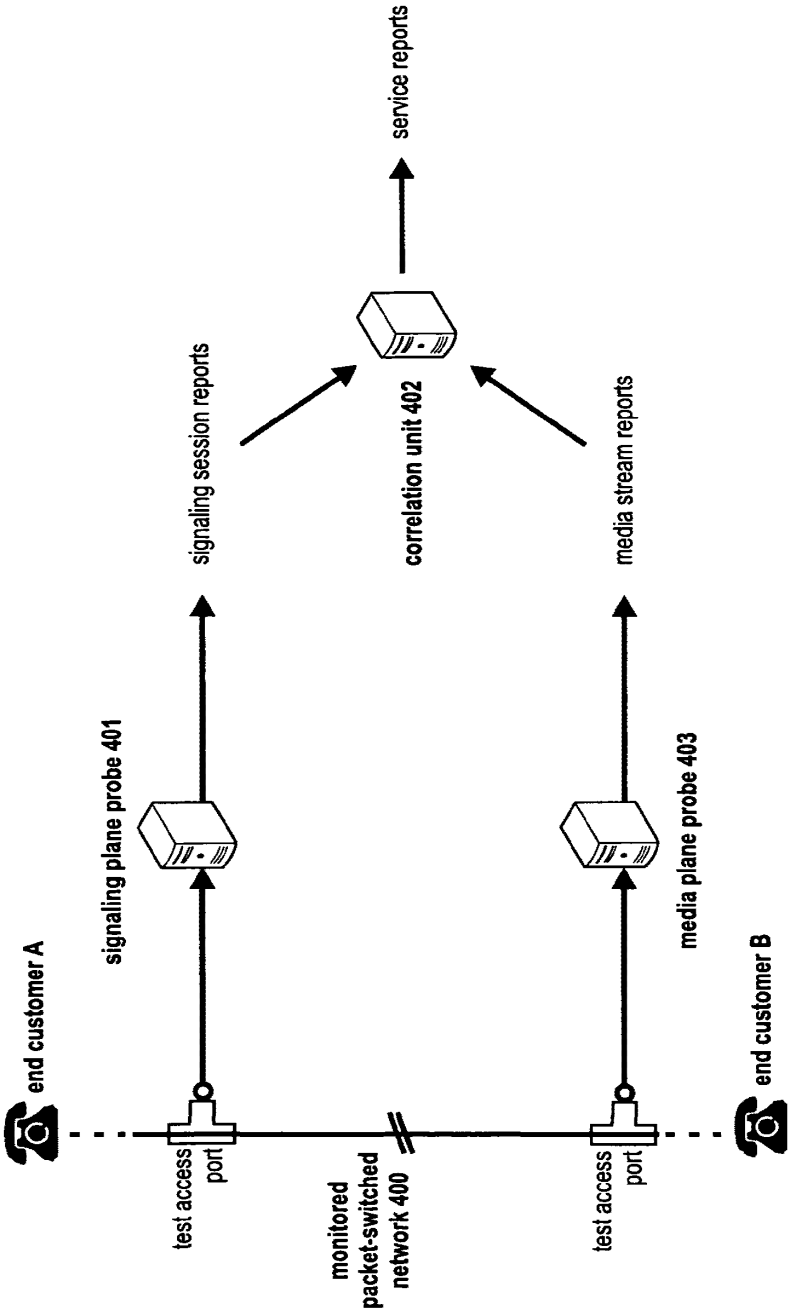

service reports
signaling session reports
correlation unit 402
media stream reports
signaling plane probe 401
media plane probe 403
end customer A
end customer B
test access port
test access port
monitored packet-switched network 400

Fig. 4

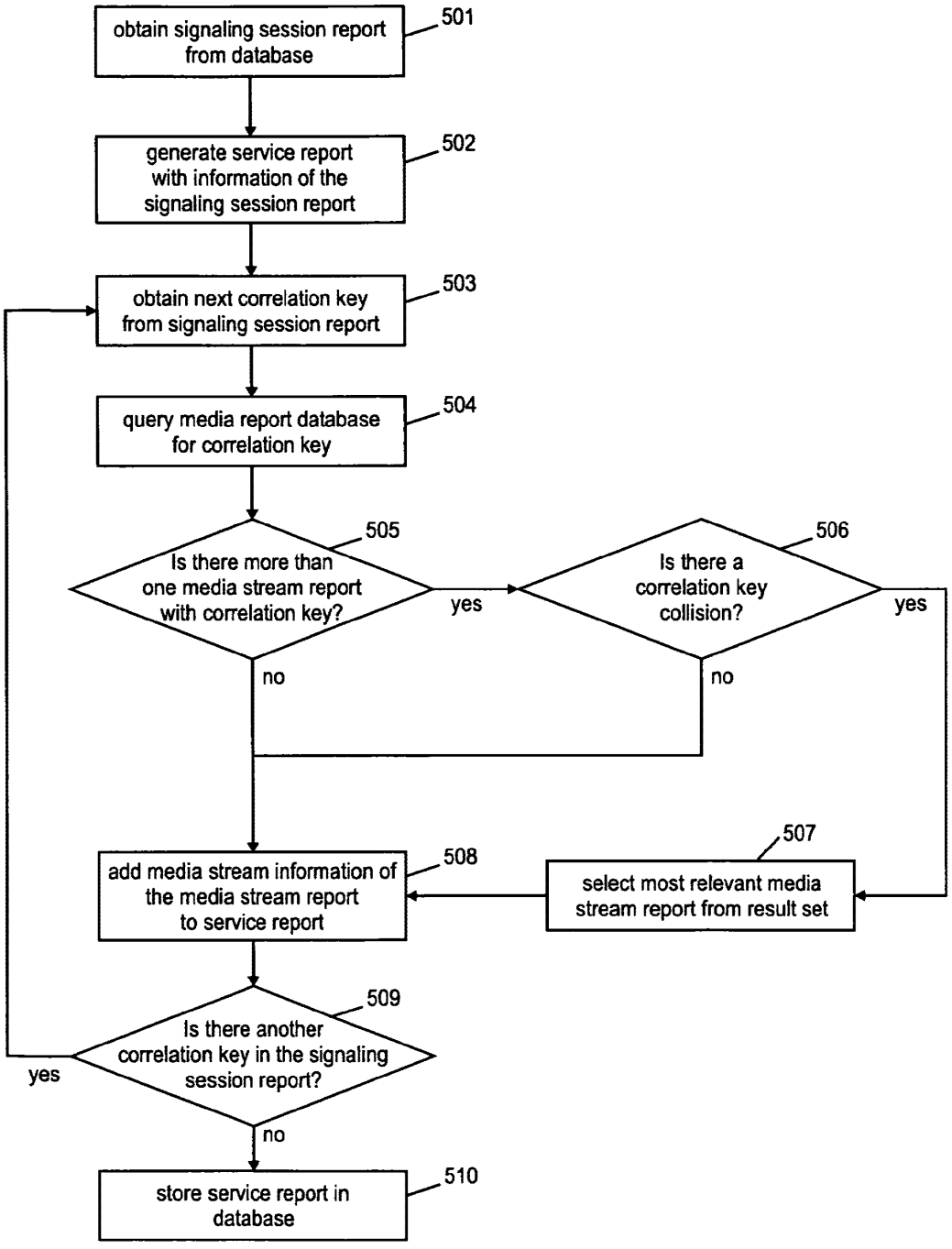

obtain signaling session report from database
501
generate service report with information of the signaling session report
502
obtain next correlation key from signaling session report
503
query media report database for correlation key
504
Is there more than one media stream report with correlation key?
505
yes
Is there a correlation key collision?
506
yes
no
no
add media stream information of the media stream report to service report
508
select most relevant media stream report from result set
507
Is there another correlation key in the signaling session report?
509
yes
no
store service report in database
510

Fig. 5

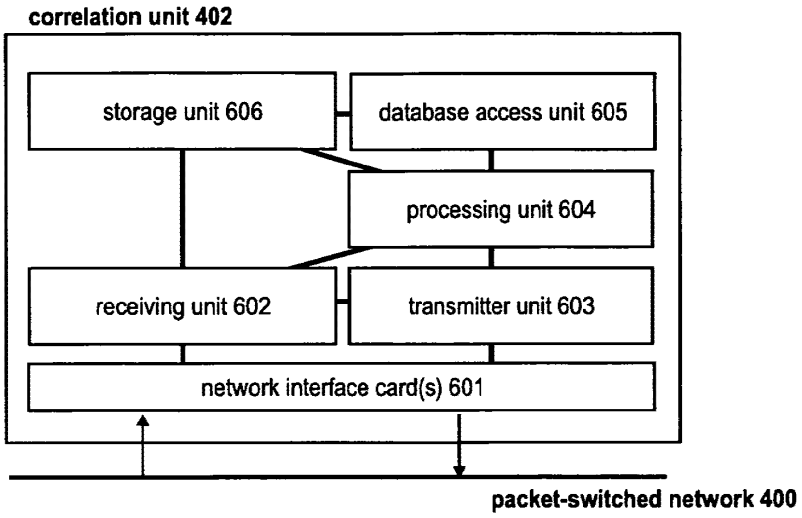

correlation unit 402
storage unit 606
database access unit 605
processing unit 604
receiving unit 602
transmitter unit 603
network interface card(s) 601
packet-switched network 400

Fig. 6

Fig. 7

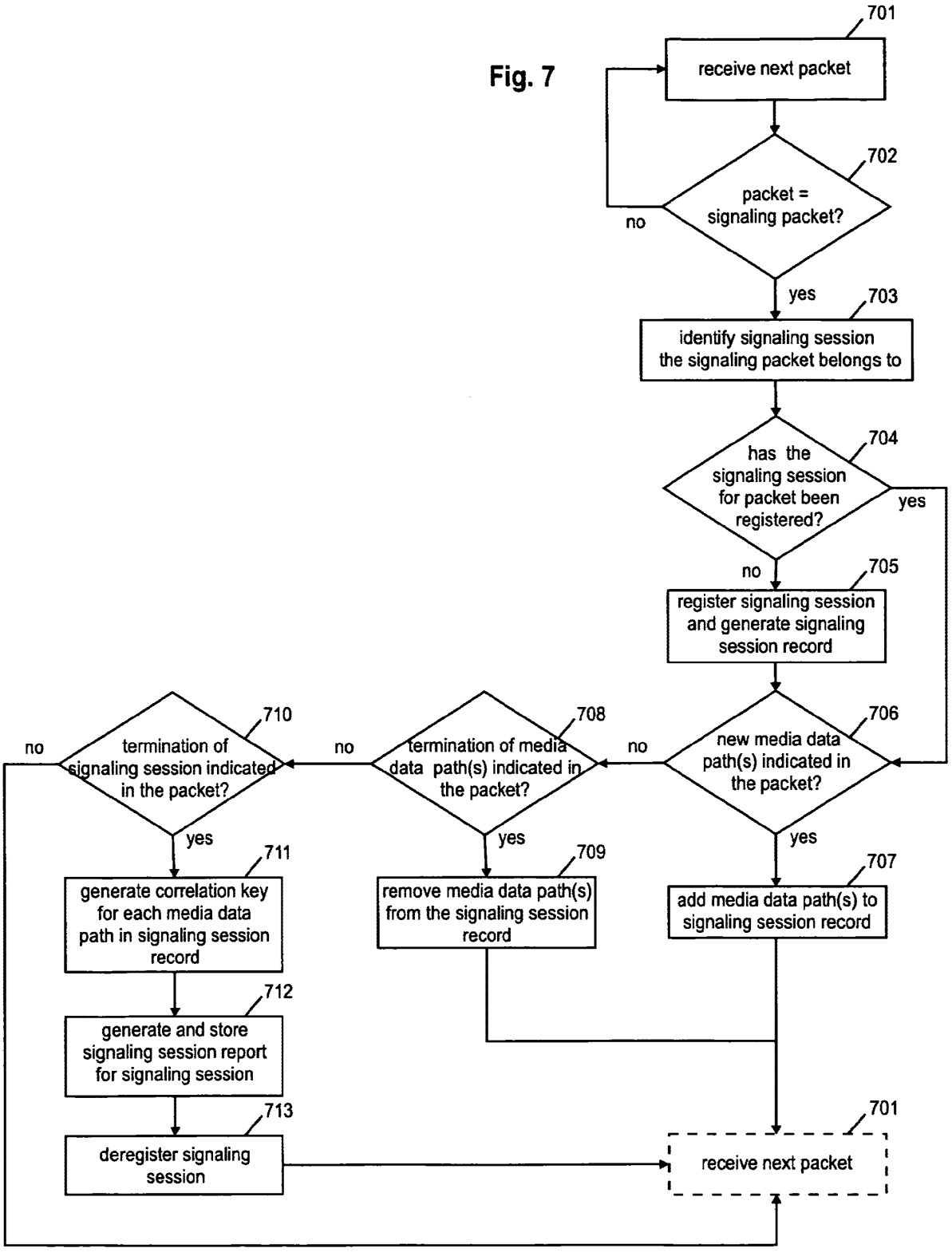
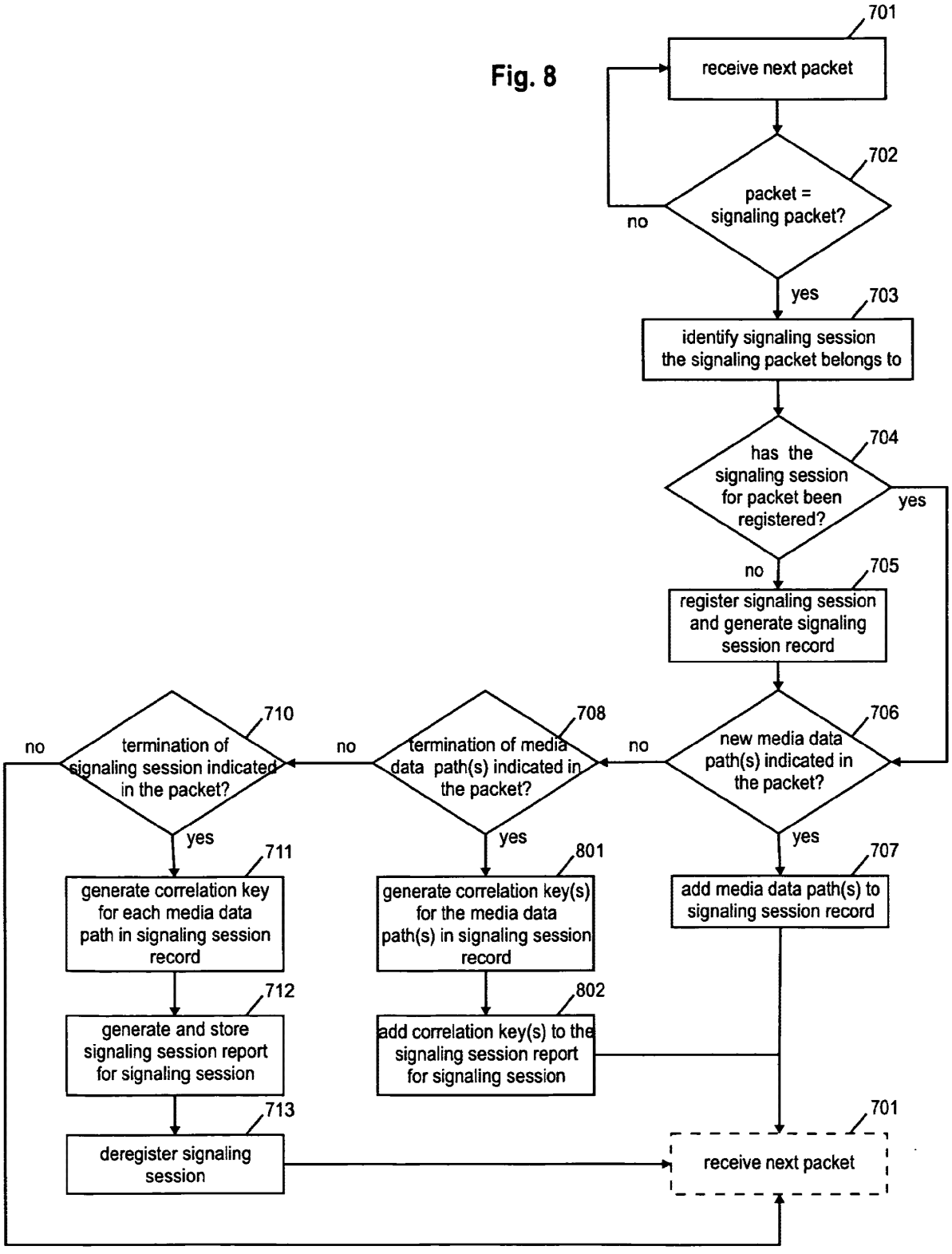

701
receive next packet
702
packet = signaling packet?
no
yes
703
identify signaling session the signaling packet belongs to
704
has the signaling session for packet been registered?
yes
no
705
register signaling session and generate signaling session record
706
new media data path(s) indicated in the packet?
no
yes
708
termination of media data path(s) indicated in the packet?
no
yes
709
remove media data path(s) from the signaling session record
707
add media data path(s) to signaling session record
710
termination of signaling session indicated in the packet?
no
yes
711
generate correlation key for each media data path in signaling session record
712
generate and store signaling session report for signaling session
713
deregister signaling session
701
receive next packet

Fig. 8


701
receive next packet
702
packet = signaling packet?
no
yes
703
identify signaling session the signaling packet belongs to
704
has the signaling session for packet been registered?
yes
no
705
register signaling session and generate signaling session record
706
new media data path(s) indicated in the packet?
no
708
termination of media data path(s) indicated in the packet?
no
710
termination of signaling session indicated in the packet?
no
yes
yes
yes
707
add media data path(s) to signaling session record
801
generate correlation key(s) for the media data path(s) in signaling session record
802
add correlation key(s) to the signaling session report for signaling session
711
generate correlation key for each media data path in signaling session record
712
generate and store signaling session report for signaling session
713
deregister signaling session
701
receive next packet

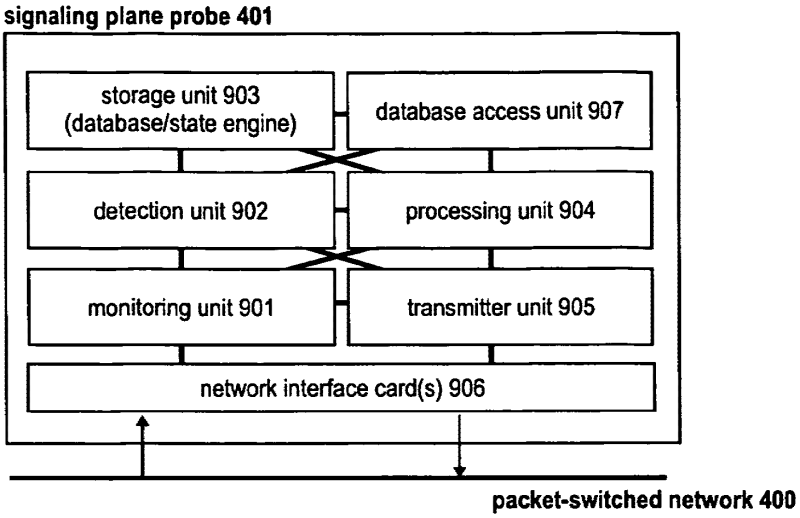

signaling plane probe 401
storage unit 903 (database/state engine)
database access unit 907
detection unit 902
processing unit 904
monitoring unit 901
transmitter unit 905
network interface card(s) 906
packet-switched network 400

