

TBONE: A Mobile-Backbone Protocol for Ad Hoc Wireless Networks

Izhak Rubin¹ Arash Behzad Runhe Zhang Huiyu Luo Eric Caballero

University of California, Los Angeles
Electrical Engineering Department
56-125B Engineering IV Building
Los Angeles, CA 90095-1594
310-825-2326
rubin@ee.ucla.edu

Abstract—We introduce an ad hoc wireless mobile network that employs a hierarchical networking architecture. The network uses high capacity and low capacity nodes. We present a topological synthesis algorithm that selects a subset of high capacity nodes to form a backbone network. The latter consists of interconnected backbone nodes that intercommunicate across high power links, and also makes use of (airborne, ground and underwater) Unmanned Vehicles (UVs). Each backbone node manages the allocation of communications resources for transport of messages from/to itself and among nodes that reside in its managed cluster of nodes (access net). Backbone nodes also interact to coordinate the allocation of MAC layer communications assets (such as time slots) in their access nets to prevent (cross net) interferences. When covered by a backbone node, a mobile node is granted a proper set of time slots (or, equivalently, FDMA and/or CDMA slots) for direct communications to a local destination, or for accessing the dynamically configured backbone network for long-range communications. When uncovered, a node uses a flat multi-hop ad hoc networking scheme. We introduce the TBONE protocol to implement the key networking schemes for such a Mobile Backbone Network (MBN). It includes combined network layer operation, i.e. mobile backbone network topological synthesis, and MAC layer resource allocation schemes. The TBONE protocol serves to allocate resources across the network to ensure that user applications are granted acceptable quality-of-service (QoS) performance, while striving to ensure a highly survivable and robust backbone-oriented networking architecture. We present elements of the protocol and key involved algorithms, and illustrate the distinctive advantages offered by the TBONE based mobile backbone network.

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I. INTRODUCTION

The key feature that sets ad hoc wireless networks apart from traditional cellular radio systems is their ability to operate without aid of any established infrastructure or centralized administration. Networking protocols developed for ad hoc networks are generally based on a flat, single level of hierarchy [9]. These algorithms expand the packet overhead to maintain routing and topology tables or to discover routes on demand. As the network size increases, such protocols can demand excessive overhead [8]. Hierarchical structures have been used to provide scalable solutions in many large networking systems. They are also attractive when considering the functional composition of many commercial and military organizations, and their needs for ad hoc wireless networking connections. For example, a military task force may consist of tank and infantry units. A tank node can be outfitted with more capable communications equipment, enabling it to employ a more powerful radio system and attain higher communications capacity and better storage and processing capabilities.

We have recently been investigating the operation of mobile wireless networks through the embedded establishment of a Mobile Backbone Network (MBN). In [1]-[4], we have presented objectives and methods for the design of MBN topological layouts. A mobile backbone network consists of a backbone network (Bnet; or a multiple number of Bnet components), access nets (Anets), and regular (flat) ad hoc network(s). Its structure is illustrated in Figure 1. Thick solid lines connecting large solid circles represent the Bnet. Dashed ovals consisting of thin solid lines connecting small solid circles represent the Anets. The small solid circles and the thin dashed lines connecting them to each other represent the regular ad hoc network. In this paper, we concentrate on protocols governing the operation of the MBN's Bnet and Anets. The MBN is designed so that it involves a sufficient but not excessive number of backbone nodes (minimality feature), while providing high coverage, so that high fraction of the low power nodes can access at least a single Backbone Node (BN) through a path of at most h hops. The MBN should also implement a survivable / robust topology, such as that realized by a k -connected backbone network.

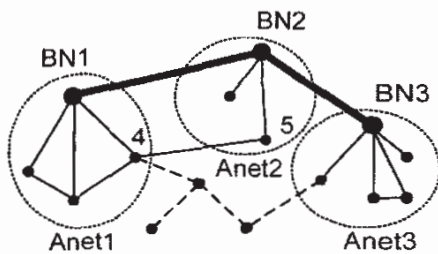


Fig. 1- The decomposition of a mobile backbone network into a Bnet, three Anets, and a regular ad hoc network with $h=1$ and $k=1$.

