# Policy based Management of Content Distribution Networks

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***Abstract*: We present a policy-based architecture for the control and management of content distribution networks that form an overlay of caching proxies over an underlying physical network. The architecture extends the policy framework used for controlling network Quality of Service (QoS) and security to the case of content distribution networks. The fundamental advantage of a policy-based framework is that it allows a machine-independent scheme for managing multiple devices from a single point of control. In this paper, we describe this architecture and demonstrate how it enables dynamic updates to content distribution policies. Furthermore, we analyze the impact of such dynamic distribution on the cost of content serving.**

***Index Terms:* Distributed Systems, Web Services, Application Acceleration, Content Distribution.**

## I. Introduction

Ensuring a satisfactory performance level for web-based applications on the Internet is a long-standing problem within the networking research community. In order to address the performance issues, several approaches have been developed. The three most prominent approaches to managing the performance of applications include the IntServ/RSVP [1] signaling approach, the DiffServ approach [2] and the content distribution approach [3] [4]. The IntServ approach is based on the notion of reserving resources within the network, the DiffServ approach is based on the notion of mapping traffic aggregates into several different service classes, and the content distribution approach is based upon deploying a number of proxy servers scattered within the network that use a variety of caching techniques to improve the response time of web-based applications.

While each approach has its own advantages and disadvantages, they all share one common problem. The proper operation of each approach requires a consistent configuration of a large number of widely distributed devices. The policy based management paradigm, which has recently gained prominence, provides mechanisms that can be used to address this problem. Policy based techniques are being developed for the Integrated Services and the Differentiated Services technologies by various working groups within the IETF [5]. In this paper, we explore the methods by which the same technical approach can be applied to a content distribution network.

The rest of this paper is organized as follows: We begin with a brief overview of policy-based networking and its operation, followed by an overview of content distribution networks. Then we discuss the application of policy based techniques to content distribution networks, and discuss the form that typical policy rules for such an environment would take. Subsequently, we present a system architecture for a content distribution network that employs the techniques of policy based management. Finally, we highlight our conclusions and provide a summary discussion.

## II. Policy Based Networking

Network policies are a set of rules to administer, manage, and control access to network resources [13]. They are defined by an administrator and specify how the devices in the network should deal with different types of traffic. Policies provide a way to consistently manage multiple devices deploying complex technologies.

The policy framework defined by the IETF/DMTF consists of four basic elements as shown in Figure 1. The basic elements are: the *policy management tool*, the *policy repository*, the *policy enforcement point* (PEP), and the *policy decision point* (PDP). An administrator uses the *policy*

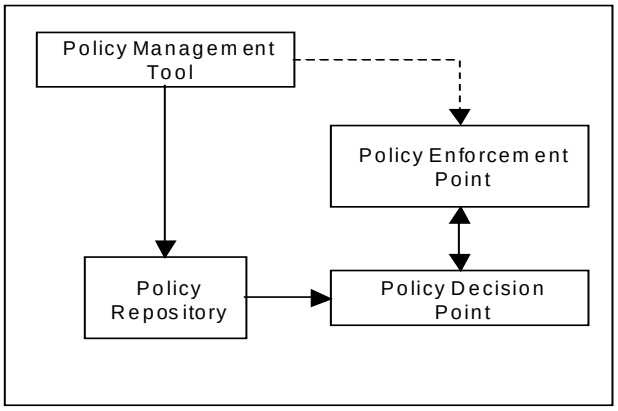


Figure 1. The Policy Architecture as defined by the IETF. The solid lines define normal flow of information among different components of the architecture. The dotted line shows optional communication between the components.


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*management tool* to define the different policies that are to be enforced in the network. The logical entities that can take actions to enforce the policies are known as the *policy* enforcement points (PEPs). The policies that the PEPs need to act upon are accessed from a policy repository. The *policy repository* is used to store the policies generated by the management tool. The policy decision point is an entity that is responsible for retrieving the policies from the repository, and for interpreting them and deciding on which set of policies ought to be enforced by the PEP.

The logical entities described by the standard model can be mapped onto physical devices in the network. In the domain of QoS, the PEP would be the function inside the router that makes QoS decisions (e.g. marks packets in accordance with the DiffServ standard). The PDP would be a software module inside the same router (or another router) that decides which set of DiffServ markings are to be active at any given time. The repository could be implemented as an LDAP directory storing DiffServ policies.