Fig. 9

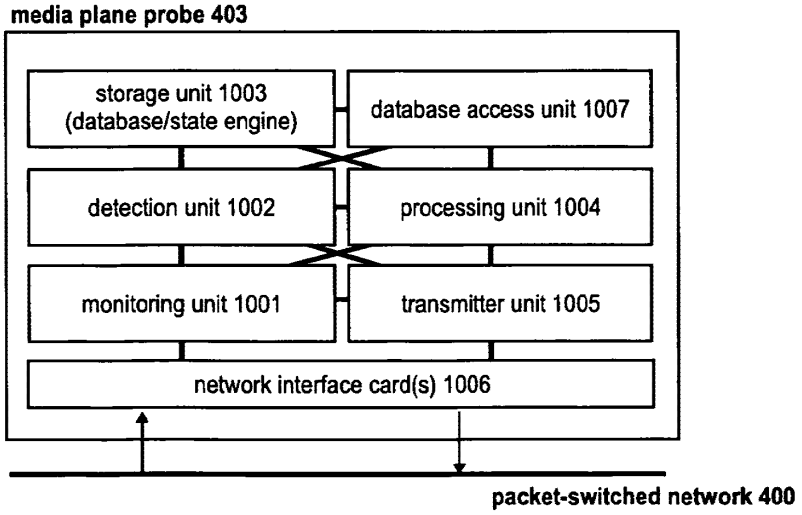

media plane probe 403
storage unit 1003 (database/state engine)
database access unit 1007
detection unit 1002
processing unit 1004
monitoring unit 1001
transmitter unit 1005
network interface card(s) 1006
packet-switched network 400

Fig. 10

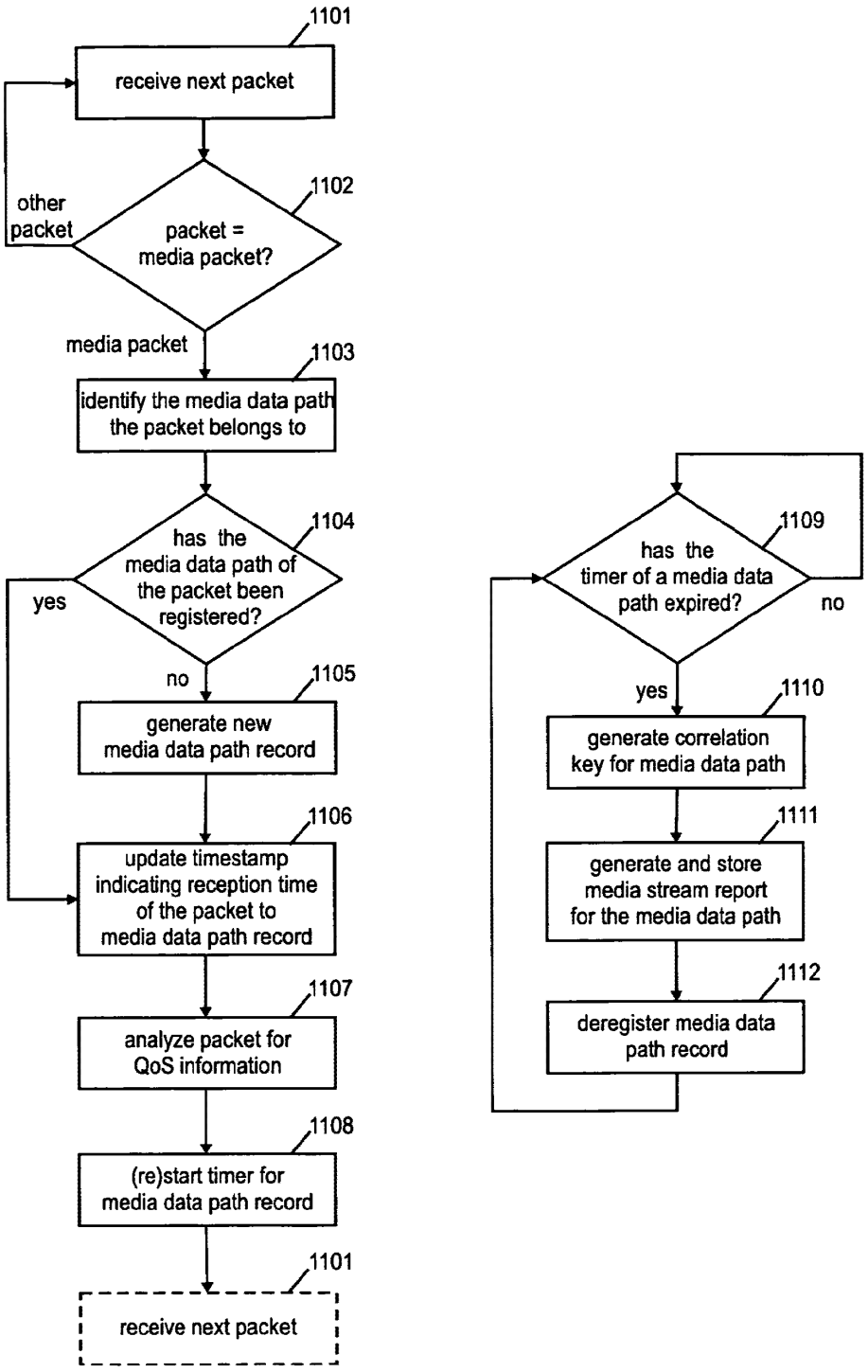

1101
receive next packet
1102
other packet
packet = media packet?
media packet
1103
identify the media data path the packet belongs to
1104
has the media data path of the packet been registered?
yes
no
1105
generate new media data path record
1106
update timestamp indicating reception time of the packet to media data path record
1107
analyze packet for QoS information
1108
(re)start timer for media data path record
1101
receive next packet
1109
has the timer of a media data path expired?
no
yes
1110
generate correlation key for media data path
1111
generate and store media stream report for the media data path
1112
deregister media data path record

Fig. 11

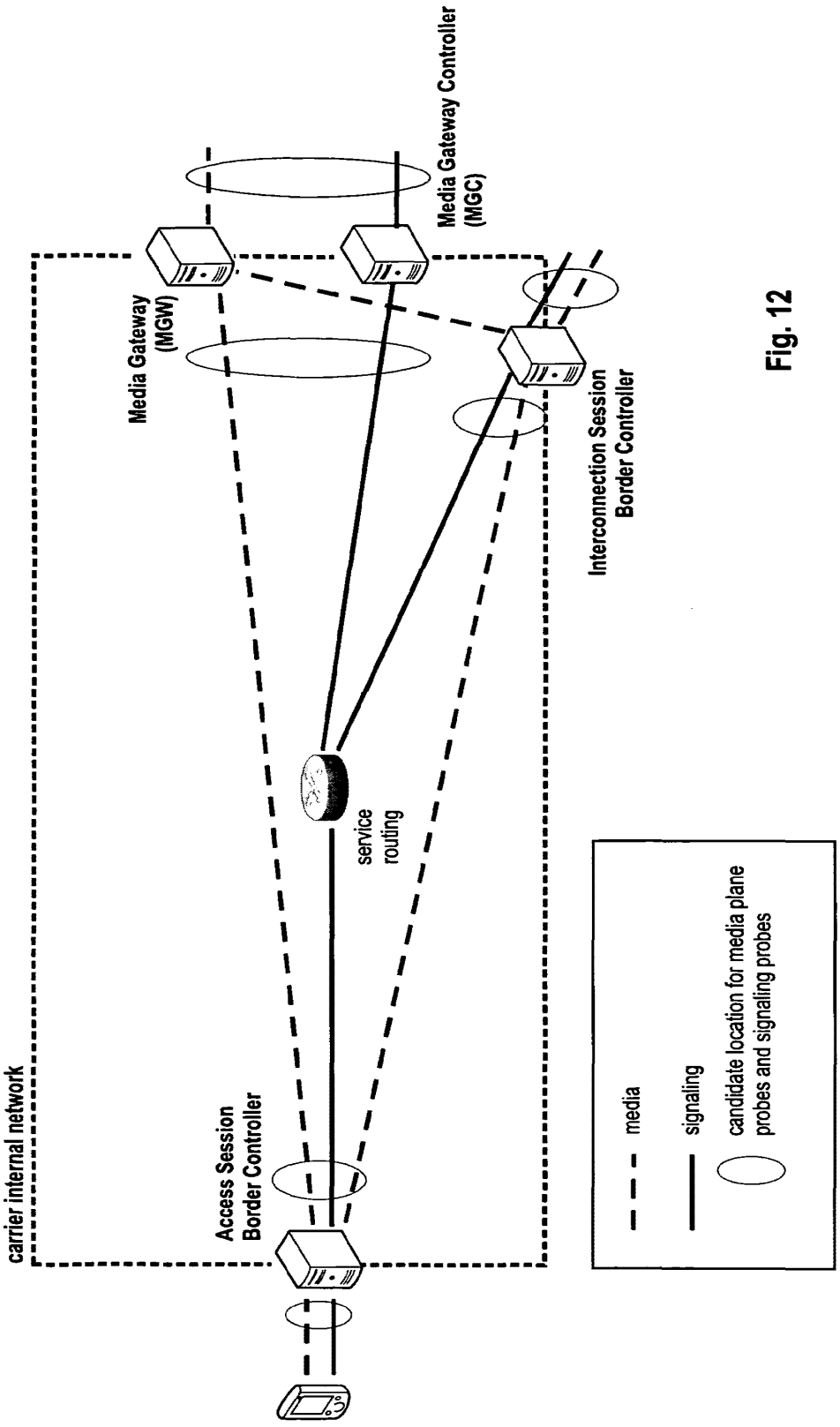

Media Gateway Controller (MGC)
Media Gateway (MGW)
Interconnection Session Border Controller
service routing
carrier internal network
Access Session Border Controller
media
signaling
candidate location for media plane probes and signaling probes

Fig. 12

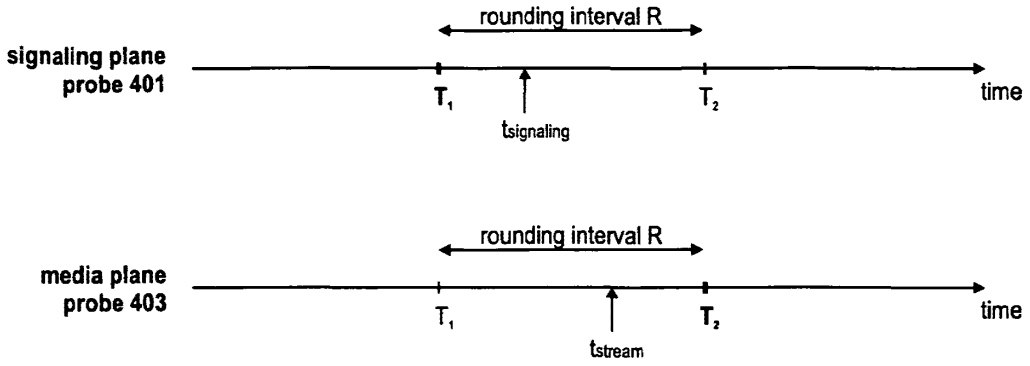

rounding interval R
signaling plane
probe 401
T1
tsignaling
T2
time
rounding interval R
media plane
probe 403
T1
tstream
T2
time

Fig. 13

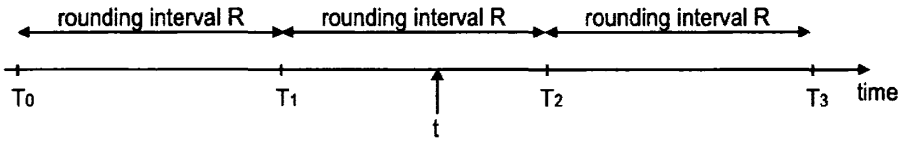

rounding interval R
rounding interval R
rounding interval R
T0
T1
t
T2
T3
time

Fig. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/002145

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L29/06 H04L12/24
ADD. H04L12/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, COMPENDEX, INSPEC, IBM-TDB, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ATSUSHI KOBAYASHI ET AL: "VoIP Measurement Architecture Using Data Mediation", 29 October 2009 (2009-10-29), IP OPERATIONS AND MANAGEMENT, SPRINGER BERLIN HEIDELBERG, BERLIN, HEIDELBERG, PAGE(S) 15 - 26, XP019133039, ISBN: 978-3-642-04967-5 page 18, line 5 - page 20, line 35	1-27
A	US 2008/151918 A1 (FOTI GEORGE [CA]) 26 June 2008 (2008-06-26) the whole document	1-27
A	WO 2010/106075 A1 (KONINKL KPN NV [NL]; TNO [NL]; STOKKING HANS MAARTEN [NL]; WALRAVEN FA) 23 September 2010 (2010-09-23) page 4, line 16 - page 8, line 26	1-27

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 January 2012	17/01/2012

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Aura Marcos, F

3

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2011/002145

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2008151918 A1	26-06-2008	US 2008151918 A1	26-06-2008
		WO 2008078209 A2	03-07-2008
WO 2010106075 A1	23-09-2010	EP 2409432 A1	25-01-2012
		KR 20110125674 A	21-11-2011
		WO 2010106075 A1	23-09-2010

Form PCT/ISA/210 (patent family annex) (April 2005)

Electronic Acknowledgement Receipt

EFS ID:	25345318
Application Number:	14757638
International Application Number:	
Confirmation Number:	9492
Title of Invention:	Rule-based network-threat detection for encrypted communications
First Named Inventor/Applicant Name:	David K. Ahn
Customer Number:	22907
Filer:	Bradley C. Wright/Holly Parker
Filer Authorized By:	Bradley C. Wright
Attorney Docket Number:	007742.00059
Receipt Date:	30-MAR-2016
Filing Date:	23-DEC-2015
Time Stamp:	13:53:16
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Non Patent Literature	12871806_17748470.pdf	732085 2a34455f7f90840a6f7a21d383c468f4c799cac2	no	7

Warnings:	
Information:	

2	Non Patent Literature	128718063_17748468.pdf	1693547 ba5c31882f9787e2ecd23ed1ce54a0f53f07b8df	no	21
Warnings:					
Information:					
3	Non Patent Literature	128718063_17748464.pdf	1210320 146d8a2fe7e3bb0cf21b700f047ad15909315d15	no	25
Warnings:					
Information:					
4	Non Patent Literature	128718063_17748458.pdf	3239881 e395eba28f8604973c9bb837217d4d755d203ca3	no	40
Warnings:					
Information:					
5	Non Patent Literature	128718063_17748456.pdf	920276 190c9f0448edc31547b0cc19fbb60ebdc4103a57	no	16
Warnings:					
Information:					
6	Non Patent Literature	128718063_17748450.pdf	1331868 48b1a01defbf29b5f288ee8887e8c4467304d3d8	no	14
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7	Non Patent Literature	128718063_17748446.pdf	463011 fbdf3061cc05d35a338f7f55aea7b621fea7fa9f	no	5
Warnings:					
Information:					
8	Non Patent Literature	128718063_17748444.pdf	486111 d98688f170b4b3d00908b0480ae591948adf4064	no	8
Warnings:					
Information:					
9	Non Patent Literature	128718063_17748442.pdf	1820688 8cd6d88bcf14c95f95d05c5f0936c59af596164f	no	27
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10	Non Patent Literature	128718063_17748729.pdf	125961 d0e799e835b53bc9542ab489078408f1ddfd2faa	no	4
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Information:					

11	Non Patent Literature	128718063_17748727.pdf	1457696 fdaf7e08ea22271791869cdfea47c8ae05e27489	no	16
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12	Non Patent Literature	128718063_17748748.pdf	202311 d1be9bb8cdc413159ad1666cfa4319695486413e	no	6
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13	Non Patent Literature	128718063_17748741.pdf	114514 a2c06b74ce562b85ec3c311b441b4dac68e23a60	no	3
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14	Non Patent Literature	128718063_17748734.pdf	245205 61c594a1c82e88ac4bd5d5a245b0f5a2f4879713	no	3
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15	Non Patent Literature	128718063_17748766.pdf	282709 389e10afbd02afbfcc755285dd4bda35484710a3	no	4
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16	Non Patent Literature	128718063_17748764.pdf	108988 d96beeb8b5e3d9e49b59799b7caefc7e504f61d8	no	3
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Information:					
17	Non Patent Literature	128718063_17748760.pdf	2533792 45ea01d4b457774a01670e82e8a04ecd358d5db1	no	62
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18	Non Patent Literature	128718063_17748773.pdf	48581 9eef5fc00a34cc7e354f17b4d82fc48b3cdb54f7	no	1
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19	Non Patent Literature	128718063_17750290.pdf	436983 dcf36d568d3932bafc15b58fc4fe86344a11e88d	no	15
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20	Non Patent Literature	128718063_17750237.pdf	1206684 0044a226d9c011010f6d8ecf62b589c51a6611e1	no	27
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21	Non Patent Literature	128718063_17750240.pdf	637605 57627bd99c5d17db648705cbc74e424bf87acfc8	no	21
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22	Non Patent Literature	128718063_17750245.pdf	607940 e3193f3218896730ca77045b69d11f333eb71489	no	20
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23	Non Patent Literature	128718063_17750248.pdf	659756 aa9de2722748dd0111873f944e94c2f1ba9de19d	no	10
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24	Non Patent Literature	128718063_17750229.pdf	238710 8c34046e74fcbd728967753cd8a303b7c952903d	no	6
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25	Non Patent Literature	128718063_17750226.pdf	160790 2e0bf87d22fa9e1e6fc994dc8d5eb4440f2921a6	no	3
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26	Non Patent Literature	128718063_17750235.pdf	121567 96ad7b5996c3eac66a9ec1489d78ab155c57da3f	no	2
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27	Non Patent Literature	128718063_17750279.pdf	891534 83d6eb67909e68839fe14d24cdfd2300f76b215d	no	27
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28	Non Patent Literature	128718063_17750277.pdf	918733 eca7ef41a2f4fd1439ea36b27914b8c2c7394e2d	no	28
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29	Non Patent Literature	Corr_from_WIPO__-_N__of_Transmittal_of_the_International_Search_Report_17713511.PDF	8618992 3d1c384aa26e1d72a68822e3e4c8bd9f2de5249f	no	126
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Information:					
30	Non Patent Literature	Statement_17761124.pdf	66900 0c2d5d1785db2e8352fd788df77b2eb9cd7979e4	no	1
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Information:					
31	Non Patent Literature	Final_Rejection__1449_17645159.pdf	2839706 a8a9e7d43df581cbe3ff549c6bb5d8f0996c4060	no	68
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32	Non Patent Literature	Non-Final_Rejection__892__1449_17737382.pdf	1405925 31cf56d4367545d6e32c691c7085e75f5b184ae0	no	36
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33	Information Disclosure Statement (IDS) Form (SB08)	Information_Disclosure_Statement_Fillable_PDF_2_of_2_17791347.pdf	1037097 ceb7cadf9832b19c0c83b58e114222a7fe515450	no	8
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Information:					
A U.S. Patent Number Citation or a U.S. Publication Number Citation is required in the Information Disclosure Statement (IDS) form for autoloading of data into USPTO systems. You may remove the form to add the required data in order to correct the Informational Message if you are citing U.S. References. If you chose not to include U.S. References, the image of the form will be processed and be made available within the Image File Wrapper (IFW) system. However, no data will be extracted from this form. Any additional data such as Foreign Patent Documents or Non Patent Literature will be manually reviewed and keyed into USPTO systems.					
34	Other Reference-Patent/App/Search documents	ISA_Comm_dated_07-10-2015_17791693.PDF	817142 58a34465de3fc4cd92bdd252aee97f5d82d82c11	no	6
Warnings:					
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35	Other Reference-Patent/App/Search documents	WO2014143673_17791459.PDF	238193 5c30981f29a53e5331a157b4d76afe6316810c92	no	7
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36	Other Reference-Patent/App/Search documents	WO2014164713_17791454.PDF	178111 ec7002ab21a04ce6e2a91f328421cb594c9ef236	no	6
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37	Other Reference-Patent/App/Search documents	WO2014065943_17791450.PDF	162288 bc6a1f77e76eb307f25c54939ac6af2fade146dd	no	5
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38	Other Reference-Patent/App/Search documents	WO2014109843_17791444.PDF	162757 16cf49e3c80078bbf4f33b610ab92b79e059e538	no	5
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39	Other Reference-Patent/App/Search documents	WO2015160567_1_17791384.PDF	160557 1346e81c72ffbe833f253dba3f32fbd5e6062dff	no	6
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Information:					
40	Foreign Reference	EP1677484A2_16712298.pdf	773874 47dd5a5c781f0fd2a220829489e9b07dca656db2	no	14
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41	Foreign Reference	EP1313290A1_16689905.pdf	1181323 0d673c0a51b64a7a9da6dec238ebe98d483c6031	no	18
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42	Foreign Reference	WO2005046145_16811218.PDF	1189526 12556d88fc51d8167206348609ca3e7c4e53943b	no	27
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43	Foreign Reference	EP2385676A1_16818890.pdf	780191 b81189390d037dff528b0afcc8f407a761e32de5	no	17
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44	Foreign Reference	EP2498442A1_16818909.pdf	1749069 e86e61d1c020da22685c864e51bdf4c636777f30	no	28
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45	Foreign Reference	KR20010079361A_17690002.pdf	755268 996a657ccd2abe1d4285baa60bb510a5b1dccd29	no	19
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Information:					