In this paper, we consider MBN in which some nodes are outfitted with higher capability mechanisms that make them more attractive as backbone capable nodes. A tank node (or high capacity unmanned vehicle) can thus be regarded as a candidate for selection as a BN. In turn, a small sensor node is highly power limited and is not expected to perform demanding processing and communications operations; it is thus effective for its communications flows to be managed by a backbone node. The Bnet is dynamically formed to consist of interconnected BNs. Low power nodes can communicate to each other either through a flat multi-hop ad hoc networking route, or through the Bnet. Under the latter approach, the nodes form a hierarchical communications networking mobile infrastructure, which is particularly attractive when demanding the provision of a communications route that guarantees a flow distinct quality of service (QoS) performance. The role of a backbone node can be served by a wide range of specially designated nodes that have advantageous capabilities involving attributes of: communications-access and geographical coverage (as is the case for orbiting, roving or guided airborne, ground or underwater unmanned vehicles); designated organizational or functional roles (headquarters or command posts), and higher communications and processing capacities.

In forming an MBN, a Bnet topology that consists of interconnected BNs is formed while a clustering process is performed. A cluster consists of low power nodes that are associated with a designated BN. The network consisting of a BN and its cluster members is identified as the BN's "Anet." A number of different methods for clustering nodes to provide network coverage have been investigated (see, for example, [12] Chapter 4 for a summary). The lowest-ID and highest-connectivity clustering algorithms are examples of such simple mechanisms; see [1]-[2] for overviews of other and graph theoretical based covering techniques. In comparing these methods in [10], the lowest-ID algorithm was noted (using simulation runs) to yield a more robust configuration. Note, however, that lowest-ID clustering algorithms may lead to radically distinct BN selections when performed on networks that have identical topological layouts, depending upon the procedure used to assign ID labels to the nodes. Another lowest-ID type covering algorithm is presented in [11].

In both [10] and [11], since different clusters utilize distinct CDMA spreading codes, inter-cluster traffic flows must be routed through gateway nodes. Under other channelization plans, as considered in this paper, Anets may use the same frequency bands and thus require MAC layer based coordination in performing the allocations of transmission time periods to avoid transmission interferences. For coordination, we introduce the following definitions. Two Anets require MAC layer coordination if it is possible for a transmission by a low power node located in one cluster to interfere with the transmission of a low power node that is associated with the other cluster. In this case, we identify these two clusters as (MAC Coordinating) MC-Anets. The corresponding BNs managing these Anets are identified as MC-BNs. For example, in Figure 1, Anet1 and Anet2 are MC-Anets, and BN1 and BN2 are MC-BNs.

Under the typically employed clustering schemes, the selection of clusterhead nodes provides for graph covering (so that each node is directly attached to a clusterhead node), while not necessarily providing for the formation of a connected network of clusterheads (a Bnet). To interconnect clusterheads, gateway nodes are elected. Yet both clusterheads and gateways are typically selected based on topological (or locational) features, and do not incorporate capacity, application layer desired quality of service (QoS) levels and MAC layer constraints, as required for proper design of an effective Bnet for our MBN based network system. We demonstrate in this paper that the inclusion of such objectives in the MBN synthesis procedure leads to radical improvements in the operational efficiency of the designed ad hoc network. Furthermore, we integrate the required connectivity feature of the Bnet into the iterative process of our topological synthesis algorithm.

In this paper, we present the elements of an algorithm employed for the joint mobile backbone network synthesis and MAC protocol management for MBNs. To ensure effective allocation of resources across both the MAC and network layers, we integrate the design and operation of the MBN topological layout algorithm with the organization and management of the MAC layer access protocol. Through this integration, we are able to achieve a higher level of spatial reuse, leading to significantly higher network transport capacity.