The simplification in management is obtained primarily by centralizing the definition of policies in a single repository, and by defining abstractions that provide a machine-independent specification of policies. The centralization goal is obtained by defining the policies that apply to the entire networked system at a single location. This allows checking the consistency among the policies being defined for different devices in the network. The policy specification contained within the repository is defined in terms of the technology to which a policy would apply, rather than in terms of the configuration parameters of the device. Thus, a policy may specify which DiffServ Per-Hop Behavior (PHB) should be used for a specific application flow, rather than how this mapping would be configured for a specific device.

The specification of policy rules within the repository is key to obtaining inter-operability. The information model for the rules to be specified is being defined by standards bodies [5]. While the intricacies of the information model are beyond the scope of this paper, we will follow the basic principle of defining a policy as an expression of the form “if condition then action”. Here, the conditional part describes a specific situation that can be encountered by a network device, and the action component specifies the action that is to be performed by the device in that situation.

There are many ways to interpret and implement the rule-based format of the policies. In the most general sense, the action may be construed as a procedure that is defined and stored in the repository (e.g. a piece of Java code, or a program in a language like CacheL [6] or PONDER[7]). A less general interpretation is to consider the policies as instances of first order predicate expressions. An even more limited interpretation is to consider the policy conditions as key fields that are used to index a table of actions, where the corresponding actions are the set of simple operations that need to be performed. When a more general implementation of policies is followed, more complex policies can be specified, but they are also much harder to analyze for consistency. The standards bodies have tended to follow the limited tabular approach, leading to policies that are easier to analyze, and can be stored conveniently in an LDAP repository.[1] The information model defined in the standards drafts is more complex than the simple tabular model we are presenting, but the two can be mapped onto each other. For the networking disciplines that have been the focus of policy based management, namely Integrated Services, Differentiated Services and IP-security, the tabular approach has been found to be adequate. The goal of this paper is to examine whether the same approach can be used in defining distribution policies for content replication.

## III. CONTENT DISTRIBUTION NETWORKS

Content Distribution Networks attempt to reduce user response time by caching content closer to the end user. The primary focus of this approach has been on web-based applications. A content distribution network consists of a network of caching proxy servers to which clients are directed transparently using various wide-area load balancing schemes. The caching approach works well for data that is static and unchanging, e.g. images, video clips, etc. There are many companies providing such a service for static content. The research community is also exploring approaches that would enable more of the content to become cacheable. This is achieved by deploying a variety of techniques such as query-result and database caching [8], high-volume publish-subscribe systems [9], change graphs [10], active middleware [11], etc.

A typical content distribution environment is shown in Figure 2. It contains machines belonging to three different

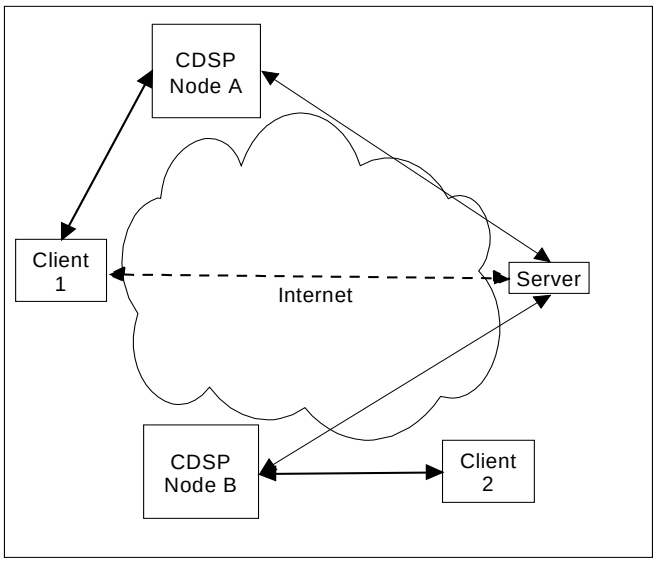


Fig. 2. The typical architecture of a content distribution network.

[1] In addition to the tabular representation, the standards also define several other aspects, e.g. scope restrictions of policies, and grouping of policies into roles. However, the structure of the policies is similar to the tabular representation.

administrative entities. A web-browser is used by the client to access a web-server on the Internet. The web-server owner has a contract with another organization (which we refer to as a CDSP or Content Distribution Service Provider) that has multiple sites hosted throughout the network. These sites are shown as the crosshatched boxes in Figure 2.