46	Foreign Reference	EP1006701A2_17690010.pdf	779545 f2da2b4b1c1220d3c5ce4d5982f3fece2efff587	no	15
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47	Foreign Reference	WO2006105093A2_17690109.pdf	2750332 d8f7a6023f473296c2e990d0aadf80b708b2c230	no	62
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48	Foreign Reference	WO2006093557A2_17690117.pdf	3097033 8c3b461d2321cbe7ec5f8f229c40c85cbf0f9440	no	72
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49	Foreign Reference	128718063_17748754.pdf	3103892 30b788b05754645d32577638f64f4565dd006372	no	74
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Information:					
50	Foreign Reference	WO2011038420A2_17690375.pdf	2007006 6c4c9c4f60be9e685c65752da01e8856c0f6cc73	no	34
Warnings:					
Information:					
51	Foreign Reference	EP1484884A2_17690384.pdf	1943998 a07deab9e2c710976dc4bd58d26f822f871d1c5d	no	32
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52	Foreign Reference	128718063_17748768.pdf	2289665 5ceeb63cf91f9aad8cf39d604e915d3d8d04db49	no	60
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Information:					
53	Foreign Reference	EP1864226B1_17690406.pdf	2030938 b36cae0ea8bd094f45d8a5285b295af62b60849a	no	44
Warnings:					
Information:					
54	Foreign Reference	128718063_17750217.pdf	2385931 edf220ad5b5dc6ca0e270598a7fffb36d983a9ce	no	56
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Information:					

55	Foreign Reference	WO2012146265A1_17715972.pdf	4103078 4a100c960bd1ab5910a84302cda0371ff1bb080d	no	78

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Information:	
Total Files Size (in bytes):	69506183

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To:
Wright, Bradley
BANNER & WITCOFF, LTD.
1100 13th Street, N.W. Suite 1200
Washington, DC 20005-4051
ETATS-UNIS D'AMERIQUE

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

	Date of mailing *(day/month/year)* 28 January 2016 (28-01-2016)
Applicant's or agent's file reference 007742.00064	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2015/062691	International filing date *(day/month/year)* 25 November 2015 (25-11-2015)
Applicant CENTRIPETAL NETWORKS, INC.	

1. [X] The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the International Application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the International Search Report.

   How? Directly to the International Bureau of WIPO, 34 chemin des Colombettes 1211 Geneva 20, Switzerland, Fascimile No.: (41-22) 338.82.70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 - 9.011.

2. [ ] The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. [ ] **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   [ ] the protest together with the decision thereon has been transmitted to the International Bureau together with any applicant's request to forward the texts of both the protest and the decision thereon to the designated Offices.

   [ ] no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may **submit comments on an informal basis on the written opinion of the International Searching Authority** to the International Bureau. These comments will be made available to the public after international publication. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established.

   Shortly after the expiration of **18 months from the priority date, the international application will be published** by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for **entry into the national phase** before those designated Offices. In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months. For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

   Within **19 months from the priority date, the applicant may request that a supplementary international search be carried out** by a different International Searching Authority that offers this service (Rule 45*bis*.1). The procedure for requesting supplementary international search is described in the *PCT Applicant's Guide*, International Phase, paragraphs 8.006-8.032.

Name and mailing address of the International Searching Authority	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel. (+31-70) 340-2040 Fax: (+31-70) 340-3016	FINNIE, Alistair Tel: +49 (0)89 2399-8251 FEB 8 - 2016

Form PCT/ISA/220 (July 2014)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
007742.00064		
International application No.	International filing date *(day/month/year)*	(Earliest) Priority Date *(day/month/year)*
PCT/US2015/062691	25 November 2015 (25-11-2015)	10 February 2015 (10-02-2015)
Applicant		
CENTRIPETAL NETWORKS, INC.		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language,** the international search was carried out on the basis of:
      [X] the international application in the language in which it was filed
      [ ] a translation of the international application into _____, which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b))
   b. [ ] This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. [ ] With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. [ ] **Certain claims were found unsearchable** (See Box No. II)

3. [ ] **Unity of invention is lacking** (see Box No III)

4. With regard to the **title,**
   [X] the text is approved as submitted by the applicant
   [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract,**
   [X] the text is approved as submitted by the applicant
   [ ] the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority

6. With regard to the **drawings,**
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      [X] as suggested by the applicant
      [ ] as selected by this Authority, because the applicant failed to suggest a figure
      [ ] as selected by this Authority, because this figure better characterizes the invention
   b. [ ] none of the figures is to be published with the abstract

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/062691

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L12/701 H04L12/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/281030 A1 (CUI LIANG [CN] ET AL) 18 September 2014 (2014-09-18) paragraph [0002] - paragraph [0003] paragraph [0004] paragraph [0034] paragraph [0046] - paragraph [0048] paragraph [0053]	1-25
X	US 2004/073655 A1 (KAN CHAO [US] ET AL) 15 April 2004 (2004-04-15)	1,24,25
A	paragraph [0006] paragraph [0037]	2-23
A	WO 2012/146265 A1 (VOIPFUTURE GMBH [DE]; SCHOLZ HENDRIK [DE]; WALLBAUM MICHAEL [DE]; KRUE) 1 November 2012 (2012-11-01) abstract	1-25

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 January 2016	28/01/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Pais Gonçalves, A

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2015/062691

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014281030 A1	18-09-2014	NONE	
US 2004073655 A1	15-04-2004	EP 1418705 A2	12-05-2004
		US 2004073655 A1	15-04-2004
WO 2012146265 A1	01-11-2012	CA 2834168 A1	01-11-2012
		EP 2702740 A1	05-03-2014
		US 2014089504 A1	27-03-2014
		WO 2012146265 A1	01-11-2012

Form PCT/ISA/210 (patent family annex) (April 2005)

Information on Search Strategy - Pilot phase (see OJ 2015, A86)
The type of information contained in this sheet may change during the pilot for improving the usefulness of this new service.

Application Number
PCT/US2015/062691

TITLE: CORRELATING PACKETS IN COMMUNICATIONS NETWORKS

APPLICANT: CENTRIPETAL NETWORKS, INC.

IPC CLASSIFICATION: H04L12/701, H04L12/26

EXAMINER: Pais Gonçalves, A

CONSULTED DATABASES: WPI, EPODOC

CLASSIFICATION SYMBOLS DEFINING EXTENT OF THE SEARCH:

IPC:

CPC: H04L45/00, H04L43/00

FI/F-TERMS:

KEYWORDS OR OTHER ELEMENTS FEATURING THE INVENTION:

EPO FORM P04A42

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing
(day/month/year) see form PCT/ISA/210 (second sheet)

Applicant's or agent's file reference
see form PCT/ISA/220

FOR FURTHER ACTION
See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2015/062691	25.11.2015	10.02.2015

International Patent Classification (IPC) or both national classification and IPC
INV. H04L12/701 H04L12/26

Applicant
CENTRIPETAL NETWORKS, INC.

1. This opinion contains indications relating to the following items:

- ☒ Box No. I Basis of the opinion
- ☐ Box No. II Priority
- ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- ☐ Box No. IV Lack of unity of invention
- ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step and industrial applicability; citations and explanations supporting such statement
- ☐ Box No. VI Certain documents cited
- ☒ Box No. VII Certain defects in the international application
- ☒ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will usually be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notifed the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

Name and mailing address of the ISA:	Date of completion of this opinion	Authorized Officer
European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Fax: +49 89 2399 - 4465	see form PCT/ISA/210	Pais Gonçalves, A Telephone No. +49 89 2399-0

Form PCT/ISA/237 (Cover Sheet) (January 2015)

Box No. I Basis of the opinion

1. With regard to the **language**, this opinion has been established on the basis of:

   ☒ the international application in the language in which it was filed.

   ☐ a translation of the international application into , which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1 (b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing:

   a. ☐ forming part of the international application as filed:

      ☐ in the form of an Annex C/ST.25 text file.

      ☐ on paper or in the form of an image file.

   b. ☐ furnished together with the international application under PCT Rule 13*ter*.1(a) for the purposes of international search only in the form of an Annex C/ST.25 text file.

   c. ☐ furnished subsequent to the international filing date for the purposes of international search only:

      ☐ in the form of an Annex C/ST.25 text file (Rule 13*ter*.1(a)).

      ☐ on paper or in the form of an image file (Rule 13*ter*.1(b) and Administrative Instructions, Section 713).

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that forming part of the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-25
	No:	Claims	
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-25
Industrial applicability (IA)	Yes:	Claims	1-25
	No:	Claims	

2. Citations and explanations

see separate sheet

Box No. VII Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

see separate sheet

Box No. VIII Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:

see separate sheet

Reference is made to the following documents:

D1 US 2014/281030 A1 (CUI LIANG [CN] ET AL) 18 September 2014 (2014-09-18)

D2 US 2004/073655 A1 (KAN CHAO [US] ET AL) 15 April 2004 (2004-04-15)

section VIII

1 Claims 1, 24 and 25 do not fulfil the requirements of Article 6 PCT for the following reasons:

1.1 In the claims it is not clear what is meant by the expression "data identifying the host", how such data is determined or the purpose of generating and transmitting said data.

1.2 According to the description, it seems that this data is used to identify which packets are associated with a particular flow or session. However, this is not clear from the wording of the claims.

1.3 In addition, the desired scope of protection of independent claim 25 is not clearly defined due to the wording "one or more".

section V

2 Assuming the interpretation indicated in point 1.2 above, it seems that claim 1 would be directed to a method of monitoring packets received by a network device and packets transmitted by the device and correlating them in order to determined that the packets are associated with a flow.

2.1 Such a method is already known from the disclosure of D1, see e.g. [0002] to [0004] or D2, see e.g. [0037].

2.2 The only apparent distinguishing feature between claim 1 and e.g. D1 could be that the network device and the host are located in different networks.

2.3 However, such distinguishing feature is a simple modification of the basic concept disclosed in D1 lying within the general design competence of a person skilled in the art who would consider such measure to be at least implicitly disclosed in D1, see e.g. figures 7 and 10A.

2.4 In addition, these arguments are also valid for independent Claim 24, which contains the same combination of features as claim 1 in terms of an apparatus claim, i.e. the apparatus (system) for carrying out the method of claim 1.

2.5 Said arguments are also valid for independent claim 25 which is directed to computer-readable media comprising instructions essentially to carry out the method of claim 1.

2.6 Therefore, the subject-matter of Claims 1, 24 and 25 does not involve an **inventive step**, Article 33 (1), (3) PCT.

2.7 The additional features of the dependent claims seem to relate to minor design details and/or implementation measures, which are known or directly derivable from the above-referred documents or constitute normal practice of a person skilled in the art. These claims thus, either alone or in combination, do not seem to add anything new or of inventive significance to any of the previously-referred claims, see passages indicated in the search report.

section VII

3 Having regard to the above objections, it is not clear at present which part of the application could serve as a basis for a new and inventive subject-matter.

4 Should the Applicant nevertheless regard some particular matter of the application as having an inventive contribution over the prior art, then an independent claim relating to such subject-matter should be filed. The Applicant is also requested to indicate in the letter of reply the difference of said subject-matter vis-à-vis the state of the art and the significance thereof.

4.1 The above-cited documents D1 and D2 should be acknowledged and briefly discussed in the opening part of the description, Rule 5.1 (a) (ii) PCT, making clear any inventive contribution of the claimed invention over the prior art.

4.2 The independent claims should be drafted in a two-part form, having in their pre-characterizing part all features known from D1 (refer to point 2 above), Rule 6.3 (b) (ii) PCT.

4.3 The opening part of the description should be modified to bring it into agreement with the amended claim, Rule 5.1(a)(iii) PCT, if required.

4.4 The claims should include reference signs relating to the features referred to therein, Rule 6.2 (b) PCT.

US 20140281030A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2014/0281030 A1**

(43) **Pub. Date: Sep. 18, 2014**

Cui et al.

(54) **VIRTUAL NETWORK FLOW MONITORING**

(71) Applicant: **VMWARE, INC.**, Palo Alto, CA (US)

(72) Inventors: **Liang Cui**, Beijing (CN); **Wei Zhang**, Beijing (CN); **Jingchun Jason Jiang**, Beijing (CN); **Caixia Jiang**, Beijing (CN)

(73) Assignee: **VMWARE, INC.**, Palo Alto, CA (US)

(21) Appl. No.: **13/831,685**

(22) Filed: **Mar. 15, 2013**

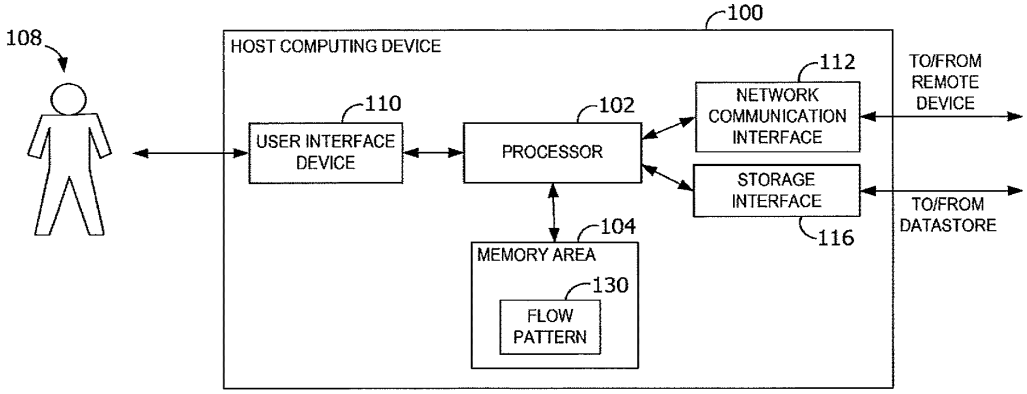
Publication Classification

(51) **Int. Cl.**
H04L 12/717 (2006.01)

(52) **U.S. Cl.**
CPC ***H04L 45/42*** (2013.01)
USPC **709/244**

(57) **ABSTRACT**

Embodiments perform end-to-end virtual network flow monitoring in a virtual datacenter and provide differentiated views to users based on user role. A target flow pattern describing data packets of interest is distributed to a plurality of applications managing VMs in the virtual datacenter, such as hosts, virtual gateways, and other virtual network applications. Each of the applications monitors data packets routed by the application by comparing the data packets to the flow pattern and selectively collecting context data describing the data packets. The context data collected by the applications is aggregated at a remote server for analysis and reporting.