The BNs play a key role in allocating Anet resources. We have identified our underlying protocols, designed to jointly synthesize the backbone topology and the MAC structure, as **XBONE**. A wide range of MAC layer resource allocation techniques can be employed by the **XBONE** suite of protocols. For specific illustration, we assume in this paper that a DA/TDMA MAC (demand assigned / time division multiple access medium access control) mechanism is used, identifying this latter scheme as **TBONE**. In comparison, in [14], a fully distributed DA/TDMA resource allocation scheme, which provides for spatial reuse, is described. There, all involved mobile units have to be informed as to the current state of slot assignments in each time frame. When active, mobile nodes send requests for the use of available time slot

resources. In turn, under the TBONE protocol, a quasi-distributed architecture is used to provide for MAC layer time slot allocations. Each BN is responsible for managing the time slot allocations (or any other resource allocation) to the low power nodes that are associated to its Anet. To avoid interferences and attain high level of spatial reuse, the BN also has to coordinate these assignments with its neighboring MC-BNs. In the same manner, integrated allocation of time, frequency or CDMA slots can be invoked. Hence, our scheme permits the employment of a combination of demand assigned time division multiple access, demand assigned frequency division multiple access (DA/FDMA), and demand assigned code division multiple access (DA/CDMA) mechanisms.

BNs play a fundamental role in routing messages. We assume that message transmissions between two non-neighboring low power nodes must traverse through the Bnet. However, communications between two low power neighboring nodes proceed through direct transmissions. For example, in Figure 2 message transmissions between nodes 1 and 2, as well as between nodes 3 and 4 are carried out across their respective direct links. However, message transmissions between nodes 2 and 4 must first traverse through their respective backbone nodes BN5 and BN6. In this manner, a high spatial reuse factor is attained.

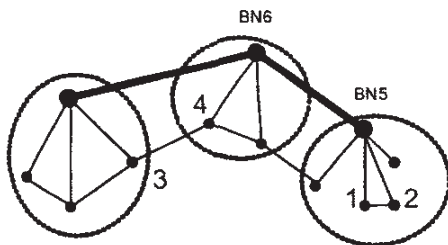


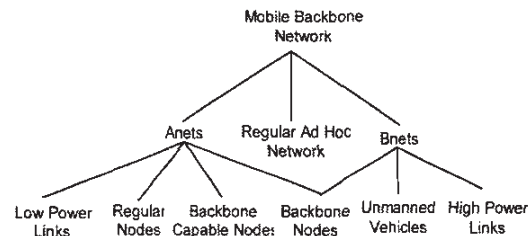
Fig 2 - A routing example in an MBN

To dynamically adapt the selected MBN to variations in network conditions, we identify the key changes to which our scheme must adapt. These changes include modifications that are topologically based (induced by initialization, mobility, activation or deactivation processes) and/or changes triggered by traffic flow fluctuations (due to variabilities in application oriented service requirements or induced by certain network failures). Such changes lead to violation of one (or more) of the scheme's targeted attributes causing our protocol to take action in adapting to the newly sensed scenario. We classify these events into distinct categories. We show how our algorithm reacts to the occurrence of each such key event.

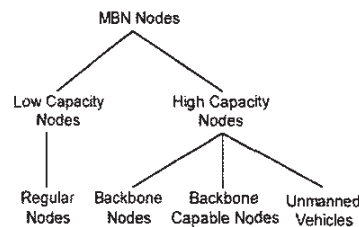
The remaining of this paper is structured as follows. The mobile backbone system is described in Section II. In Section III, we present the TBONE protocol. We evaluate and exhibit our algorithms by presenting several examples in Section IV. Conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION

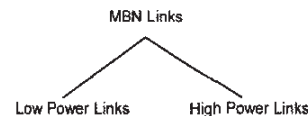
The classification of the elements of a mobile backbone network is illustrated in Figure 3. We identify three key classes of mobile nodes: high capacity nodes, low capacity nodes, and Unmanned Vehicles (UVs). High capacity nodes include Backbone Nodes (BNs) and Backbone Capable Nodes (BCNs). BNs have high storage and processing resources, and include low power and high power radio modules that allow them to transmit/receive data and control messages in two different frequency bands simultaneously: the low power radio module is used by a BN to communicate to nodes that are in low-power communications range while the high power radio module is employed by a BN to communicate to its peer-level BNs (across the Bnet, spanning longer distances and operating at higher data rates). BCNs also have high storage and processing resources and include low power and high power radio modules. These nodes, similar to BNs, are set to continuously and simultaneously listen for messages transmitted in their reception ranges across the two frequency bands. However, BCNs are restricted to using their high power radio module for only receiving/transmitting the control packets that are used to establish the connectivity of