Normally, the client browser interacts with the origin web-server (the dashed flows). The goal of the content distribution network is to replace the client-server communication by a set of communication flows, one occurring between the client and one of the CDSP nodes (thick solid flow), and the other occurring between the CDSP node and the origin server (thin solid flow). The assumption is that there are a large number of applications where the dashed flows can be decomposed into a set of solid and dotted flows such that the solid flows predominate, and the bandwidth/frequency of dotted flows are relatively small. In these circumstances, execution of web-based applications at a CDSP node would result in reduced response time to the end user, as well as a reduced load on the network and the main web-server.

In this model, the browser would end up communicating with a CDSP node that is close to it, and retrieve files from that node. In their most common format, CDSP nodes consist of web-proxies caching static content. However, there is an increasing trend of CDSP provides to add support for dynamic content, such as execution of cgi-bin programs, servlets, or JSPs at the CDSP node. The program at the CDSP node may in turn invoke programs at the origin web-server, or access databases at the origin web-server. However, the latter invocations would be less frequent and would require less bandwidth.

Note that different clients may access different CDSP servers. Figure 1 shows client 1 accessing the CDSP node A, while client 2 accesses the CDSP node B. We assume that there is a business agreement between the CDSP nodes and the web-server owner that allows for the execution of programs owned by the web-server at the CDSP nodes. This will allow offload of dynamic content as well as static content [12].

Within such an environment, one needs to determine the policies that would be appropriate for controlling the distribution of programs and files across the various nodes. Not all types of data and programs are suitable for execution within the proxy environment. The decision on what can be moved out for execution and caching at the different edge servers depends upon several factors, such as: the type of page being accessed, the URL being invoked, or the frequency of access to a site. The intent of this paper is to explore whether the tabular paradigm used in the policy framework is adequate for controlling the distribution of code and data in this environment.

## IV. Policy Rules for Content Distribution Networks

In order to examine whether the simple policy model can be applicable to content distribution networks, we look at the different components that will make up its condition and action parts. Specifically, we look at the individual fields that would constitute the condition and action parts of the policy statement. A policy in the context of a content distribution network would be a statement defining what type of programs/data can be moved out to a CDSP node and what type of programs/data must be executed at the origin server.

With this definition of policy, there are only two types of actions that are possible, namely a piece of program/data is either edgeable or not edgeable, where edgeable means that the program is capable of executing at a CDSP proxy or that a piece of data is cacheable at the CDSP proxy. However, any type of caching comes with assumptions regarding how the consistency of the cached data ought to be maintained. Thus, when an action directs that a piece of program/data be edgeable, the action must also specify the consistency model that must be followed by the cached data/program.

Various applications have different cache consistency requirements. However, for each application, one can enumerate a small number of consistency models that are appropriate for that application. As an illustrative example, let us consider the situation where CDSP nodes are caching static web pages. In this case, three different consistency models are commonly used. The first model, *strong consistency*, requires that an access to the cached page return the most up-to-date copy of the page (the page last written to the origin server). This type of consistency can be guaranteed, for example, by validating a cached page against the origin server upon every access to the cache using the conditional-get request of the HTTP protocol. Another approach that can be used is to have the origin server invalidate (or update) all copies at the caches before completing an update to the master copy of the page. That is, an update at the main site is pushed to all the edges before the update is considered complete. A second consistency model, *time-limited inconsistency*, requires that a cached page be updated within a specified maximum time window following an update to the main page at the origin site. This model can be implemented, for example, by refreshing cached data at frequent-enough regular time intervals. A third consistency model, *loose consistency*, requires that pages at the cache be updated as soon as the network can do so. This can be achieved by having the origin server batch updates or invalidations and broadcast them to the edge caches less frequently according to a best-effort policy. Such a protocol

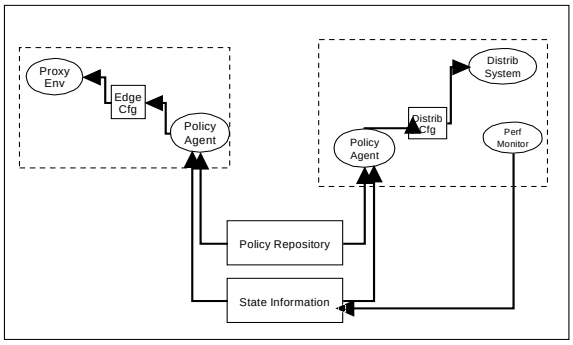


Fig. 3. A policy based Architecture for content distribution networks.

may help conserve load and network bandwidth and may be sufficient for some applications.