BNSDOCID: <US____20140281030A1_I_>

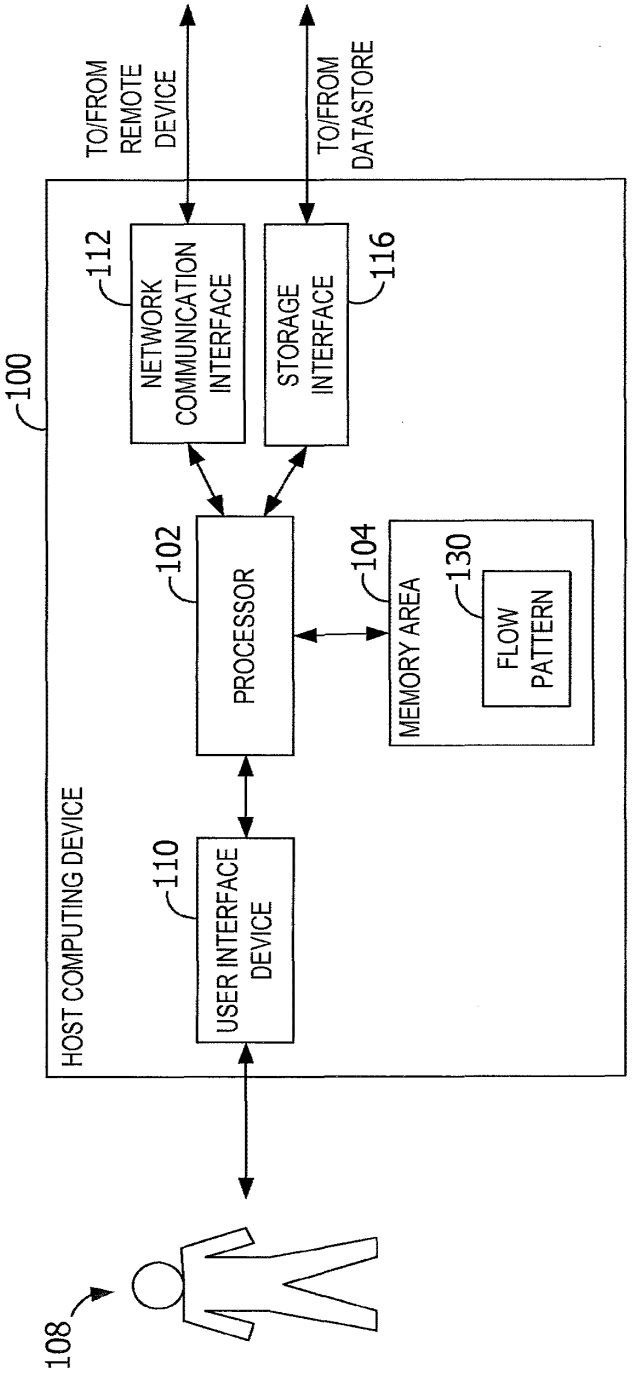


FIG. 1

BNSDOCID: <US____20140281030A1_I_>

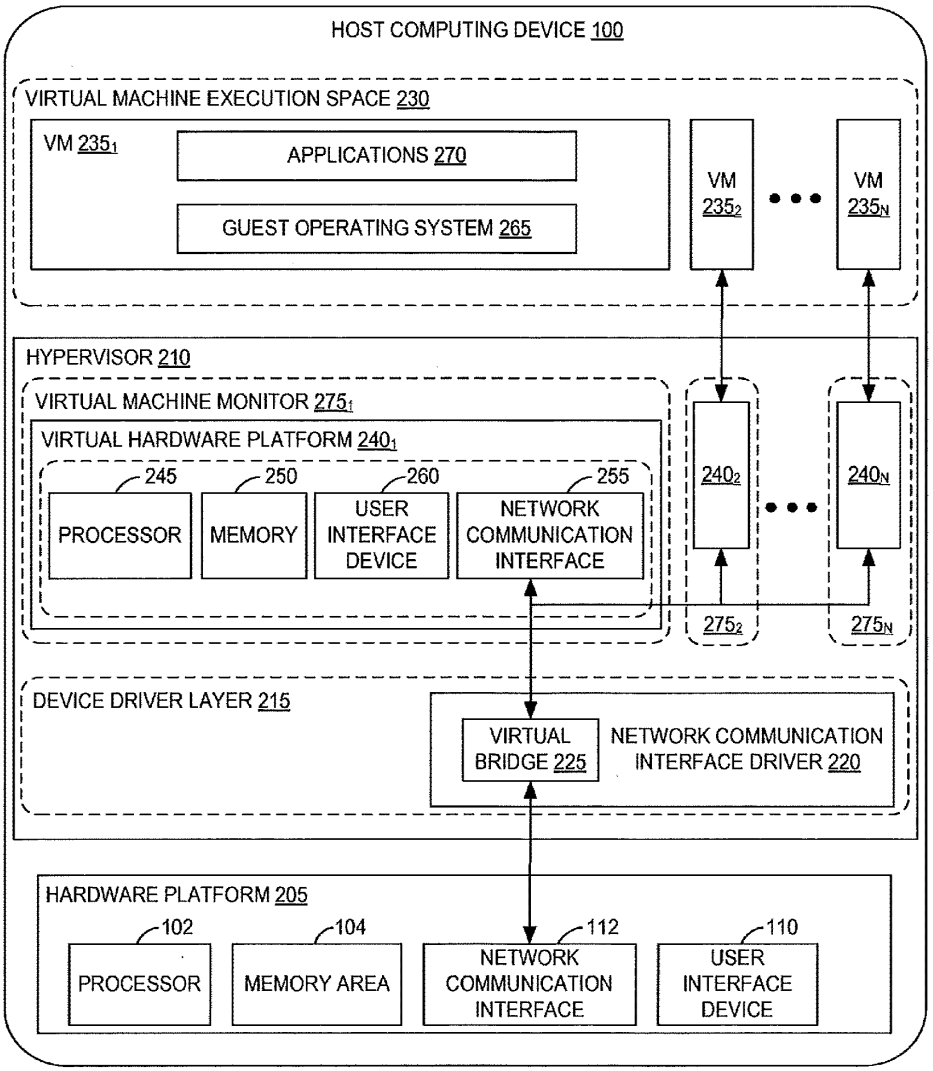


FIG. 2

BNSDOCID: <US____20140281030A1_I_>

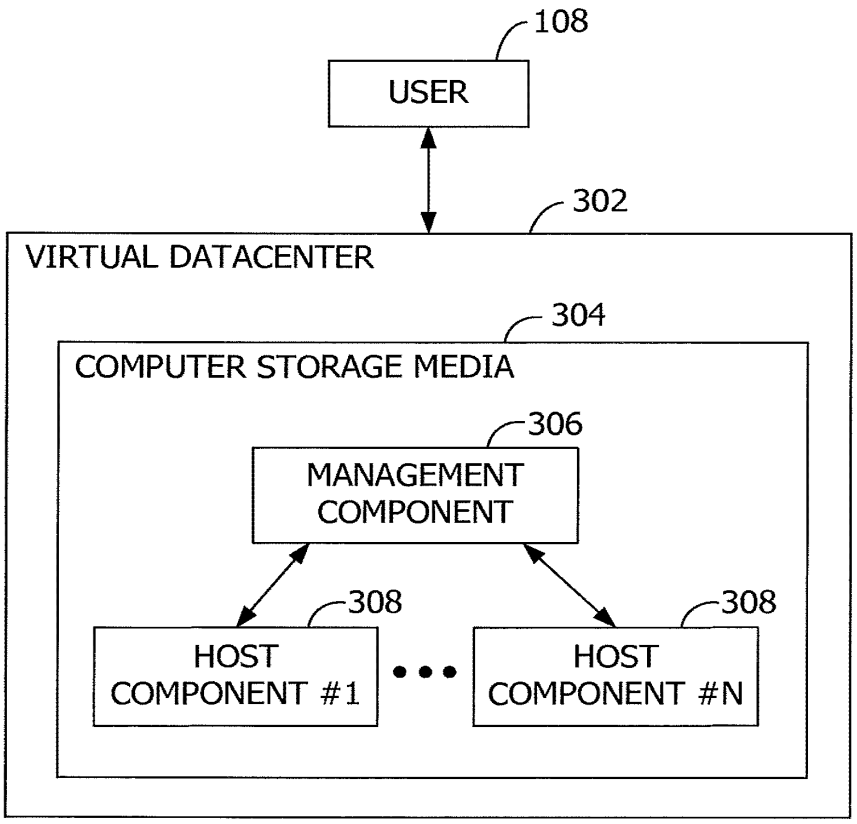


FIG. 3

BNSDOCID: <US____20140281030A1_I_>

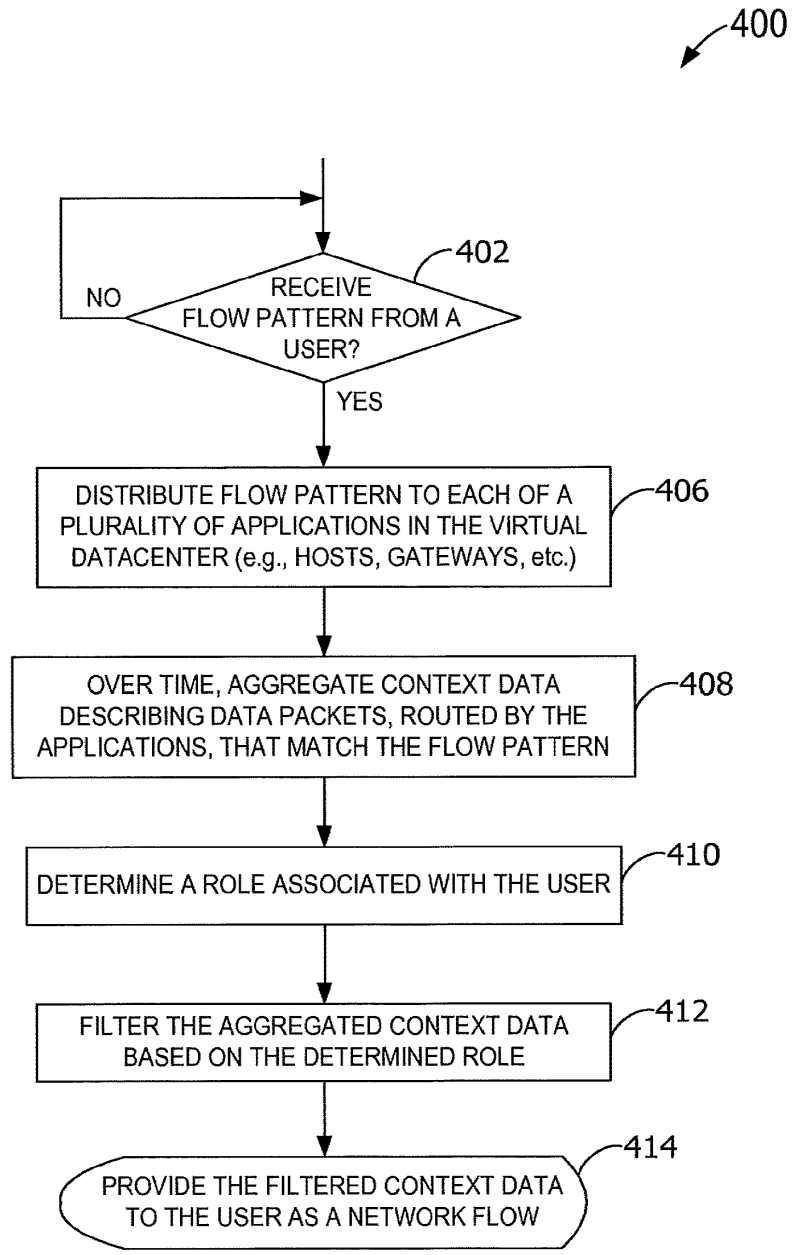


FIG. 4

BNSDOCID: <US____20140281030A1_I_>

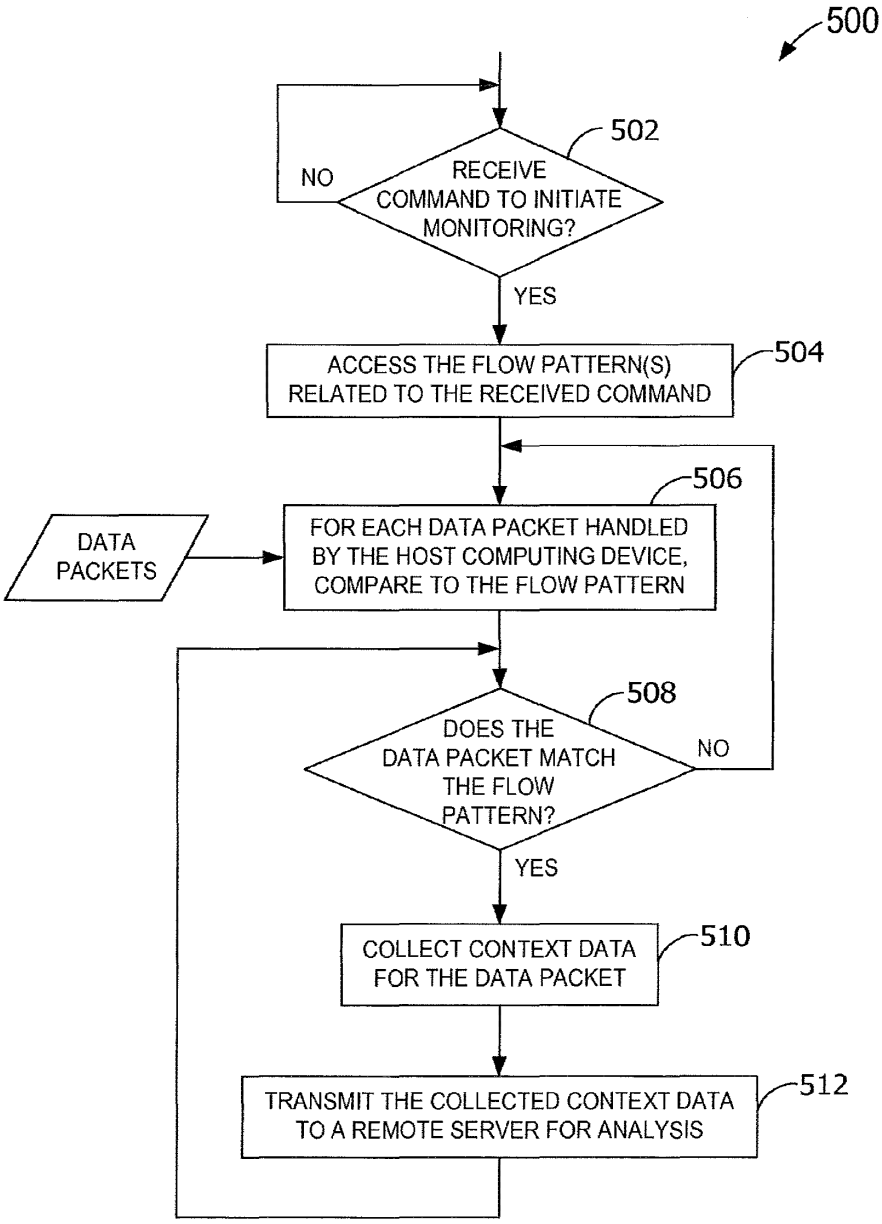


FIG. 5

BNSDOCID: <US_____20140281030A1_I_>

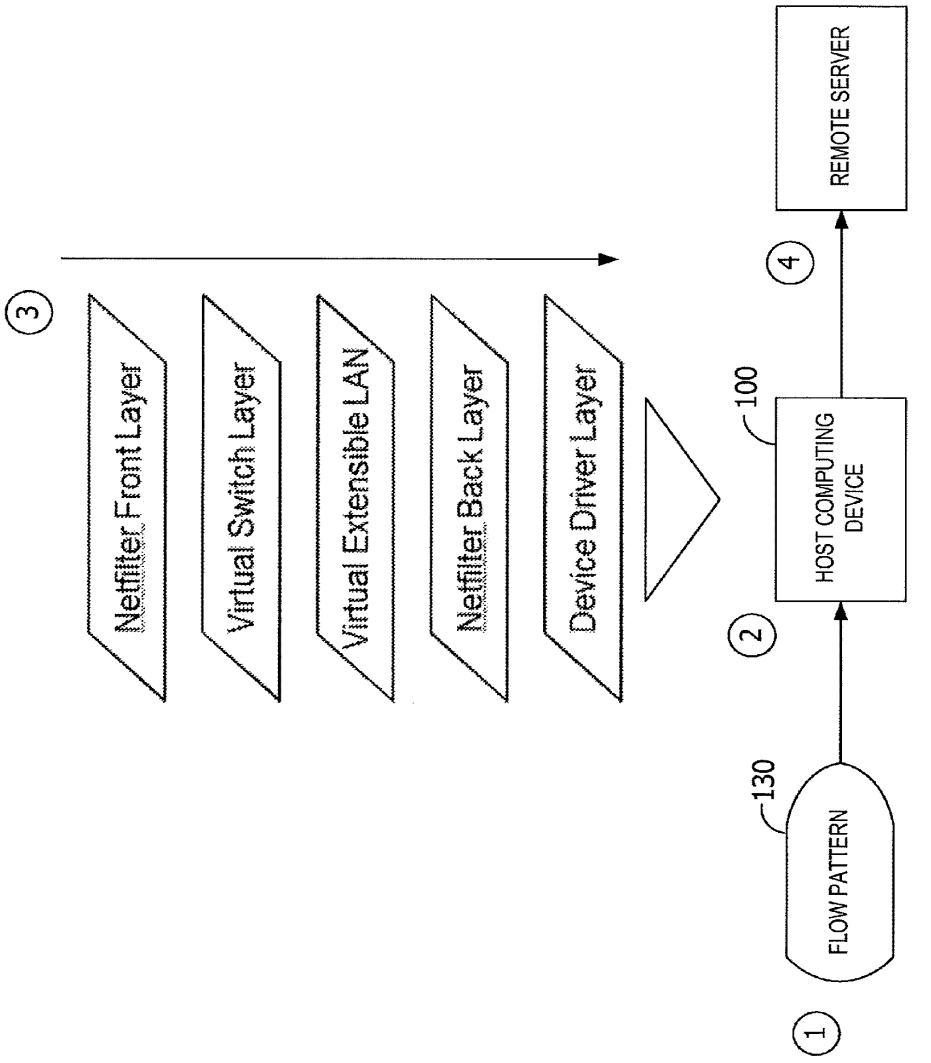

REMOTE SERVER
4
3
Netfilter Front Layer
Virtual Switch Layer
Virtual Extensible LAN
Netfilter Back Layer
Device Driver Layer
100
HOST COMPUTING DEVICE
2
130
FLOW PATTERN
1