a. The general decomposition of an MBN



b. The classification of nodes in an MBN



c. The Classification of Links in an MBN

Fig. 3- The classification of the elements of an MBN

the Bnet. A BCN has the capability to be converted into a BN, when selected to act as a BN by the TBONE protocol. Low capacity nodes act merely as Regular Nodes (RNs). RNs are limited in their power, storage, processing and communications assets and they employ just a single low power radio module. For brevity, we may refer to any BCN or RN as a Low Power Node. We may also include Unmanned Vehicles (UVs). The latter (e.g., satellites or terrestrial relays) can be employed as relays to provide high power links or to enable range extension of a high power link. They can functionally serve as BNs and BCNs.

In our graphical representation of the network topology, we depict both high and low power links. The network topological layout is characterized by the union of two adjacency matrices, corresponding to the "low power graph" and the "high power graph". However, for simplicity, we depict the high power links only between BNs. In Figure 4, large solid circles represent BNs and UVs. Small solid circles represent RNs and BCNs. Thick and thin solid lines denote high and low power links, respectively. While connected to low power nodes via low power links, backbone nodes communicate with each other through high power links. We construct an MBN structure through the following steps: 1. Election of BNs among the set of BCNs. 2. Establishment of high power links among the BNs. 3. Formation of clusters through the association of low power nodes with their selected BN; the low power nodes' selected BN is identified as their "associated BN"; the low power nodes that are associated with a BN are called its "associated low power nodes." 4. Formation of the Anet, consisting of the BN and its associated low power nodes, through the allocation of MAC-layer time-slots to the low power nodes for the transport their messages to/from their associated BN and directly to their low-power link neighbors. 5. Network and MAC layer configuration of the networking operation across the Bnet. (Further details of the latter step operation are not included in this paper.)

The covering feature of an effective mobile backbone is characterized by the "h-covering requirement". A node is said to be h-covered (and be a member of a span h cluster) if it is at a distance of at most h hops (over the low power graph) from at least one of the BNs. Other key desired qualities of a synthesized Bnet are k-connectivity, minimality, provision of QoS support guarantees, and robustness with respect to changes in topology. (A graph is k-connected if it requires the failure of at least k elements to become disconnected. For simplicity, we assume in the remaining of this paper the targeted objectives for the synthesized MBN to be characterized by the values $k = 1$ and $h = 1$.)

Although directional antennas [5] or adaptive antennas [6] can improve the ad hoc network capacity, we assume the mobile nodes in our system to be equipped with omnidirectional antennas [7], as this is the most common configuration of current interest. We use different frequencies for transmissions across high and low power links, so that no interferences take place between transmissions carried out across the Bnet and the Anets. We also assume in this paper

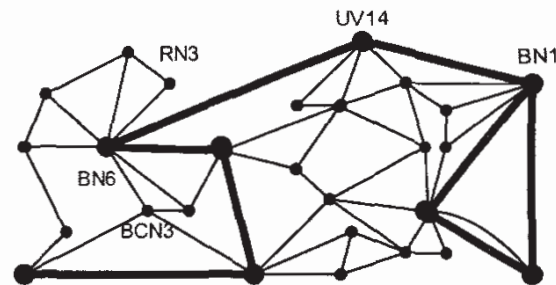


Fig.4 - An ad hoc network with different classes of nodes

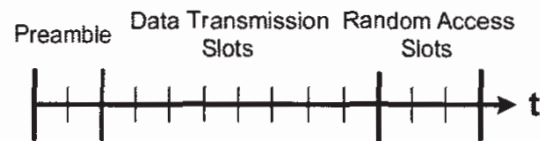


Fig 5-The Time frame structure

that the radio (high and low) power levels have been pre-selected and set.