In summary, we can distinguish three types of application consistency models for statically cached web-pages. For each consistency model, one or more possible consistency protocols can be employed to actualize that model. However, the number of interesting protocols and models is finite and therefore can be summarized in a concise table. The action field in the table can specify the particular protocol that ought to be used for the particular deployment.

Not all data may be considered cacheable at all locations. Our assumption is that the CDSP proxies may be located throughout the world, and some of them may be subject to regulations that prevent them from caching specific types of content. Therefore, a policy action must be able to restrict the caching function to be performed only at specific sites. As an example, the site restriction may be specified by either a subnet mask of the IP addresses that a proxy may have, or by a regular expression that ought to be matched by the domain name of the proxy server.

For the condition field, the standard 5-tuple that is ubiquitously present in the current schemes for QoS and IP-security would also form part of the condition field for content distribution. Each CDSP edge-server may only be caching content for a certain set of origin sites, so the source IP address will be part of the condition. The source port number is not required for web-based clients, but may be needed for some applications that will only use a specific range of port addresses. The destination IP address is needed to restrict the scope of distribution to a specific server, and the destination port number is needed for identifying the specific application at the server. The protocol field is also needed as part of the process for identifying the application.

This 5-tuple is not sufficient for identifying the type of application that can be cached. Assuming a web-based application, the cacheability of the application/data can also be determined by the type of Universal Resource Identifier (URI) that the client is accessing. The URI may define whether or not a specific resource is edgeable. The URI is often used to map to a specific program that is executed, or a file that is retrieved. The class of programs, or the exact name of the program can determine whether or not a resource is edgeable. As an example, a website may decide to put all servlets that are edgeable under a subtree `/edgeable_code` under the root of the website, and the prefix of the program name invoked by a specific access would then determine whether or not the program was edgeable.

Other application level data can also be used to determine if parts of a user-interaction can be satisfied by a CDSP proxy. The user identity could determine whether the contents being accessed by the user were to be made edgeable. Since CDSP offload may be associated with a charge, a site may decide only to offload contents for its Gold-quality customers rather than for all its customers. In some application instances, the type of offload that is feasible would depend on the nature of the user. As an example, for LDAP directory query caching, it is straightforward to support offload for the user-id of anonymous or for users that only have read-only access, but relatively difficult to satisfy the offload for users that have write-access, or varying security and access control needs.

In many instances, the decision to allow offloading of applications or data to a CDSP site is determined by the current state of the network. As an example, a CDSP site may only be needed if there are some congested spots in the network impacting user performance, and does not provide much value in an un-congested network. Similarly, some origin sites may want to use the CDSP network only when there is a sudden surge of load on the site. In these cases, a minimum threshold can be defined to determine the arrival rate beyond which offloading would be enabled. We assume that there is a separate process for monitoring the workload in the system outside of the policy framework. The monitoring process must monitor the origin site, and can also monitor the CDSP sites. When monitoring the CDSP sites, the monitor would consist of monitoring subsystems at each site, and a central monitor to collect statistics from the other sites. A single CDSP proxy server is usually unaware of the current load on the entire distributed system. Therefore, it would be appropriate for a CDSP to use a monitoring system to track the load on a specific site, map it onto two or more levels, and use these levels to determine whether the contents of the site are to be made edgeable or not. As an example, a performance monitor may use the information about a backend site's load to classify it as under-loaded, moderately busy, or very busy. Application offload and caching would be enabled only when the site's load was considered to be very busy. The status of the performance monitor would need to be part of the condition rule in the policy clause.

The condition and action components as described above can be used for a tabular representation of policies related to content distribution networks, or they may be stored in the information model being considered within the IETF.

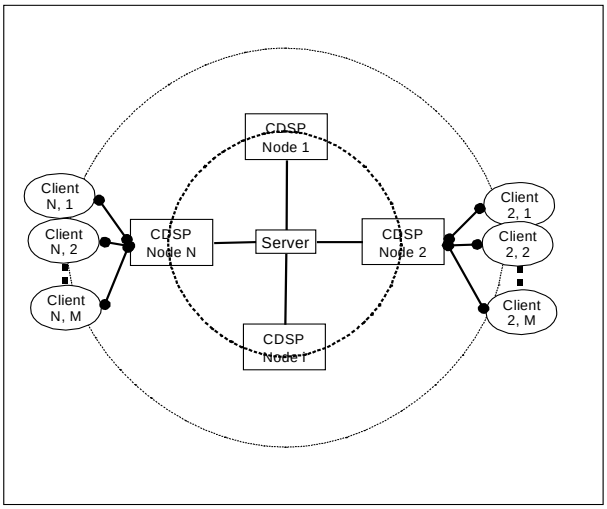


Fig. 4. The model for analyzing effectiveness of content distribution networks.