FIG. 6

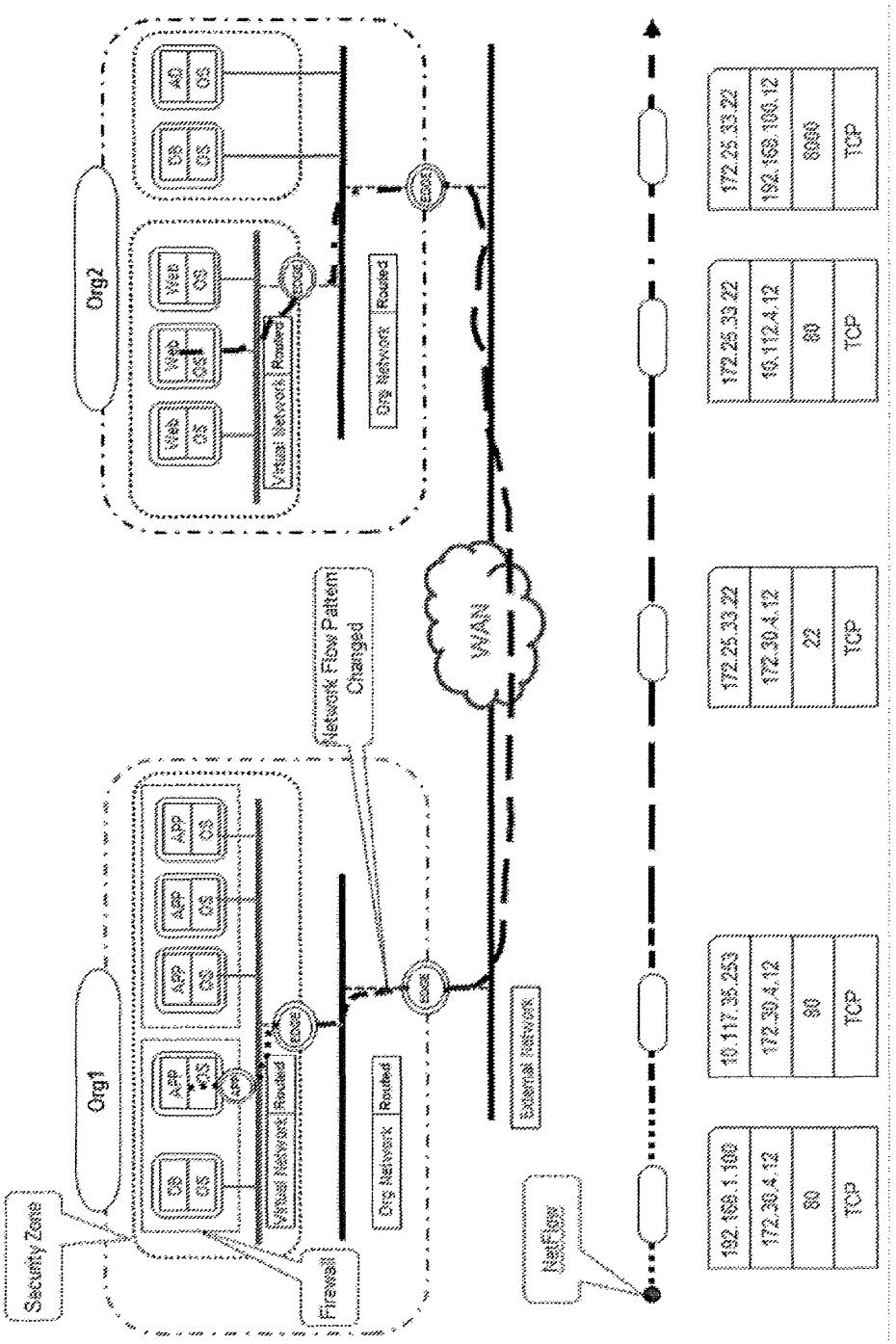


FIG. 7

BNSDOCID: <US____20140281030A1_I_>

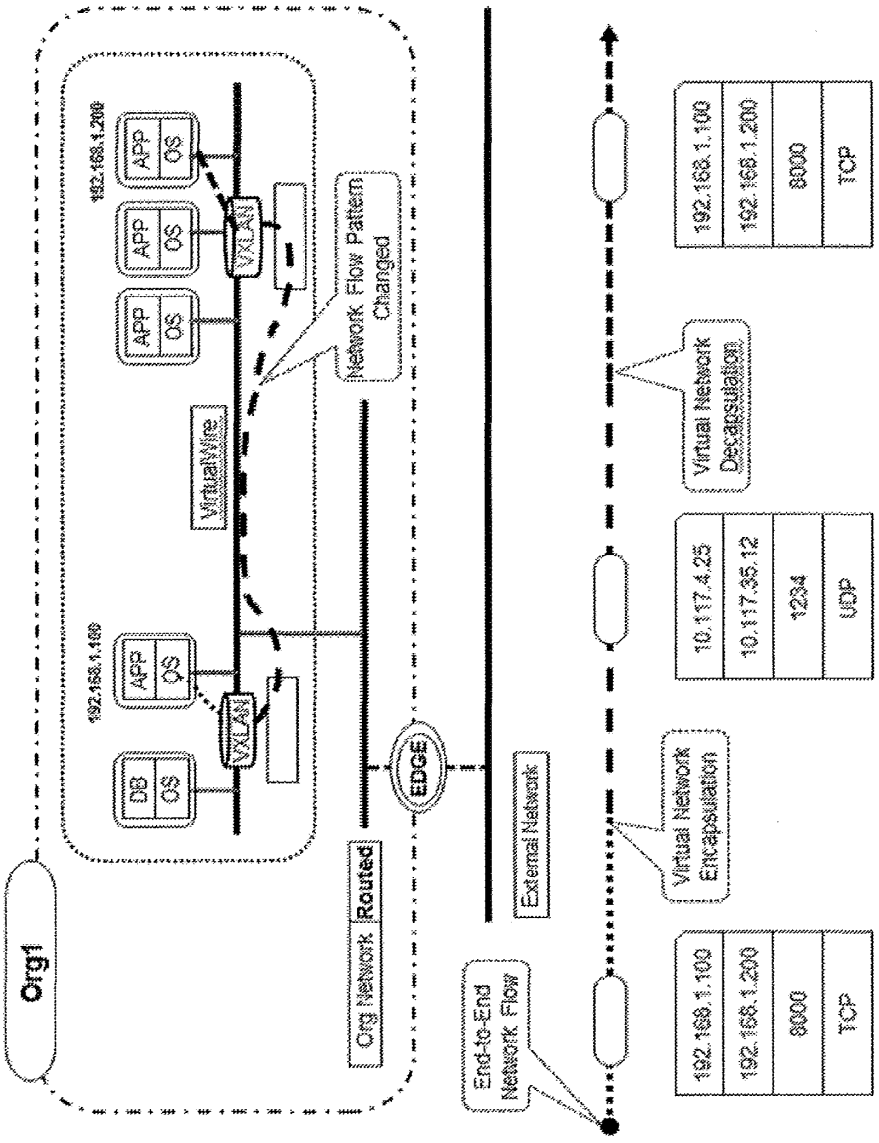


FIG. 8

BNSDOCID: <US____20140281030A1_I_>

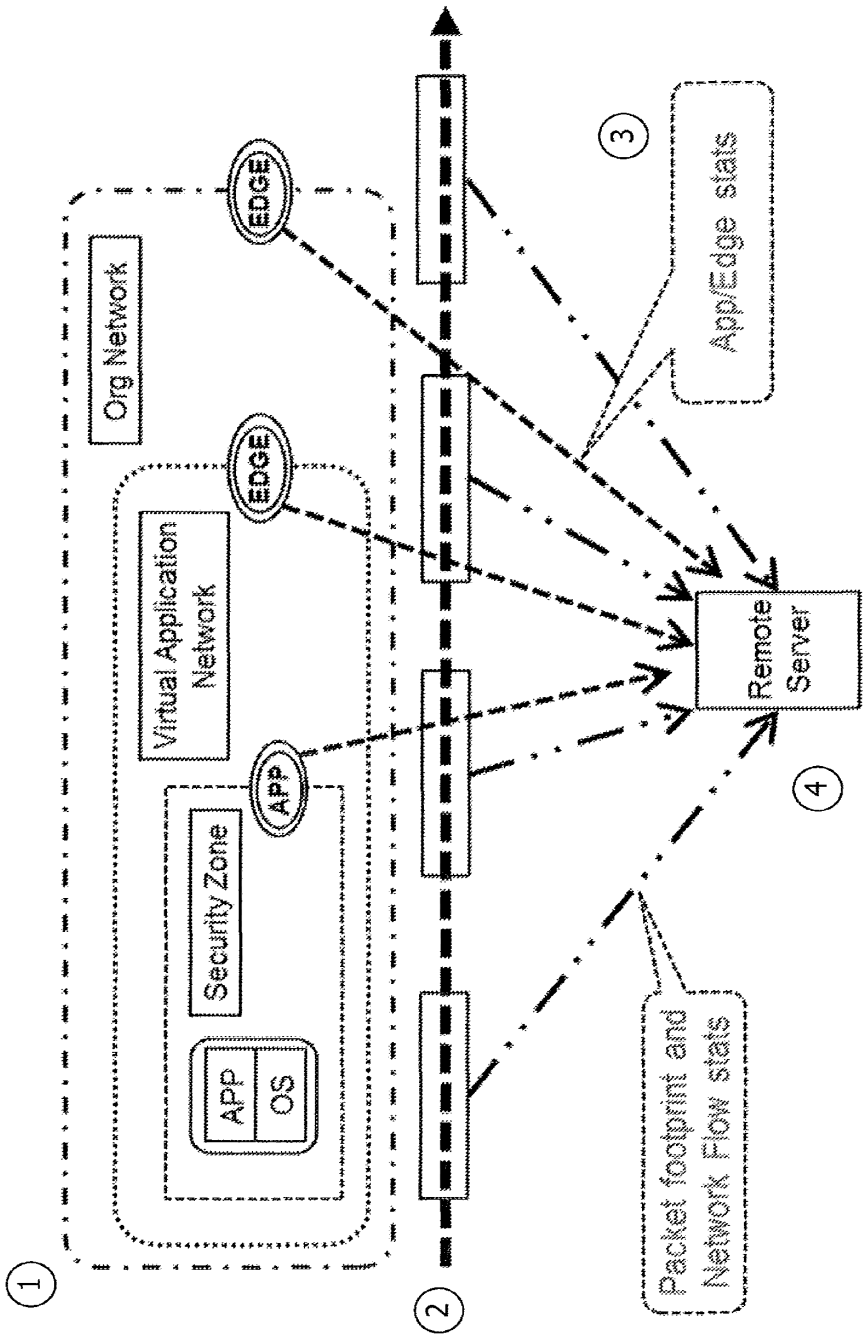


FIG. 9

BNSDOCID: <US____20140281030A1_I_>

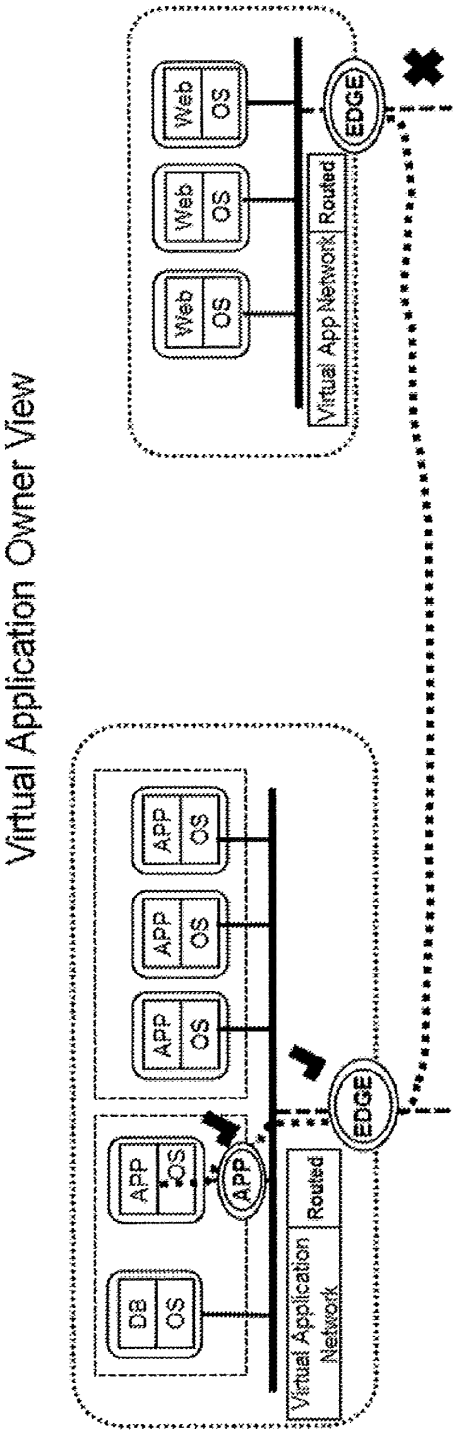

Virtual Application Owner View
Web
OS
Web
OS
Web
OS
EDGE
Routed
Virtual App Network
APP
OS
APP
OS
APP
OS
APP
OS
APP
DB
OS
EDGE
Routed
Virtual Application Network

FIG. 10A

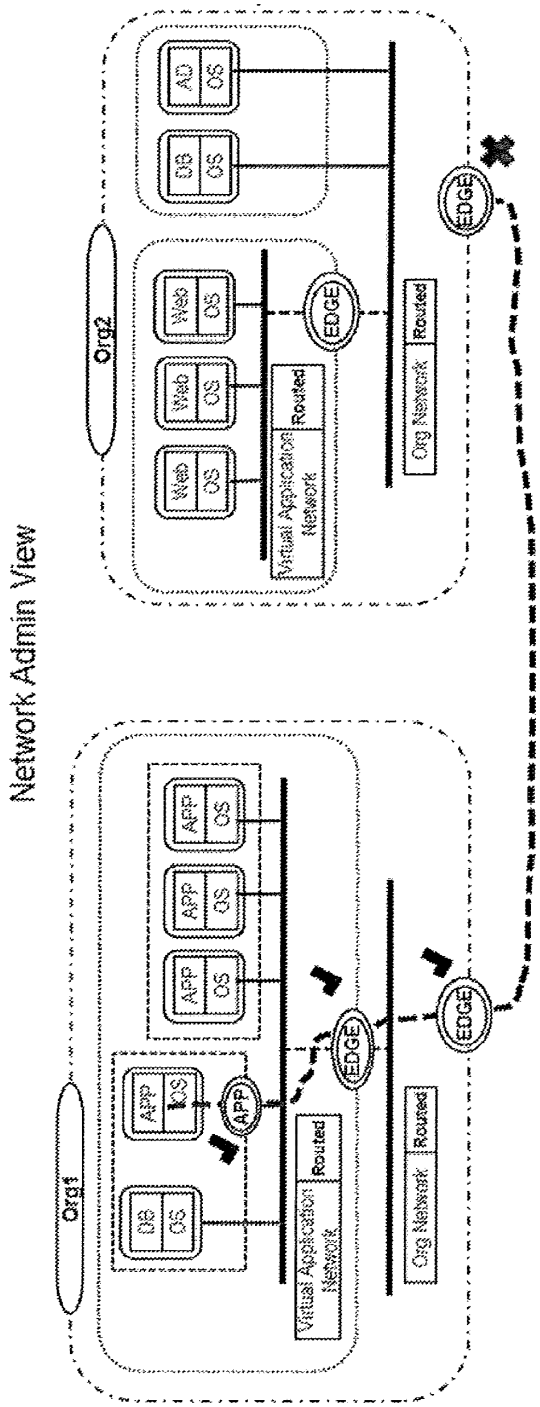


FIG. 10B

BNSDOCID: <US____20140281030A1_I_>

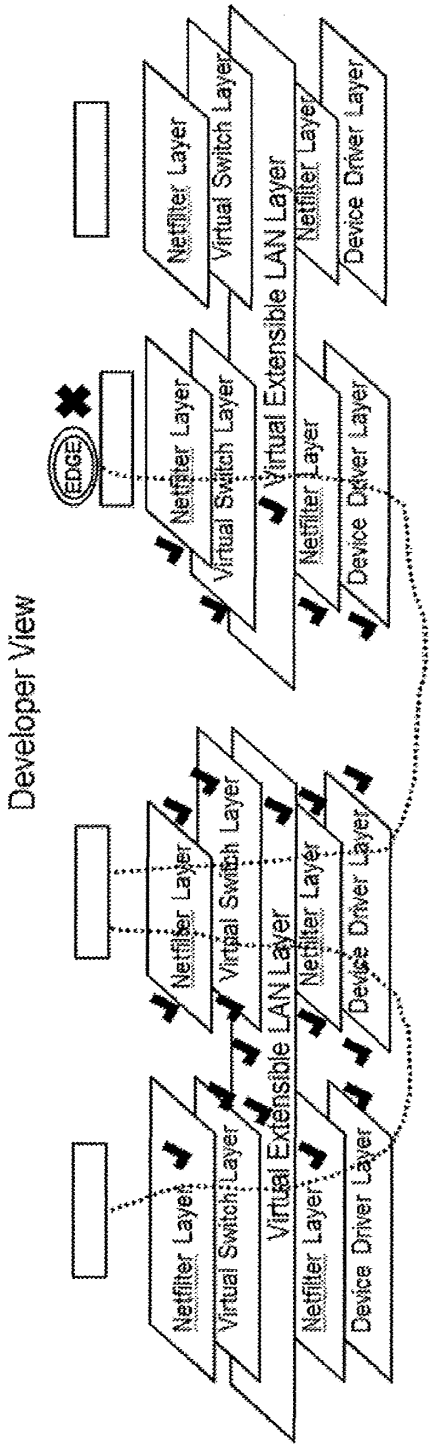


FIG. 10C

BNSDOCID: <US____20140281030A1_I_>

VIRTUAL NETWORK FLOW MONITORING

BACKGROUND

[0001] With the increased use of cloud computing and virtualization technologies, virtual datacenter architectures have grown in scale and complexity. In some instances, thousands of virtual machines (VMs) act as hosts, virtual gateways, and other network appliances to implement complex virtual networks. Troubleshooting network problems in such virtualized environments is difficult with existing monitoring systems that are not adapted to operate in cloud computing environments. Further, some virtual datacenters have multiple management and data path layers on top of the physical network infrastructure. For example, a data path may have a network interface card layer, a local area network encapsulation layer, a virtual network appliance layer, an input/output layer, and so on. Further, there may be logical network concepts such as a virtual network, an organization network, zone, endpoint, and so on. Because some of these layers and logical network concepts do not correspond to traditional physical infrastructure, some of the existing monitoring systems are in capable of identifying the source of network problems in virtualized environments.

[0002] Some existing monitoring systems provide packet-based probing by sending probe packets along the data path to identify physical network connectivity issues. Such systems, however, fail to present a high-level logical view to users, fail to provide network flow-based monitoring, and fail to provide detailed flow information within hosts. Further, the probe packets typically terminate at virtual gateways within the virtual datacenter due to security policies. In addition, such systems have a high resource cost (e.g., processing, memory, latency, etc.) by collecting all network traffic going through routers and switches.

[0003] Other existing systems focus on recording packet information within a single host, but these systems fail to provide end-to-end network flow monitoring along the entire network data path.

SUMMARY

[0004] One or more embodiments described herein provide end-to-end virtual network flow monitoring in a virtual datacenter having a plurality of virtual machines (VMs). In some embodiments, the virtual datacenter distributes a flow pattern to a plurality of applications managing the VMs. For example, the applications are associated with host computing devices, virtual gateways, and other network applications. The flow pattern describes data packets of interest to a user. Each of the applications monitors data packets routed by the application by, for example, comparing the data packets to the flow pattern. For each of the routed data packets that match the flow pattern, applications collect context data describing the data packet and transmit the collected context data to a remote server. In this manner, the virtual datacenter aggregates, from the plurality of applications routing data packets, context data for the data packets that match the flow pattern. The virtual datacenter filters the aggregated context data based on a role associated with the user. The filtered context data is presented to the user.

[0005] This summary introduces a selection of concepts that are described in more detail below. This summary is not intended to identify essential features, nor to limit in any way the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** is a block diagram of an exemplary host computing device.

[0007] FIG. **2** is a block diagram of virtual machines that are instantiated on a computing device, such as the host computing device shown in FIG. **1**.

[0008] FIG. **3** is a block diagram of components associated with a virtual datacenter.

[0009] FIG. **4** is a flowchart of an exemplary method performed by the virtual datacenter to initiate flow monitoring in virtual networks in the virtual datacenter.

[0010] FIG. **5** is a flowchart of an exemplary method performed by a host computing device, or other entity managing virtual machines, to monitor data packets and collect context data for selected data packets.

[0011] FIG. **6** is a block diagram illustrating exemplary flow monitoring in a stack in a host computing device.

[0012] FIG. **7** is a block diagram illustrating exemplary end-to-end flow monitoring between two organizations.

[0013] FIG. **8** is a block diagram illustrating exemplary end-to-end flow monitoring with network encapsulation.

[0014] FIG. **9** is a block diagram illustrating exemplary flow monitoring at virtual gateways.

[0015] FIGS. **10**A, **10**B, and **10**C are block diagrams illustrating exemplary filtering of flow information based on user role.

[0016] Corresponding reference characters indicate corresponding parts throughout the drawings.

DETAILED DESCRIPTION

[0017] Embodiments described herein provide a virtual network tracing and monitoring system that identifies and selectively monitors network flows, based on a target flow pattern **130**, end-to-end across a virtual network path in a virtual datacenter **302**. In addition to tracing the network flow within hosts, aspects of the disclosure leverage knowledge of virtual datacenter **302** infrastructure to identify, and enable tracing across, logical network edges or other boundaries (e.g., virtual network edges, organization network edges, zones, etc.) along the virtual network path. In some embodiments, virtual network appliances selectively produce a "footprint" of context data for data packets matching flow pattern **130** (e.g., provided by a user **108**). The context data is aggregated at a remote server for analysis and reporting.

[0018] Aspects of the disclosure further enable different users **108** to troubleshoot and identify the source of network issues in different levels within virtual datacenter **302**. In particular, the aggregated context data is filtered or otherwise mined based on different user roles to generate different virtual network monitoring views for presentation to the users **108**. This enables the different users **108** to identify the source of network issues within virtual datacenter **302** according their goals and knowledge levels.

[0019] Accordingly, aspects of the disclosure trace and selectively collect context data for data packets along the entire virtual network data path, including across multiple processing layers. Further, the tracing may occur periodically, intermittently, and/or on-demand, with a reduced negative impact on performance and traffic flooding relative to existing systems due at least to the selectively monitoring. For example, the network traffic is monitored without generating ping messages. As such, aspects of the disclosure provide a consistent, user-differentiated, one-stop troubleshooting and

BNSDOCID: <US____20140281030A1_I_>

reporting experience to users **108**. For example, different users **108** can troubleshoot network issues by operating on the same management workflow and user interface, without accessing lower level infrastructure information.

[0020] An example of a virtualized environment is next described.

[0021] FIG. **1** is a block diagram of an exemplary host computing device **100**. Host computing device **100** includes a processor **102** for executing instructions. In some embodiments, executable instructions are stored in a memory area **104**. Memory area **104** is any device allowing information, such as executable instructions and/or other data, to be stored and retrieved. For example, memory area **104** may include one or more random access memory (RAM) modules, flash memory modules, hard disks, solid state disks, and/or optical disks.

[0022] As described further herein, memory **104** stores at least one of flow pattern **130** for use in monitoring data packets.

[0023] Host computing device **100** may include a user interface device **110** for receiving data from user **108** and/or for presenting data to user **108**. User **108** may interact indirectly with host computing device **100** via another computing device such as VMware's vCenter Server or other management device. User interface device **110** may include, for example, a keyboard, a pointing device, a mouse, a stylus, a touch sensitive panel (e.g., a touch pad or a touch screen), a gyroscope, an accelerometer, a position detector, and/or an audio input device. In some embodiments, user interface device **110** operates to receive data from user **108**, while another device (e.g., a presentation device) operates to present data to user **108**. In other embodiments, user interface device **110** has a single component, such as a touch screen, that functions to both output data to user **108** and receive data from user **108**. In such embodiments, user interface device **110** operates as a presentation device for presenting information to user **108**. In such embodiments, user interface device **110** represents any component capable of conveying information to user **108**. For example, user interface device **110** may include, without limitation, a display device (e.g., a liquid crystal display (LCD), organic light emitting diode (OLED) display, or "electronic ink" display) and/or an audio output device (e.g., a speaker or headphones). In some embodiments, user interface device **110** includes an output adapter, such as a video adapter and/or an audio adapter. An output adapter is operatively coupled to processor **102** and configured to be operatively coupled to an output device, such as a display device or an audio output device.