A component of a graph is a subgraph that is maximal with respect to the property of being connected. For every BN, we define an "iso-component" BN as a BN that belongs to the same component. A BN is defined as "isolated" if it cannot hear any other BNs through its high power radio module. A "local registration list" managed by a BN contains the IDs of all of its associated low power nodes. A node's "low power link neighboring list" is a classified list of the nodes (BCNs, RNs, BNs, and UVs) that are in the low power communications range of this node. A "high power link neighboring list" identifies the BNs, BCNs, and UVs that can be heard by the high-power radio of a node. We assume that every BCN periodically transmits a control packet using its high power radio module to its high power link neighbors. This allows its high power link neighbors to update their high power link neighboring lists.

The operation of the MAC layer is dependent on the layout of the mobile backbone network established by the topology synthesis protocol. BNs serve as controllers for their associated low power nodes to allocate resources and provide control information. The set of associated low power nodes of every BN is a subset of its low power link neighbors, which forms the BN's Anet. To coordinate the allocation of MAC layer time slots by BNs to their associated low power nodes, we note the following space-time resource allocation process.

Each BN establishes a time frame, identified as the Anet time frame, for regulating nodal transmissions across its Anet (Figure 5). In this manner, the BN manages the assignment of time slots to its associated low power nodes. The BN assigns initially to each low power node in its Anet a certain preliminary number of slots to be used by the low power node for sending messages across the Anet (to the BN or to other associated low power nodes). Based on desired flow rates, a

number of nodes can be directed to share designated slots. The BN also allocates slots for use for its own transmissions. A certain number of slots are allocated for random access (RA) transmissions; the collection of these slots is identified as an RA period. In addition, the BN transmits periodically frame-structure and frame-synchronization messages. Each message transmitted by any node also includes synchronization preambles and other control information. The rest of the slots in the Anet frame are kept by the BN and allocated to its associated Anet members, based on its receipt of reservation requests, or based on its own on-going evaluations of capacity needs.

Each low power node dynamically informs its associated BN as to its communications capacity requirements. For each application flow, the low power node identifies the underlying service class desired, traffic descriptor, and QoS performance required. The BN then calculates the level of capacity required by the low power node across its Anet and accordingly allocates time slots across this net, if available. To allow for statistical multiplexing of flows across slots allocated to a low power node, the latter (or the BN) calculates an aggregate capacity level that may be allocated to the low power node for shared use by all of its traffic flows. In addition, the BN also calculates the aggregate capacity requirements it has, for each service class and QoS category, for message transport across the Bnet. QoS based resource allocations are carried out across the Bnet among all the network's BNs. The nodes employ then proper scheduling schemes (such as priority oriented, Weighted Fair Queuing, or Generalized Processor Sharing type) to ensure that QoS guarantees are satisfied. Note that the availability of capacity, at the desired QoS level, must also be determined based on capacity resources that are available for message transport across the destination Anet in transporting messages from the destination BN to its associated destination low power nodes.

Consequently, the BN's decision related to time slot allocation across its Anet depends on the level of resources available on its source Anet, the Bnet and the destination Anet. In addition, we note that nodes may be able to directly (without traversing the Bnet) receive transmissions initiated by nodes that are members of their own Anet as well as those that are members of other Anets (which, in this case are identified as MC-Anets). If MC-Anets re-use the same communications resources (as is the case when transmissions in the Anets are carried out across the same frequency bands, with no CDMA differentiation, as we assume here), it is necessary for BNs that manage Anets to properly coordinate the allocation of their slots to minimize interferences and achieve high spatial reuse.

When its resource allocation process is complete, the BN sends its assignments to the involved low power nodes and to the BNs that control the MC-Anets impacted by this allocation and residing in the same component to which the underlying BN belongs. For every BN, we identify the latter BNs as "iso-component MC-BNs." On the Bnet, backbone nodes relay and transmit data packets, while exchanging control information. As the number of nodes in the Bnet is far

fewer than those of the whole network, the MAC and routing protocols for the MBN are simpler to implement. To reduce processing requirements, we have been considering the implementation of MPLS (or MPLS+, see [13]) routing schemes across the Bnet. These routing methods are not discussed further in this paper.