## V. POLICY ARCHITECTURE FOR CONTENT DISTRIBUTION NETWORKS

This section describes the architecture of a CDSP node as well as an origin site when the policy-based framework is used to drive the operation of a content distribution network. The basic architecture is as shown in Figure 3.

The policies are stored in a policy repository. We assume that there is a performance monitor component that collects information about the current state of the network, and stores it in a state repository accessible by the various sites. The performance monitor has to monitor the performance of the origin site, and can also monitor the performance of the CDSP sites. Each of the CDSP sites and the origin site need to have specific contents active as shown in the figure. We assume that the performance monitor that determines the network state is at the origin web-server, since it would typically want to control the times when application offload begins or ends.

In addition to the performance monitor, both the edge-site and the origin site need a policy agent. The policy agent is responsible for retrieving the content distribution policies from the single repository, and for determining the appropriate configuration at the local site for content distribution. The origin site configures its content distribution system to act in accordance with the distribution policies. The edge-server configures its environment to ensure that the policies are complied with for offloading specific applications.

We can map the policy model shown in Figure 1 to the components of Figure 3. The policy repository has the same function in both the figures. The distribution system and the proxy environment shown in Figure 3 are instances of PEPs (policy enforcement points) and are responsible for enforcing the content distribution policies stored at the repository. The Policy agent shown active at the different nodes in the system are instances of the PDP (Policy decision points). The policy agents help the distribution system and the proxy environment determine the set of policies that ought to be enforced at each site.

The policy management tool is not shown in Figure 3. However, it would be the tool that an administrator would use, in conjunction with the state information, to define the content distribution policies for the system.

A policy-based framework as described above can simplify the complexities involved in the operation and management of a large content distribution network. This also enables the creation of dynamic policies, wherein the characteristics of an application can be used to determine the fraction of the application components that can be deployed at an edge-server. Enabling dynamic policies can result in significant cost-savings and performance gains for the users of content distribution. In the next section, we look at the gains that dynamic policy mechanisms can provide to the users of a content distribution service.

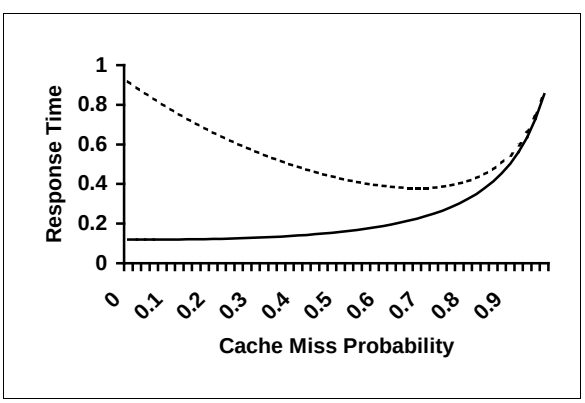


Fig. 5. The impact of cache miss probability on user response time. The dashed curve shows the response time when service rate of a proxy is 2 and service rate of server is 10. In the solid curve, both service rates are 10.

## VI. DYNAMIC POLICY MANAGEMENT

In order to understand the potential benefits of a policy based system, we look at the cost savings that can be obtained in a content distribution environment when we include the use of dynamic policies. We consider a symmetric environment as shown in Figure 4, where the content distribution network consists of the server in the center of the circle and a number of proxies that are distributed around the server at equal distances. Each proxy services a set of clients which we assume are also at equal distance from their closest proxies.