[0024] Host computing device **100** also includes a network communication interface **112**, which enables host computing device **100** to communicate with a remote device (e.g., another computing device) via a communication medium, such as a wired or wireless packet network. For example, host computing device **100** may transmit and/or receive data via network communication interface **112**. User interface device **110** and/or network communication interface **112** may be referred to collectively as an input interface and may be configured to receive information from user **108**.

[0025] Host computing device **100** further includes a storage interface **116** that enables host computing device **100** to communicate with one or more datastores, which store virtual disk images, software applications, and/or any other data suitable for use with the methods described herein. In exemplary embodiments, storage interface **116** couples host computing device **100** to a storage area network (SAN) (e.g., a Fibre Channel network) and/or to a network-attached storage (NAS) system (e.g., via a packet network). The storage interface **116** may be integrated with network communication interface **112**.

[0026] FIG. **2** depicts a block diagram of virtual machines 235_1, 235_2 . . . 235_N that are instantiated on host computing device **100**. Host computing device **100** includes a hardware platform **205**, such as an x86 architecture platform. Hardware platform **205** may include processor **102**, memory area **104**, network communication interface **112**, user interface device **110**, and other input/output (I/O) devices, such as a presentation device **106** (shown in FIG. **1**). A virtualization software layer, also referred to hereinafter as a hypervisor **210**, is installed on top of hardware platform **205**.

[0027] The virtualization software layer supports a virtual machine execution space **230** within which multiple virtual machines (VMs 235_1-235_N) may be concurrently instantiated and executed. Hypervisor **210** includes a device driver layer **215**, and maps physical resources of hardware platform **205** (e.g., processor **102**, memory area **104**, network communication interface **112**, and/or user interface device **110**) to "virtual" resources of each of VMs 235_1-235_N such that each of VMs 235_1-235_N has its own virtual hardware platform (e.g., a corresponding one of virtual hardware platforms 240_1-240_N), each virtual hardware platform having its own emulated hardware (such as a processor **245**, a memory **250**, a network communication interface **255**, a user interface device **260** and other emulated I/O devices in VM 235_1). Hypervisor **210** may manage (e.g., monitor, initiate, and/or terminate) execution of VMs 235_1-235_N according to policies associated with hypervisor **210**, such as a policy specifying that VMs 235_1-235_N are to be automatically restarted upon unexpected termination and/or upon initialization of hypervisor **210**. In addition, or alternatively, hypervisor **210** may manage execution VMs 235_1-235_N based on requests received from a device other than host computing device **100**. For example, hypervisor **210** may receive an execution instruction specifying the initiation of execution of first VM 235_1 from a management device via network communication interface **112** and execute the execution instruction to initiate execution of first VM 235_1.

[0028] In some embodiments, memory **250** in first virtual hardware platform 240_1 includes a virtual disk that is associated with or "mapped to" one or more virtual disk images stored on a disk (e.g., a hard disk or solid state disk) of host computing device **100**. The virtual disk image represents a file system (e.g., a hierarchy of directories and files) used by first VM 235_1 in a single file or in a plurality of files, each of which includes a portion of the file system. In addition, or alternatively, virtual disk images may be stored on one or more remote computing devices **100**, such as in a storage area network (SAN) configuration. In such embodiments, any quantity of virtual disk images may be stored by the remote computing devices **100**.

[0029] Device driver layer **215** includes, for example, a communication interface driver **220** that interacts with network communication interface **112** to receive and transmit data from, for example, a local area network (LAN) connected to host computing device **100**. Communication interface driver **220** also includes a virtual bridge **225** that simulates the broadcasting of data packets in a physical network received from one communication interface (e.g., network communication interface **112**) to other communication interfaces (e.g., the virtual communication interfaces of VMs

235_1-235_N). Each virtual communication interface for each VM 235_1-235_N, such as network communication interface **255** for first VM 235_1, may be assigned a unique virtual Media Access Control (MAC) address that enables virtual bridge **225** to simulate the forwarding of incoming data packets from network communication interface **112**. In an embodiment, network communication interface **112** is an Ethernet adapter that is configured in "promiscuous mode" such that all Ethernet packets that it receives (rather than just Ethernet packets addressed to its own physical MAC address) are passed to virtual bridge **225**, which, in turn, is able to further forward the Ethernet packets to VMs 235_1-235_N. This configuration enables an Ethernet packet that has a virtual MAC address as its destination address to properly reach the VM in host computing device **100** with a virtual communication interface that corresponds to such virtual MAC address.

[0030] Virtual hardware platform 240_1 may function as an equivalent of a standard x86 hardware architecture such that any x86-compatible desktop operating system (e.g., Microsoft WINDOWS brand operating system, LINUX brand operating system, SOLARIS brand operating system, NETWARE, or FREEBSD) may be installed as guest operating system (OS) 265 in order to execute applications **270** for an instantiated VM, such as first VM 235_1. Virtual hardware platforms 240_1-240_N may be considered to be part of virtual machine monitors (VMM) 275_1-275_N that implement virtual system support to coordinate operations between hypervisor **210** and corresponding VMs 235_1-235_N. Those with ordinary skill in the art will recognize that the various terms, layers, and categorizations used to describe the virtualization components in FIG. **2** may be referred to differently without departing from their functionality or the spirit or scope of the disclosure. For example, virtual hardware platforms 240_1-240_N may also be considered to be separate from VMMs 275_1-275_N, VMMs 275_1-275_N may be considered to be separate from hypervisor **210**. One example of hypervisor **210** that may be used in an embodiment of the disclosure is included as a component in VMware's ESX brand software, which is commercially available from VMware, Inc.

[0031] In some embodiments, host computing device **100** represents any device executing instructions (e.g., as application programs, operating system functionality, or both) to implement the operations and functionality described herein. For example, one or more of host computing devices **100** execute instructions to implement the operations illustrated in FIG. **4** and/or FIG. **5**. Host computing device **100** may include any computing device or processing unit. For example, host computing device **100** may represent a group of processing units or other computing devices, such as in a cloud computing configuration.

[0032] Processor **102** includes any quantity of processing units, and is programmed to execute computer-executable instructions for implementing aspects of the disclosure. The instructions may be performed by processor **102** or by multiple processors executing within host computing device **100**, or performed by a processor external to host computing device **100** (e.g., another processor available within virtual datacenter **302**). In some embodiments, processor **102** is programmed to execute instructions such as those illustrated in the figures.

[0033] Memory area **104** includes any quantity of computer-readable media associated with or accessible by host computing device **100** or other entity within virtual datacenter **302**. Memory area **104**, or portions thereof, may be internal to host computing device **100**, external to host computing device **100**, or both.

[0034] FIG. **3** is a block diagram of components associated with virtual datacenter **302**. In the example of FIG. **3**, user **108** interacts with virtual datacenter **302**. User **108** may be classified, categorized, or typed based on a role, employment title, and/or interests of user **108**. For example, user **108** includes, but is not limited to, an administrator of virtual datacenter **302**, an owner of a virtual application, a developer, and/or other user involved with virtual datacenter **302**. In some embodiments, the amount and content of flow monitoring and/or tracing data (e.g., collected context data describing data packets) is dependent on the type, category, role, or classification of user **108**.

[0035] As shown in FIG. **3**, virtual datacenter **302** includes one or more computer storage media **304**, such as memory area **104** in some embodiments. Computer storage media **304** store components that, when executed by a processor such as processor **102**, perform various operations. The components illustrated in FIG. **3** include a management component **306** communicating with each of a plurality of host components **308**, such as host component #1 through host component #N.

[0036] The functionality associated with management component **306** is described below with reference to FIG. **4**. In some embodiments, this functionality is implemented by a cloud operating system, a cloud application, a virtual datacenter operating system, a virtual datacenter application, and/or other logic or code supporting an environment having a plurality of VMs executing therein. An example of a cloud operating system includes VMware's vSphere brand software, while an example of a virtual datacenter operation system and/or application includes VMware's vCloud Director software.

[0037] Further, the functionality associated with host components **308** is described below with reference to FIG. **5**. In some embodiments, this functionality is implemented by a virtualization layer such as hypervisor **210**. For example, each of host components **308** manages a plurality of VMs.

[0038] FIG. **4** is a flowchart of an exemplary method **400** performed by virtual datacenter **302** to initiate flow monitoring in virtual networks in virtual datacenter **302**. For example, one or more of the operations illustrated in FIG. **4** may be performed by management component **306** illustrated in FIG. **3**. However, while method **400** is described with reference to execution by virtual datacenter **302** (shown in FIG. **3**), it is contemplated that method **400** may be performed by any computing device, application, and/or other entity. For example, method **400** may be performed by host computing device **100**.

[0039] At **402**, virtual datacenter **302** checks whether flow pattern **130** has been received from user **108**. For example, flow pattern **130** may be received or identified as part of a request from user **108** to initiate virtual network flow monitoring. Flow pattern **130** describes characteristics of data packets of interest to user **108**. The characteristics relate to the content and/or structure of the data packets. In some embodiments, an exemplary flow pattern **130** includes a source address and a destination address. Flow pattern **130** may include other data such as user-defined keys, a protocol type, and/or other data. Exemplary protocol types include, but are not limited to, a transmission control protocol (TCP) and/or a user datagram protocol (UDP). In some embodiments, flow pattern **130** identifies a source Internet Protocol (IP) address,

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a destination IP address, a source port for TCP/UDP, a destination port for TCP/UDP, and an IP protocol. While flow pattern **130** may be represented by any data structure, an example of a data structure includes the following 5-tuple: <sourceip_address, destination_ip_address, source port, destination port, protocol_type>.

[0040] Flow pattern **130** may also include rules or other operations or tests to be performed on the data packets when evaluating whether the data packets match flow pattern **130**. For example, as an alternative or addition to analyzing the source address and destination address of each of the data packets, a hash of each data packet may be calculated and compared to a hash included in flow pattern **130**. In this manner, particular data packets may be selected, as further described below.

[0041] Upon receipt of flow pattern **130**, virtual datacenter **302** stores flow pattern **130** in a memory area associated with virtual datacenter **302**. At **406**, virtual datacenter **302** distributes flow pattern **130** to one or more devices, applications, and/or other entities within virtual datacenter **302** that handle (e.g., route) data packets. In some embodiments, one or more of these entities manage a plurality of VMs as part of at least one virtual network. For example, virtual datacenter **302** may distribute flow pattern **130** to one or more of host components **308** illustrated in FIG. **3**.

[0042] In some embodiments, virtual datacenter **302** transmits flow pattern **130** to each of host computing devices **100** and virtual gateways within virtual datacenter **302**. In another example, only particular entities within virtual datacenter **302** are selectively targeted (e.g., a subset of the available host computing devices **100**, applications, and/or virtual gateways). In some embodiments, a plurality of applications operates as, or otherwise implements some functions of, host computing device **100** and/or a virtual gateway.

[0043] At **408**, over time, virtual datacenter **302** aggregates context data describing data packets that match the distributed flow pattern **130** from entities (e.g., host components **308**) within virtual datacenter **302**. For example, the context data is received from the entities in virtual datacenter **302** that handle the data packets, have received flow pattern **130**, and have found data packets that match flow pattern **130**. The context data may be aggregated across virtual networks within virtual datacenter **302** and/or across virtual datacenters **302**. For example, the context data may be aggregated across one or more logical network boundaries. The context data relating to a single packet may be referred to as a footprint record.

[0044] At **410**, virtual datacenter **302** determines a role of user **108**. The role may be specified in, for example, the request received from user **108**. The role may also be derived from past requests from user **108**, feedback from user **108** resulting from past requests, default values, and/or other factors.

[0045] At **412**, virtual datacenter **302** filters the aggregated context data based on the role of user **108**. For example, the context data may be reduced to a level of detail associated with the determined role of user **108**. At **414**, virtual datacenter **302** provides the filtered context data to user **108**. In some embodiments, virtual datacenter **302** displays the filtered context data to user **108**.

[0046] FIG. **5** is a flowchart of an exemplary method **500** performed by host computing device **100**, or other entity managing virtual machines (e.g., an edge appliance such as a virtual gateway at the edge of a virtual network to monitor data packets and collect context data for selected data packets. For example, one or more of the operations illustrated in FIG. **5** may be performed by one or more of host components **308** illustrated in FIG. **3**. However, while method **500** is described with reference to execution by host computing device **100** (shown in FIG. **2**), it is contemplated that method **500** may be performed by any computing device, application, and/or other entity. For example, method **500** may be performed by a virtual gateway, hypervisor **210**, VMs **235**, applications **270**, and/or guest operating system **265**.

[0047] At **502**, host computing device **100** checks whether a command or request to initiate flow monitoring has been received. For example, the command is received from management component **306** or other entity within virtual datacenter **302**. Upon receipt of the command to initiate flow monitoring, host computing device **100** receives, obtains, or otherwise accesses flow pattern **130** associated with the command at **504**. Host computing device **100** stores flow pattern **130** in memory area **104**. For example, host computing device **100** caches flow pattern **130** into a hash table at the kernel level.

[0048] At **506**, for each data packet handled by host computing device **100** (e.g., routed) within one more virtual networks, host computing device **100** compares the data packet to flow pattern **130**. For example, host computing device **100** compares the source and destination addresses of each data packet to the source and destination addresses specified in flow pattern **130**. At **508**, for each of the data packets, host computing device **100** determines whether the data packet matches flow pattern **130**, or otherwise satisfies criteria associate with flow pattern **130**.

[0049] If host computing device **100** determines that the data packet matches flow pattern **130**, host computing device **100** increases a pattern reference counter (e.g., at the kernel level) and collects context data describing the matching data packet at **510** (e.g., at the user level). For example, host computing device **100** collects the context data by identifying at least one of a forwarding port, any filters applied to the data packet, results of any applied filters, a virtual network encapsulating the data packet, and whether the received data packet has been copied, cloned, and/or dropped.

[0050] In some embodiments, host computing device **100** collects the context data for only those data packets matching flow pattern **130**, out of a plurality of data packets handled by host computing device **100**. As such, host computing device **100** does not collect the context data for each and every data packet received, but collects data for only those data packets matching flow pattern **130**. In this manner, the cost of flow monitoring, in terms of latency and/or resource consumption (e.g., processing, memory, etc.), is reduced relative to merely sending a report on every single routed data packet whether or not the data packets are of interest to user **108**.

[0051] At **512**, host computing device **100** transmits the collected context data, for each matching data packet, to a reporting device, server, or other entity. In some embodiments, each of host computing devices **100** within virtual datacenter **302** has access to the reporting device to enable the aggregate of the context data on the reporting device.

[0052] If the data packet does not match flow pattern **130** at **508**, context data is not collected and transmitted to the reporting device. Rather, processing continues with the next handled data packet at **506**.

[0053] In embodiments, the operations illustrated in FIG. **5** may be performed by a virtual gateway application, operating

as a virtual gateway from a first virtual network to a second virtual network. In such embodiments, the virtual gateway application derives flow table information from flow pattern **130**. As such, the virtual gateway application compares each routed data packet to flow pattern **130** by comparing each routed data packet to the derived flow table information.

[0054] FIG. **6** is a block diagram illustrating exemplary flow monitoring or tracing in a stack in host computing device **100**. In the example of FIG. **6**, the stack includes a netfilter front layer (e.g., an IOChain/DVFilter layer for distributed virtual filtering), a virtual switch layer (e.g., a PortGroup layer), a virtual extensible local area network (LAN) layer, a netfilter back layer (e.g., another IOChain/DVFilter layer for distributed virtual filtering), and a device driver layer (e.g., a NicDriver layer). The virtual extensible LAN, such as the VXLAN brand software from VMware, Inc., represents an encapsulation mechanism that runs between virtual switches to enable VMs **235** to be deployed on, and move between, any servers within virtual datacenter **302**.

[0055] Exemplary operations associated with flow monitoring are next described. While the operations are described as being performed by host computing device **100** in some embodiments, the operations may be performed by any module, device, application, etc. that acts as a bi-directional packet filter between a virtual switch and a device driver to filter network traffic entering the virtual switch from VMs **235** or exiting the virtual switch to VMs **235**. In some embodiments, the bi-directional packet filter is embodied in a software Ethernet switch providing network connectivity within a virtual network environment.

[0056] User **108** defines flow pattern **130** at Operation 1 and flow tracing is enabled at Operation 2. The packet footprint is traced according to flow pattern **130** at Operation 3, and the network flow is analyzed via the data packets. For each matching data packet, host computing device **100** collects the context data described in Table 1 below.

TABLE 1

Exemplary Context Data.

Packet Metadata	Layer 3 5-tuple Metadata
portIDs	List of portIDs that the packet accessed
Distributed virtual filters	List of filters that the packet passed (e.g. invoked)
IOChains	List of function addresses that the packet passed (e.g., called)
<func, result>	Function calls and the results therefrom
<clone/copy>	Clone or copy records of the packet

[0057] Each of the elements of the context data shown in Table 1 may include additional data, such as a timestamp.

[0058] At Operation 4, the collected context data is sent to a remote server. For example, the footprint record for the data packet is sent to the remote server when the data packet is about to be freed. Alternatively or in addition, the collected context data is batched for a plurality of matching data packets and flushed to the remote server periodically and/or intermittently. For example, host computing device **100** may send 32 footprints records at a time. Upon collecting enough footprint records (e.g., satisfying a pre-defined threshold), the remote server determines the flow record.

[0059] In an exemplary implementation, host computing device **100** reserves extra memory space in each data packet when creating, copying and/or cloning the packet. The extra memory space is used to capture context data, and may be referred to as the footprint record. When the data packet is copied or cloned, the footprint record is also copied. In some embodiments, host computing device **100** allocates 64 kilobytes for the footprint record, which includes 8 bytes for the functional address, 4 bytes for the result, 4 bytes for the portID, 16 bytes for the timestamp, and 32 bytes for other metadata.

[0060] FIG. **7** is a block diagram illustrating exemplary end-to-end flow monitoring between two organizations. In this example, a user in one organization (Org1) is accessing web services provided by another organization (Org2). The exemplary network path between Org1 and Org2 is illustrated in FIG. **7** and shown to pass through several zones or edges:

[0061] Source→vAppNetwork1→OrgNetwork→ExternalNetwork→OrgNetwork2→vAppNetwork2→Destination

[0062] In the example of FIG. **7**, "edge" represents an edge gateway and "app" represents an application firewall. The virtual gateways between Org1 and Org2 may be implemented using the vShield Edge and/or the vShield App, both from VMware, Inc. Aspects of the disclosure access virtual gateway network profiles for the virtual gateways to understand the virtual network flow patterns. For example, the virtual gateway network profiles may be obtained from a cloud operating system and/or cloud application executed by virtual datacenter **302**. In the example of FIG. **7**, five virtual network flow patterns are illustrated. Flow pattern **130** is given by the application in Org1 with <SRC: 192.168.1.100, DST: 172.30.4.12, DST Port: 80, Protocol: TCP>. Host computing device **100** communicates with the other virtual network appliances shown in FIG. **7** to understand the routing policies on the virtual gateways and then deduce the remaining virtual network flow patterns. The remaining virtual network flow patterns represent the flow patterns (e.g., source address, destination address, port number) along the entire network path. In the example of FIG. **7**, the virtual network flow patterns change several times as the traffic passes through several routers in the network path (e.g., from 192.168.1.100 to 172.25.33.22).

[0063] FIG. **8** is a block diagram illustrating exemplary end-to-end flow monitoring with network encapsulation. In the example of FIG. **8**, network traffic with flow pattern **130** represented by <SRC: 192.168.1.100, DST: 192.168.1.200, DST Port: 8000, Protocol: TCP> is encapsulated and decapsulated within the same virtual network. The virtual extensible LAN application performing the encapsulation and the virtual extensible LAN application performing the decapsulation execute the operations illustrated in FIG. **5** to enable identification and tracing of data packets matching flow pattern **130**. Aspects of the disclosure are operable with any encapsulation/decapsulation operations, such as those associated with the VXLAN brand software from VMware, Inc.

[0064] FIG. **9** is a block diagram illustrating exemplary flow monitoring at virtual gateways. An application implementing the operations illustrated in FIG. **4** (e.g., executing on host computing device **100**) enables flow monitoring by communicating with virtual datacenter **302** (e.g., a cloud operating system) to obtain a description of the infrastructure within virtual datacenter **302** at Operation 1. For example, the application establishes an authenticated channel with the cloud operating system managing virtual datacenter **302** to obtain a network profile describing the virtual network infrastructure. The network profile represents the virtual network

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topology and configuration information that identifies, among other data, host computing devices **100** sitting in the network flow path.

[0065] At Operation 2, the application identifies the hosts involved in a target network flow path, and distributes flow pattern **130** to each of the hosts to initiate flow monitoring. At Operation 3, flow pattern **130** is distributed to virtual gateways and other virtual network edge appliances to initiate flow monitoring. At Operation 4, the virtual network appliances (e.g., hosts, virtual gateways, etc.) send the context data for data packets matching flow pattern **130** to a remote server for analysis and reporting.

[0066] FIGS. **10**A, **10**B, and **10**C are block diagrams illustrating exemplary filtering of flow information based on user role. The flow information represents the aggregated context data for data packets matching flow pattern **130**. In this example, the flow information indicates a network issue and is filtered based on three different user roles: a virtual application owner (e.g., a customer), a network administrator, and a developer. FIG. **10**A illustrates the virtual application owner view, FIG. **10**B illustrates the network administrator view, and FIG. **10**C illustrates the developer view. The checkmarks in the figures indicate successful passing of the data packets, whereas the "X" in the figures indicates where the network issue is occurring.

[0067] The virtual application owner view represents a top level view (e.g., high-level logical view) presenting the network flow from a source virtual network to a destination virtual network. The virtual application owner view indicates to the virtual application owner that the network issue is occurring at the edge of the destination virtual network. The network administrator view represents a middle level view (e.g., infrastructure or stack view) presenting the network flow across the overall virtual network infrastructure. The network administrator view indicates to the network administrator that the network issue is occurring at the edge of the destination organization network. The developer view represents a low level view (e.g., component level) presenting the functional level packet footprints and network flow across the hosts. The developer view indicates to the developer that the network issue is occurring because of a destination edge gateway configuration.

[0068] The different views illustrated in FIGS. **10**A, **10**B, and **10**C may be presented to users **108** by an application executing on the remote server, on a device within virtual datacenter **302**, by the cloud operating system managing virtual datacenter **302**, and/or by another entity.

[0069] In this manner, aspects of the disclosure present differentiated troubleshooting views according to user role. For example, the functional packet tracing path is presented to technical support and developers, while the logical network path is presented to network administrators to enable efficient identification of network issues in a top-down fashion.

Additional Examples

[0070] The following scenarios are merely exemplary and not intended to be limiting in any way.

[0071] In one scenario, the remote server aggregating the context data for data packets matching flow pattern **130** allows third party vendors to develop filtering criteria to create customized views of the aggregated context data. For example, rather than presenting the three different views in FIGS. **10**A, **10**B, and **10**C, other views may be created.

Exemplary Operating Environment

[0072] The operations described herein may be performed by a computer or computing device. The computing devices communicate with each other through an exchange of messages and/or stored data. Communication may occur using any protocol or mechanism over any wired or wireless connection. A computing device may transmit a message as a broadcast message (e.g., to an entire network and/or data bus), a multicast message (e.g., addressed to a plurality of other computing devices), and/or as a plurality of unicast messages, each of which is addressed to an individual computing device. Further, in some embodiments, messages are transmitted using a network protocol that does not guarantee delivery, such as User Datagram Protocol (UDP). Accordingly, when transmitting a message, a computing device may transmit multiple copies of the message, enabling the computing device to reduce the risk of non-delivery.

[0073] Exemplary computer readable media include flash memory drives, digital versatile discs (DVDs), compact discs (CDs), floppy disks, and tape cassettes. By way of example and not limitation, computer readable media comprise computer storage media and communication media. Computer storage media include volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules or other data. Computer storage media are tangible and are mutually exclusive to communication media. In some embodiments, computer storage media are implemented in hardware. Exemplary computer storage media include hard disks, flash drives, and other solid-state memory. In contrast, communication media typically embody computer readable instructions, data structures, program modules, or other data in a modulated data signal such as a carrier wave or other transport mechanism and include any information delivery media.

[0074] Although described in connection with an exemplary computing system environment, embodiments of the disclosure are operative with numerous other general purpose or special purpose computing system environments or configurations. Examples of well-known computing systems, environments, and/or configurations that may be suitable for use with aspects of the disclosure include, but are not limited to, mobile computing devices, personal computers, server computers, hand-held or laptop devices, multiprocessor systems, gaming consoles, microprocessor-based systems, set top boxes, programmable consumer electronics, mobile telephones, network PCs, minicomputers, mainframe computers, distributed computing environments that include any of the above systems or devices, and the like.

[0075] Embodiments of the disclosure may be described in the general context of computer-executable instructions, such as program modules, executed by one or more computers or other devices. The computer-executable instructions may be organized into one or more computer-executable components or modules. Generally, program modules include, but are not limited to, routines, programs, objects, components, and data structures that perform particular tasks or implement particular abstract data types. Aspects of the disclosure may be implemented with any number and organization of such components or modules. For example, aspects of the disclosure are not limited to the specific computer-executable instructions or the specific components or modules illustrated in the figures and described herein. Other embodiments of the disclosure may include different computer-executable instruc-

tions or components having more or less functionality than illustrated and described herein.

[0076] Aspects of the disclosure transform a general-purpose computer into a special-purpose computing device when programmed to execute the instructions described herein.

[0077] The embodiments illustrated and described herein as well as embodiments not specifically described herein but within the scope of aspects of the invention constitute exemplary means for end-to-end tracing of the one or more data packets through virtual datacenter **302** based on a footprint for each of the one or more data packets.

[0078] At least a portion of the functionality of the various elements illustrated in the figures may be performed by other elements in the figures, or an entity (e.g., processor, web service, server, application program, computing device, etc.) not shown in the figures.

[0079] In some embodiments, the operations illustrated in the figures may be implemented as software instructions encoded on a computer readable medium, in hardware programmed or designed to perform the operations, or both. For example, aspects of the disclosure may be implemented as a system on a chip or other circuitry including a plurality of interconnected, electrically conductive elements.

[0080] The order of execution or performance of the operations in embodiments of the disclosure illustrated and described herein is not essential, unless otherwise specified. That is, the operations may be performed in any order, unless otherwise specified, and embodiments of the disclosure may include additional or fewer operations than those disclosed herein. For example, it is contemplated that executing or performing a particular operation before, contemporaneously with, or after another operation is within the scope of aspects of the disclosure.

[0081] When introducing elements of aspects of the disclosure or the embodiments thereof, the articles "a," "an," "the," and "said" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements. The term "exemplary" is intended to mean "an example of"

[0082] Having described aspects of the disclosure in detail, it will be apparent that modifications and variations are possible without departing from the scope of aspects of the disclosure as defined in the appended claims. As various changes could be made in the above constructions, products, and methods without departing from the scope of aspects of the disclosure, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

We claim:

1. A system for end-to-end virtual network flow monitoring in a virtual datacenter having a plurality of virtual machines (VMs), said system comprising:

a memory area associated with the virtual datacenter, said memory area storing a flow pattern including at least a source address and a destination address, the flow pattern being received from a user in a request to perform virtual network flow monitoring; and

a processor programmed to:

distribute the flow pattern stored in the memory area to a plurality of applications in the virtual datacenter, each of the plurality of applications managing a plurality of VMs as part of at least one virtual network;

aggregate, by the virtual datacenter from the plurality of applications, context data for one or more data packets routed by the plurality of applications and matching the flow pattern; and

determine a role associated with the user; and

filter, by the virtual datacenter based on the determined role, the aggregated context data for presentation to the user.

2. The system of claim **1**, wherein the plurality of applications operate as at least one of a host computing device or a virtual gateway.

3. The system of claim **1**, wherein the processor is further programmed to display the aggregated context data to the user.

4. The system of claim **1**, wherein the flow pattern further comprises at least one of a transmission control protocol (TCP) or a user datagram protocol (UDP).

5. The system of claim **1**, wherein the user comprises at least one of a virtual application owner, an administrator, or a developer.

6. The system of claim **1**, wherein the processor aggregates the context data across a logical network boundary.

7. The system of claim **1**, further comprising means for end-to-end tracing of the one or more data packets through the virtual datacenter based on a footprint for each of the one or more data packets.

8. A method comprising:

for each of a plurality of computing devices associated with one or more virtual networks in a virtual datacenter, the virtual datacenter comprising a plurality of virtual machines (VMs):

accessing, by the computing device, a flow pattern providing a source address and a destination address;

receiving a data packet from the one or more virtual networks;

comparing, by the computing device, the received data packet to the accessed flow pattern; and

based on the comparison, collecting data describing the received data packet and transmitting the collected data for analysis to a reporting device accessible by each of the plurality of computing devices associated with the one or more virtual networks in the virtual datacenter.

9. The method of claim **8**, wherein collecting the data comprises identifying at least one of a forwarding port, a filter applied to the data packet, a virtual network encapsulating the data packet, whether the received data packet has been copied, or whether the received data packet has been cloned.

10. The method of claim **8**, wherein collecting the data comprises collecting the data on determining that the received data packet matches the accessed flow pattern.

11. The method of claim **8**, wherein the computing device receives a plurality of the data packets, and wherein collecting the data comprises collecting the data for only those data packets, from the plurality of data packets, that match the accessed flow pattern.

12. The method of claim **8**, wherein receiving the data packet comprises receiving, by a host computing device, a data packet.

13. The method of claim **8**, wherein the computing device comprises a virtual gateway application, and further comprising deriving, by the virtual gateway application, flow table information from the accessed flow pattern.

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14. The method of claim **13**, wherein comparing the received data packet to the accessed flow pattern comprises comparing the received data packet to the derived flow table information.

15. The method of claim **8**, wherein the computing device comprises a host, and wherein collecting the data comprises collecting the data across a network stack within the host.

16. One or more computer-readable storage media storing computer-executable components for performing end-to-end virtual network flow monitoring in a virtual datacenter having a plurality of virtual machine (VMs), the computer-executable components comprising:

a plurality of host components that each, when executed, cause at least one processor to:

receive a data packet;

compare the received data packet to a flow pattern defined by a user, the flow pattern including at least a source address and a destination address; and

based on the comparison, collect context data describing the received data packet; and

a management component in communication with each of the plurality of host components, the management component, when executed, causing at least one processor to:

aggregate the collected context data from one or more of the plurality of host components;

determine a role associated with the user; and

filter, based on the determined role, the aggregated, collected context data for presentation to the user.

17. The computer storage media of claim **16**, wherein the management component further receives, from the user, a request to perform the virtual network flow monitoring, the request including the flow pattern.

18. The computer storage media of claim **16**, wherein the management component further distributes the flow pattern to each of the plurality of host components.

19. The computer storage media of claim **16**, wherein each of the plurality of host components manages a plurality of VMs.

20. The computer storage media of claim **16**, wherein at least one of the plurality of host components represents a virtual gateway from a first virtual network to a second virtual network.

* * * * *

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(54) **PACKET SEQUENCE NUMBER NETWORK MONITORING SYSTEM**

(76) Inventors: **Chao Kan**, Plano, TX (US); **Pierrick Guingo**, Dallas, TX (US); **Emanuele Jones**, Ottawa (CA); **Hubert Ogier**, Paris (FR); **Thierry Labbe**, Dallas, TX (US)

Correspondence Address:
ALCATEL USA
INTELLECTUAL PROPERTY DEPARTMENT
3400 W. PLANO PARKWAY, MS LEGL2
PLANO, TX 75075 (US)

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(57) **ABSTRACT**

A network monitoring system **(60)**. The system comprises storage circuitry **(32)** for storing network packet information, wherein the network packet information includes a predicted identifier. The network monitoring system also comprises at least one monitoring circuit **(36)** coupled to a network **(70)** along which network traffic flows in a form of packets. The at least one monitoring circuit programmed to perform the steps **(44)** of receiving a packet communicated along the network and determining whether the received packet is communicated between a source and destination in a first set of network nodes. Each packet in a sequence of communications between the source and the destination comprises a packet identifier that uniquely identifies the packet from all other communications in a flow between the source and the destination. The at least one monitoring circuit programmed to perform the step of, responsive to determining the received packet is communicated between a source and destination in the first set of network nodes, comparing the packet identifier of the received packet to the predicted identifier to determine an identifier deviation between the packet identifier and the predicted identifier for identifying an irregularity in the network traffic.

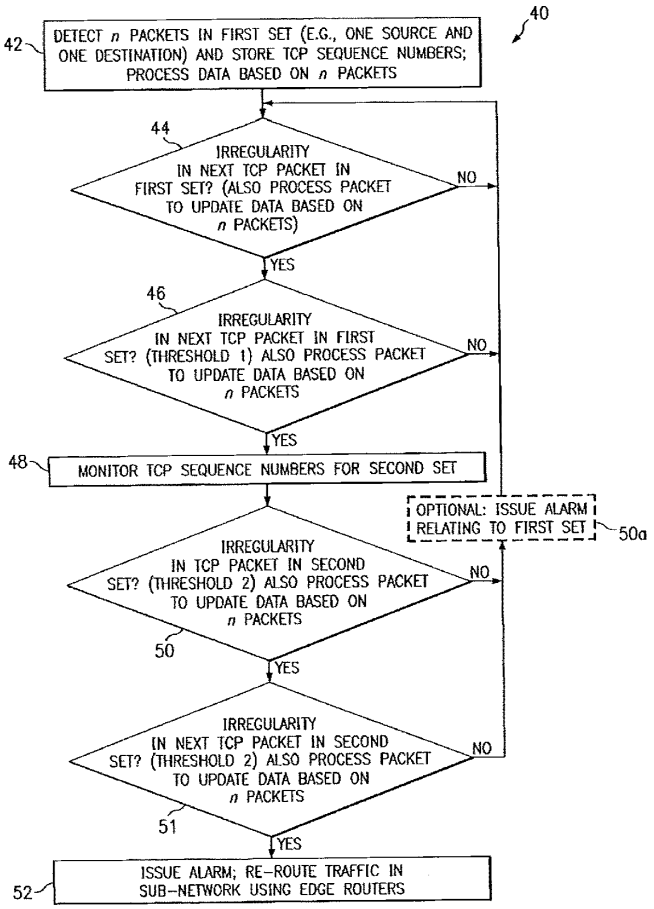

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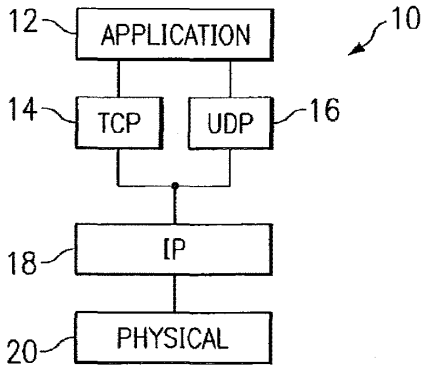
FIG. 1
(PRIOR ART)



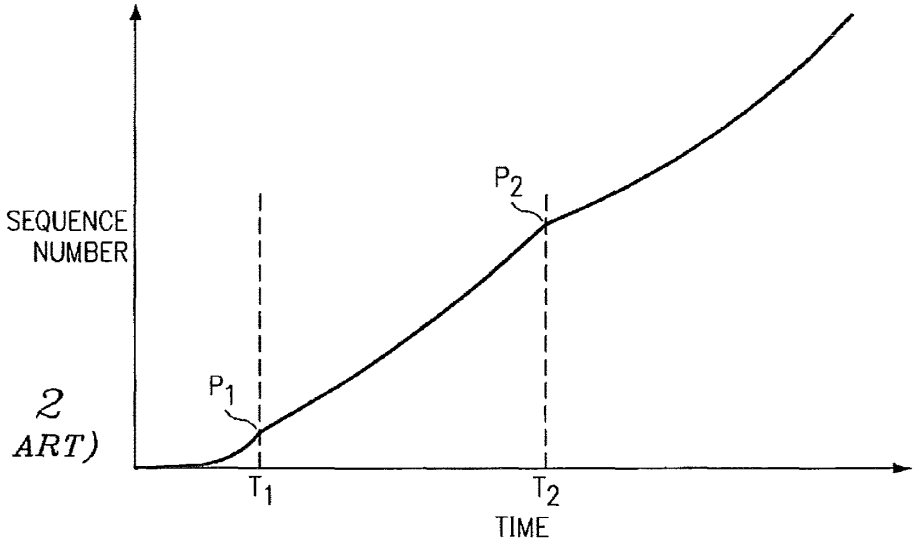


FIG. 2
(PRIOR ART)

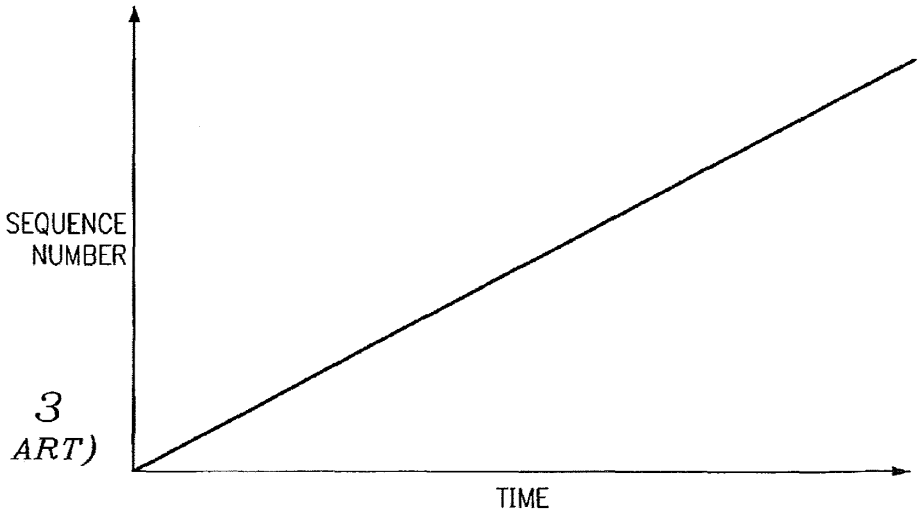


FIG. 3
(PRIOR ART)

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FIG. 4
(PRIOR ART)