We assume that a fraction $p$ of the requests originating from a client are serviced directly by the central server, while the remaining fraction of the requests are serviced by the proxy. We further assume that: the average latency between the client and proxy is $\tau_p$ ; the average latency between the client and the central server is $\tau_p + \tau_d$ ; the requests arrive at the rate of $\lambda$ per client, and there are $n$ clients; the service rate of a proxy is $\mu_p$ requests per second; and, the service rate of the central server is $\mu_s$ requests per second. Using M/M/1 models for the processing time at the servers leads to an average response time of

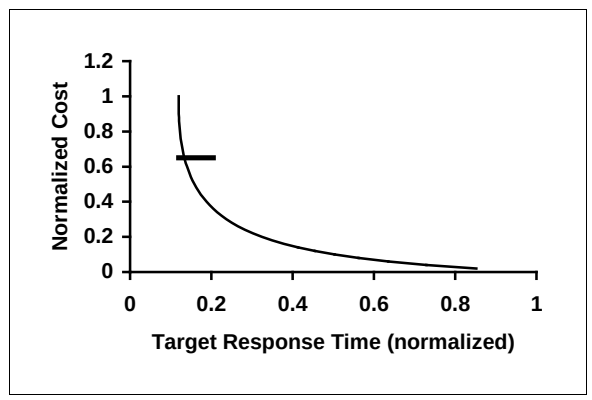


Fig 6 . The cost of supporting a response time SLA with and without dynamic policies. The normal line shows the cost of a dynamic solution. The thick horizontal line shows the constant cost of supporting a response time without dynamic content distribution policies, but the static planning can not support a response time below 0.12. Dynamic distribution policies can offer smaller target response times, as well as reduce cost for larger target response times.

$$R = \tau_p + p\tau_d + (1-p)/(\mu_p - \lambda(1-p)) + p/(\mu_s - np\,\lambda)$$

The solution is bounded provided that $\mu_p > \lambda(1-p)$ and $\mu_s > np\,\lambda$. Using simple calculus, it can be shown that the impact of distribution upon the response time of users would strongly depend upon the factor $\Gamma = \mu_p\tau_d$. The use of distribution would only help in reducing response time from a totally centralized solution if $\Gamma > 1 - \mu_p\mu_s/(\mu_s - n\lambda)^2$. In these cases, the distribution could either result in a decreasing response time (i.e., the best response time is obtained with full distribution), or there is an optimal distribution point where the response time is minimal. The other parameters in the solution determine whether or not the optimum point is less than full distribution.

Figure 5 shows the result of plotting response time as a function of the cache miss probability for 10 servers when $\tau_p$ =0.01, $\tau_d$ =0.01, $\mu_s$ = 10 and $\lambda$ = 0.9 for two values of $\mu_p$. For the dashed line, the value of $\mu_p$ is 2 while for the solid line, the value of $\mu_p$ equals $\mu_s$ (10). For the dashed line, an optimum response time is obtained when the server processes 70% of the requests, and offloads 30% of the requests to the proxy servers. For the solid line, where the proxies are comparable in performance to the central server, full distribution is the optimum solution

A direct benefit of using the policy based scheme is to reduce the costs of operating a content distribution system while satisfying a given response time SLA. In many content distribution solutions, the cost of operating the system is directly proportional to the amount of content offloaded. This is true in the model offered by content distribution providers such as Akamai, a CDSP that charges by the amount of content served from the caching infrastructure. In this case, a dynamic policy based system can minimize the cost for a specific SLA, and a given customer load. A solution with a static caching ratio will have a fixed cost for a given traffic load and a response time target. A solution with dynamic policies is able to determine the offload ratio in accordance with the desired performance targets, and can thus save in the cost of offloading the contents to remote sites.

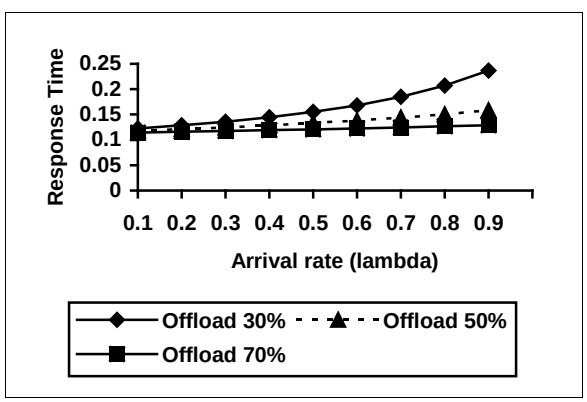


Fig. 7. The response time of a content distribution network as a function of the level of offloadable content.

Figure 6 shows the cost of supporting a specific response time SLA with and without dynamic policy based management. It is assumed that the CDN consists of 10 servers, when $\tau_p$=0.01, $\tau_d$ =0.01, $\mu_s$ = 10, and $\mu_p$ = 2. In the case of a static offload, the cost depends on the a priori fixed offload percentage. Thus, there would be a fixed upper response time beyond which a fixed offload scheme would not be able to attain the response time goal. A fixed offload scheme (shown by the thick horizontal line) with an SLA target of 0.2 time units (in terms of the scale of Figure 6) can be supported by serving about 35% of the content only from the central server.

The disadvantage of the fixed scheme is that it cannot accommodate the dynamic characteristics of a typical communications network. Since the workload on the server is not likely to stay constant, the workload generated by each client can play a dominant role in the response time perceived by the client. Figure 7 shows the results of the maximum response time that can be achieved at different client load levels using dynamic policies at a fixed cost. If we were using a fixed cost and a non-dynamic approach to content distribution, the range of load that could be supported would be limited, and a maximum load would need to be determined a-priori beyond which a response time SLA could not be supported.

Our analysis of the dynamic policy based distribution assumes that the applications can be offloaded to any arbitrary level of granularity. However, this would not be the case for a real application where the offload would be limited by application characteristics as well as latencies in measuring current client load and server response times. However, the curves shown in this section provide an upper bound on the effectiveness of dynamic policy distribution.

## VII. CONCLUSIONS

In this paper, we have examined how policies can be applied to the topic of content distribution networks. We have extended the policy framework to this new domain, and proposed an architecture for policy based content distribution. We have also provided a taxonomy for specifying policies related to content distribution. With the use of the proposed policy based architecture, we show that dynamic content offload decisions are possible, and we analyze the impact of such decisions on the response time SLAs that can be provided to users of a content distribution network.

In ongoing work, we are exploring prototype implementations of the policy based architecture, and investigating schemes that would enable the offloading of dynamic content to edge caches in a real-world environment.

## REFERENCES

[1] R. Braden et al., “Resource ReSerVation Protocol (RSVP) Version 1 - Functional Specification”, IETF RFC 2205, September 1997.

[2] S. Blake et. al. “An Architecture for Differentiated Services”, IETF RFC 2475, Decemember 1998.

[3] Akamai Technologies Inc., "FreeFlow content distribution service," http://www.akamai.com.
[4] Digital Island Inc., "Footprint content distribution service," http://www.digitalisland.net/services/cd/footprint.shtml.
[5] B. Moore et. al., Policy Core Information Model -- Version 1 Specification, IETF RFC 3060, February 2001.
[6] J. Fritz Barnes and R. Pandey, "CacheL: Language Support for Customizable Caching Policies", *Proceedings of the 4th International Web Caching Seminar*, San Diego, CA. March 1999, http://workshop99.ircache.net/Papers/barnes-abstract.html.
[7] N. Damianou, N. Dulay, E. Lupu and M. Sloman, "The Ponder Policy Specification Language", *Workshop on Policies for Distributed Systems and Networks (Policy2001)*, HP Labs Bristol, 29-31 Jan 2001. URL http://www.doc.ic.ac.uk/~mss/Papers/Ponder-Policy01V5.pdf.
[8] P. Deshpande, K. Ramasamy, A. Shukla and J. Naughton, "Caching Multidimensional Queries Using Chunks", *Proceedings of ACM SIGMOD*, 1998. Volume: 27 , Number: 2, Pages: 259 - 270
[9] G. Banavar, T. Chandra, B. Mukherhee, J Nagarajarao, R Strom, and Dl Sturman, "Multicast Protocols for Content-Based Publish-Subscribe Systems", *Proceedings of International Conference on Distributed Computing Systems* (ICDCS'99), May 1999.
[10] J. Challenger, A. Iyengar, and P. Dantzig. "A Scalable System for Consistently Caching Dynamic Data". *Proceedings of IEEE INFOCOM* '99, March 1999.
[11] M. Fry and A. Ghosh, "Application Level Active Networking", *Fourth International Workshop on High performance Protocol Architectures* (HIPPARCH 98), June 98.
[12] IBM Corp., IBM WebSphere Edge Services Architecture, - Application Offload capability (Page 6). Available at URL http://www-4.ibm.com/software/webservers/edgeserver/doc/esarchitecture.pdf.
[13] A. Westerinen et. al., "Terminology for Policy based Management", IETF RFC 3198, November 2001.
[14] Common Information Model (CIM) Schema, version 2.x. DMTF, Available at http://www.dmtf.org/standards/standard_cim.php.

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