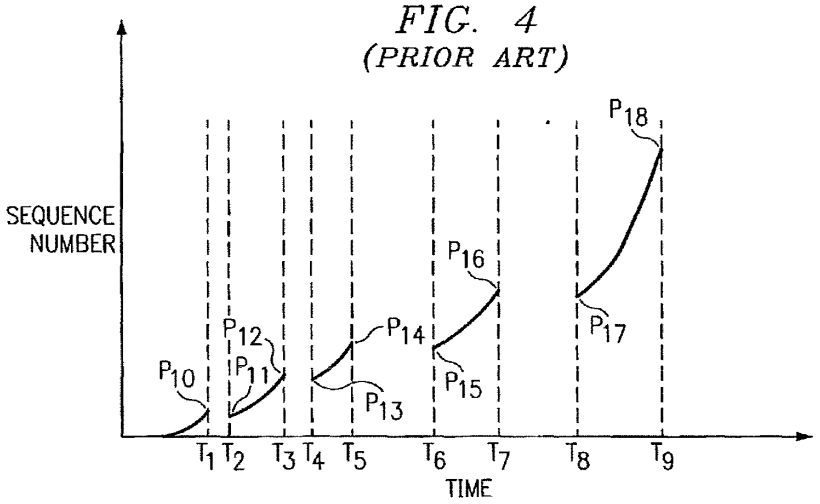
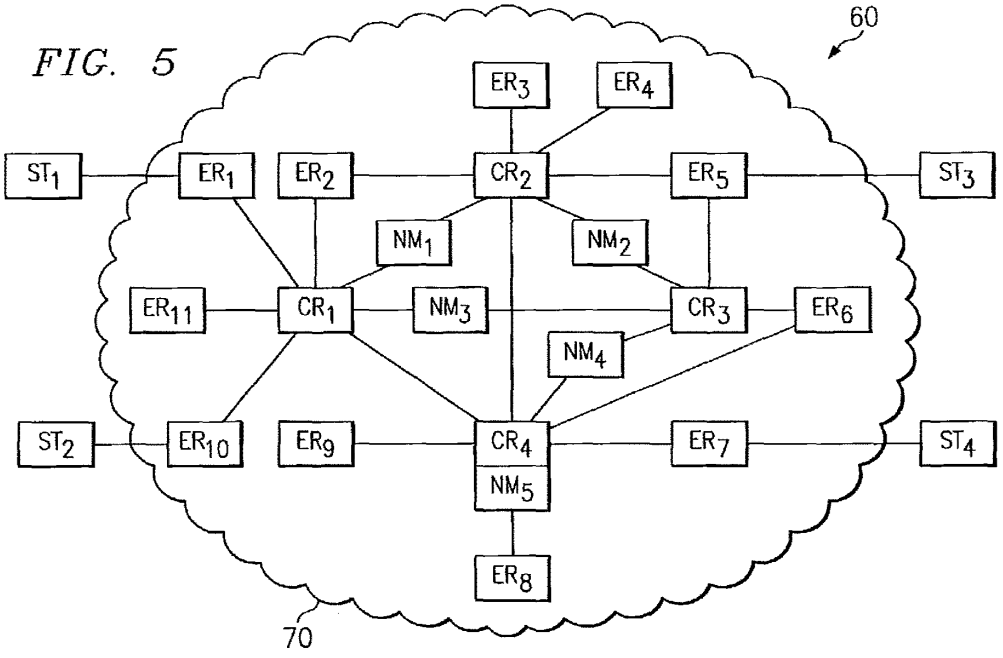


FIG. 5



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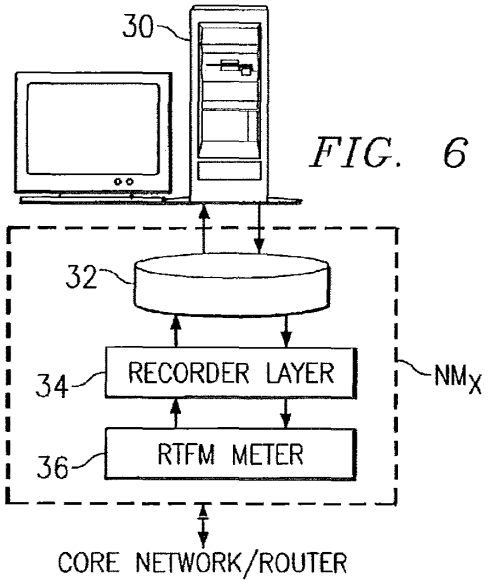

FIG. 6

FIG. 8

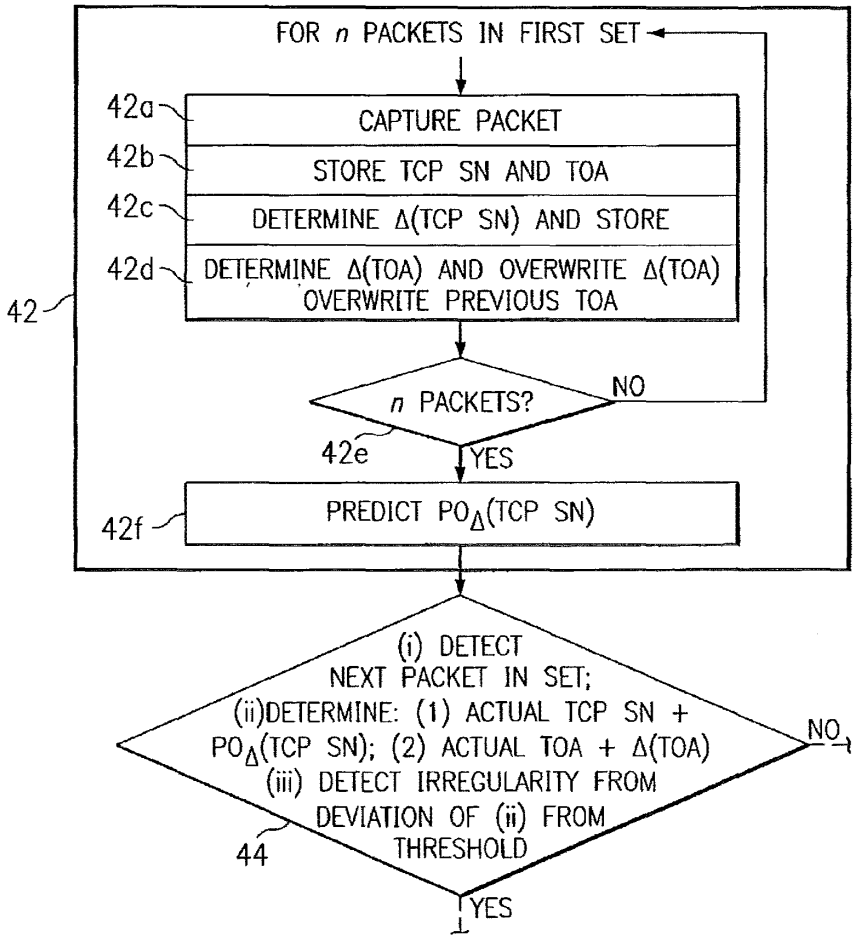

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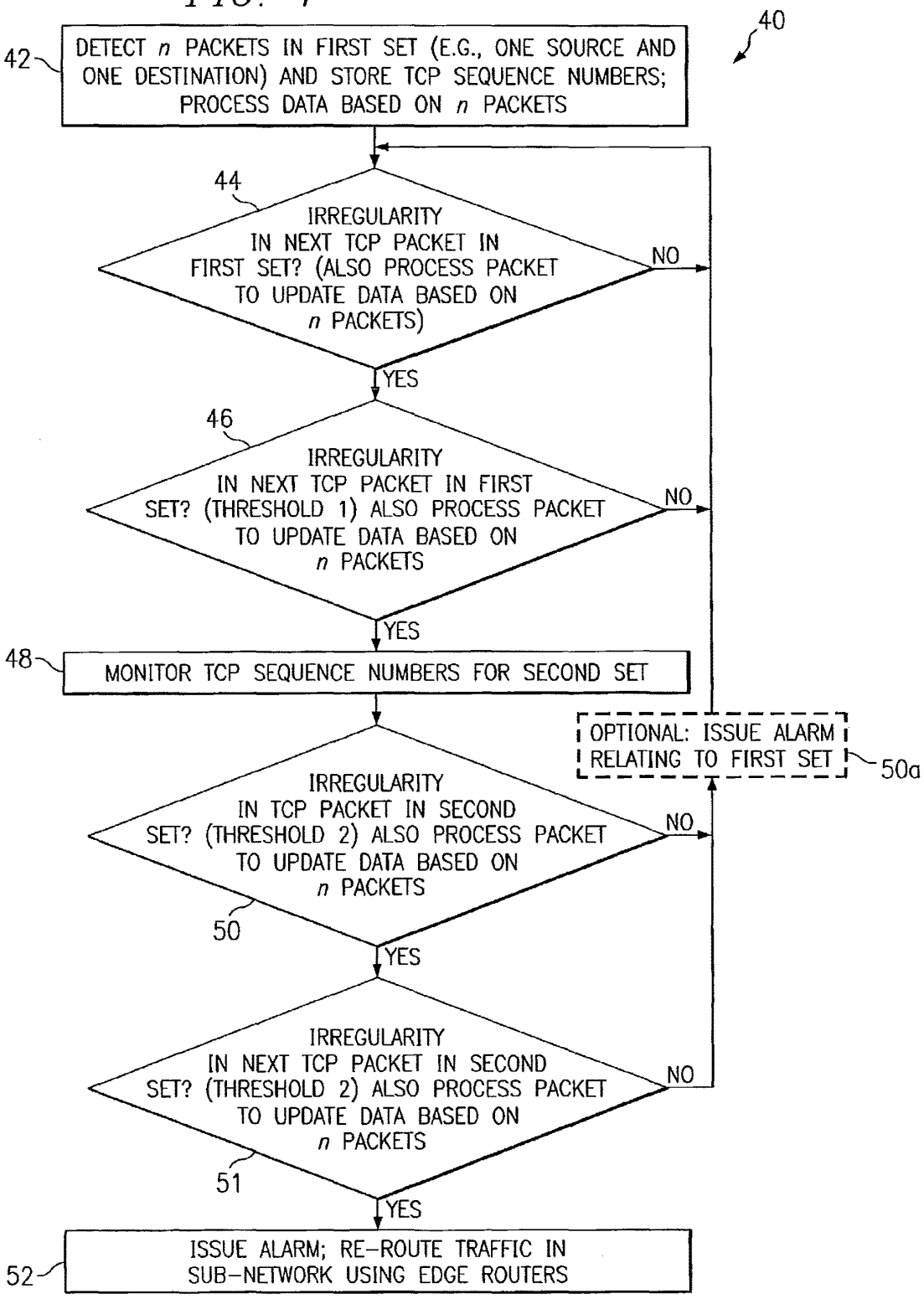
FIG. 7



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PACKET SEQUENCE NUMBER NETWORK MONITORING SYSTEM

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] Not Applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not Applicable.

BACKGROUND OF THE INVENTION

[0003] The present embodiments relate to computer networks and are more particularly directed to a real-time system for monitoring network performance by evaluating packet identifiers such as packet sequence numbers.

[0004] As the number of users and traffic volume continue to grow on the internet and other networks, an essential need has arisen for both the users and network operators to have a set of mechanisms to monitor network performance, detect router availability, and troubleshoot network congestion without introducing additional traffic on the network. This is especially true for Internet Service Providers in order to comply with the Service Level Agreements ("SLAs") that they are now providing to customers. Additionally, such a need is prevalent for the underlying internet protocol ("IP") networks in the global internet. With these mechanisms, the users and network operators also can monitor and query the reliability and availability of the network nodes (e.g., IP routers) and the given internet paths, and the mechanisms also can identify the location of a segment of a given internet path, if any, that has a limitation. Additionally, the internet is evolving towards an advanced architecture that seeks to guarantee the quality of service ("QoS") for real-time applications, such as by putting limits on the upper bound on certain QoS parameters including jitter, throughput, one-way packet delay, and packet loss ratio. Accordingly, tracking QoS performance is also desirable. Given the preceding, various mechanisms for network monitoring have been developed in the art, some of which are described below.

[0005] A first type of network performance analysis mechanism is known in the art as an active mechanism. The active network performance monitoring system sends a series of special test packets or query packets to the underlying networks or routers, and it analyzes the response with a specific purpose. Currently, most tools for active end-to-end QoS monitoring in IP networks are based on the traditional "ping" (i.e., ICMP echo and echo response messages) to measure the roundtrip delay between two hosts. Variations of ping include "Nikhef ping,""fping,""pingplotter,""gnuplotping,""Imeter," and "traceping". Several other tools are variations based on the traditional "traceroute" (which exploits the time-to-live field in the IP packet header), for example, "Nikhef traceroute,""pathchar,""whatroute," and "network probe daemon." A few large-scale research projects are using "ping" to continually and actively monitor the network performance between various points in the global internet. Examples of these types of projects are: (i) the PingER project at Stanford Linear Accelerator Center ("SLAC") uses repeated pings around various Energy Sciences Network ("ESnet") sites; (ii) the Active Measurement Program ("AMP") project by National Laboratory for Applied Network Research ("NLANR") performs pings and traceroutes between various NSF-approved high-performance connection sites; (iii) the Surveyor project attempts one-way packet delay and loss measurements between various sites using the global positioning system ("GPS") for time synchronization; and (iv) the national Internet measurement infrastructure ("NIMI") project measures the performance between various sites using traceroute or transmission control protocol ("TCP") bulk transfer.

[0006] A second type of network performance analysis mechanism is known in the art as a passive mechanism and may be contrasted to the active mechanism discussed above. The passive network performance monitoring system performs its traffic analysis in a non-invasive way with respect to the observed networking environment, namely, the system does not introduce additional test packets to the network. As a result, the system does not affect the performance of the network while doing the measurements and querying. The traditional approach usually involves the following three steps: (i) collection of the entire TCP/IP packet (e.g. traffic sniffers, etc.) or the entire packet header data into a database or databases; (ii) hardware and software for analyzing the collected database(s); and (iii) off-line traffic characterization and modeling. Various examples of passive mechanisms have been implemented by certain entities. For example, the NLANR has been using OCXmon monitors to tap into the light of a fiber interconnection by means of optical splitters, and from the connection the system collects a portion of the packet, namely, the packet header. Specifically, traffic data is collected in an abstract format by extracting and storing the packet header in the database within a preset traffic aggregation period. The packet header traffic data in the database is later analyzed (i.e., an off-line traffic analysis). As another example, Cisco offers a NetFlow capability in its large routers. NetFlow identifies traffic flows based on IP source/destination addresses, protocol ID field, type of service ("TOS") field, and router port. Once identified, statistics can be collected for a traffic flow, and exported via user datagram protocol ("UDP") when the flow expires. Flow statistics may include the flow start/stop times, number of bytes/packets, and all IP header fields. As a final example, Lucent Bell Labs has various research projects in traffic analysis, which are mainly concentrated in collection of TCP/UDP/IP packet headers and off-line traffic analysis, modeling and visualization.

[0007] A third type of network performance analysis mechanism is also a type of passive mechanism in that it does not add traffic to the network, but rather than collecting information directly from a packet it instead collects statistics pertaining to the packet; this system is sometimes referred to as a network or element management system. In this system, instead of separately setting up the packet collection process, IP routers periodically (e.g., in 30 minute intervals) store and collect a set of traffic statistics into a built-in Management Information Base ("MIB") using a simple network management protocol ("SNMP") interface, and those statistics may be retrieved by a network or element manager. Typical traffic statistics might be the number of received/forwarded packets, discarded packets, error packets, port utilization, CPU utilization, buffer utilization, and so forth. As in other passive systems, these statistics are collected for later analysis. When a network congestion or event occurs, the SNMP agent embedded in the IP router

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sends a trap message to the SNMP manager, which then indicates an alarm in its graphic user interface.

[0008] While the preceding systems have provided certain levels of information about the behavior of traffic in IP networks, the present inventors have observed that such systems also provide various drawbacks. As an example of a drawback with respect to the active systems, they are required to send special test or PING packets and, thus, these additional packets themselves introduce additional traffic onto the route of the regular data packets. Accordingly, at the time of detecting the network congestion or server availability, the network performance and associated QoS being measured will be negatively impacted by this additional burden. Additionally, the QoS is measured for the test packets instead of the actual data packets, and the QoS for the data packets must be inferred indirectly from the QoS measured for the test packets. As an example of a drawback with respect to the passive system, although many traffic studies have attempted to understand the random behavior or composition of internet traffic, these traffic studies have been off-line analysis of historical data. There are no known prominent research projects attempting traffic analysis and control based on real-time traffic measurement or comprehensive traffic profiling. For example, Lucent's projects reflect the traditional approach of collecting large traffic measurement datasets for lengthy periods of time such as on the order of many days and then performing subsequent off-line statistical analysis. Cisco NetFlow essentially measures the volume and duration of each traffic flow for the purposes of accounting and off-line traffic analysis, but is not intended to be used for real-time network monitoring and querying. The OCXmon tool from NLANR is only for asynchronous transfer mode ("ATM") traffic, and is not for the purpose of traffic monitoring and control. Given the off-line use of these tools which, by definition, is delayed by some time which may be on the order of days, any conclusion that may be drawn from the collected data is stale in the sense that it applies to the network environment as it existed at some previous time rather than having a high likelihood of characterizing the network at the time the analysis is concluded; in other words, the status of the network is likely to have changed between the time these prior art systems collect their data and the time they drawn any inferences or conclusions during their off-line analysis. Thus, by time the results provide meaningful indicators, the real-time status of the network may have changed. Finally, as an example of a drawback of the element management system, the router MIB is usually designed based on the specific structure and implementation of the underlying network or IP router and, therefore, it will not be the same for equipment from different vendors. For example, the Argent Guardian tool from Argent Software Inc. for performance monitoring and proactive problem detection and correction has different versions for different monitored entities. The Argent Guardian for Cisco can only be used for Cisco routers because it uses the Cisco router MIB to retrieve and query the traffic information. In addition, the MIB is commonly embedded in the IP router. As a result of these constraints, there is considerable difficulty in changing the MIB once the design is complete. Accordingly, there are considerable barriers to the use of such a system in the instance where there is a change in the parameters or statistics to be monitored and where the change is not already built into the MIB.

[0009] In view of the above, there arises a need to address the drawbacks of the prior art as is accomplished by the preferred embodiments described below.

BRIEF SUMMARY OF THE INVENTION

[0010] In the preferred embodiment, there is a network monitoring system. The system comprises storage circuitry for storing network packet information, wherein the network packet information includes a predicted identifier. The network monitoring system also comprises at least one monitoring circuit coupled to a network along which network traffic flows in a form of packets. The at least one monitoring circuit is programmed to perform the steps of receiving a packet communicated along the network and determining whether the received packet is communicated between a source and destination in a first set of network nodes. Each packet in a sequence of communications between the source and the destination comprises a packet identifier that uniquely identifies the packet from all other communications in a flow between the source and the destination. The at least one monitoring circuit programmed to perform the step of, responsive to determining the received packet is communicated between a source and destination in the first set of network nodes, comparing the packet identifier of the received packet to the predicted identifier to determine an identifier deviation between the packet identifier and the predicted identifier for identifying an irregularity in the network traffic.

[0011] Other aspects are also described and claimed.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

[0012] **FIG. 1** illustrates a prior art network layer stack **10** defined to include the transmission control protocol ("TCP").

[0013] **FIG. 2** illustrates a prior art plot of the evolution of TCP sequence numbers over time when a TCP session, including the source, destination, and network, behave normally.

[0014] **FIG. 3** illustrates a prior art plot of the evolution of TCP sequence numbers over time when during a TCP session the network operates normally but either the source or destination is limiting the bandwidth of communication.

[0015] **FIG. 4** illustrates a prior art plot of the evolution of TCP sequence numbers over time when during a TCP session the network is limiting the bandwidth of communication between the source and destination by dropping packets.

[0016] **FIG. 5** illustrates a block diagram of a network system **10** into which the preferred embodiments are implemented.

[0017] **FIG. 6** illustrates a block diagram of each network monitor NM_1 through NM_5 of **FIG. 5**.

[0018] **FIG. 7** illustrates a flow chart of the operation of each network monitor NM_1 through NM_5 of **FIG. 5**.

[0019] **FIG. 8** illustrates a flow chart of the predictor methodology preferably implemented within the flow chart of **FIG. 7**.