Note that each BN manages its MAC layer DA/TDMA based slot allocation process across the time frame process (consisting of periodically recurring time frame cycles) that it establishes. Associated low power nodes synchronize to the frame process of their associated BN by periodically listening to its synchronization preamble transmissions. MC-BNs need to mutually synchronize their time frame processes only for the purpose of coordinating the allocation of time periods in their corresponding MC-Anets, to avoid transmission interferences. For this purpose, a synchronization hierarchy is formed so that the involved BNs can synchronize to each other's time frame processes.

Many nodes, as assumed here, operating over a wireless metropolitan network, employ half-duplex radios. Thus, the node's radio is able to transmit and receive, but not simultaneously in time. Collision of messages is said to occur at a nodal receiver when it receives multiple message transmissions during overlapping time periods. Collisions of messages at a nodal receiver when the messages are destined to this node are classified as destructive collisions, resulting in message information losses. We categorize a collision as an "allowed collision", if and only if the location of collision is the receiver of a node that is neither a source of any one of the message transmissions nor an intended destination of any of the message transmissions. For example, in Figure 6 let node b transmit a message to node a, and node d transmit a message to node e. Assume that both transmissions are received at node c. The collision occurring at node c is an "allowed collision", since it is not an intended destination of any transmission at the underlying time slot. We identify all other collisions as "non-allowed collisions", regarding them as destructive collisions.

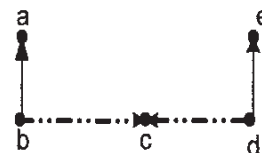


Fig 6- Example of an allowed collision at node c

As noted earlier, we require message transmissions from a source node to any non-neighboring destination node to initially pass through the associated BN of the source. The association of a node with the proper BN is thus critical in ensuring that the node's applications are granted acceptable QoS performance levels. To aid in this selection, each high capacity node keeps a dynamically updated "metric list". This list expresses the current capability of the node. Metric list

functional values convey capacity and residual capacity information about nodal mobility (velocity), processing speed, backbone and Anet transport capacity levels, queue sizes, packet delays and other congestion markers. To aid processing by lower capacity nodes, the metric list is also mapped into a single (or limited) dimensionality parameter called the nodal "dynamic weighted label."

Depending on the proliferation and locations of high power and relay nodes, and on available communications capacity (and application mixtures), there may be RNs that are not associated (or not admitted into the MBN system). These nodes are neither part of a Bnet nor are admitted into an Anet. Such nodes employ a designated regular (flat, non MBN based) multi-hop ad hoc networking protocol to communicate in their unassociated areas. This designated protocol is also used as a fall-back transport mechanism in those parts of the network that the Bnet is non-operational, or in which no access to the backbone is temporarily available.

III. THE TBONE PROTOCOL

The purpose of the TBONE protocol is to provide a mechanism to maintain connectivity, minimality, QoS performance targets, covering requirement, and attain efficient utilization of MAC-layer resources, in the presence of mobility and traffic process fluctuations. By developing a protocol that considers MAC-layer resource allocations objectives, we are able to synthesize a combined Bnet and Anet topology that is able to effectively support real time traffic while maintaining the ease-of-deployment and robustness features native to ad hoc networks.

Changes that are induced by nodal mobility, node activation/deactivation, link establishment/failure, and traffic flow process fluctuations are referred to as events. We define a key event as an event that indicates or leads to violation of at least one of the requirements that our protocol supports, focusing here on connectivity, minimality, efficiency, application adaptability, and covering requirements.

The TBONE protocol consists of four algorithms triggered by eight classes of key events. The algorithms are: the Anet association algorithm, the BN election algorithm, the BN-BCN conversion algorithm, and the time slot allocation algorithm. Control messages are distributed among nodes for allowing nodes to distribute status messages, for BNs to allocate network and MAC layer communications resources, for distributing routing table related messages, and for re-configuring the network topology. At every node, we update and transmit nodal status packets that are classified in accordance with the identity of their origin, the involved transmission operating power mode, and the identity of the destination nodes. (Every packet includes a synchronization preamble header.) For a list of control messages see Appendix B.

In this section, first each of the aforementioned algorithms, along with their applications, is described. Then, we

introduce eight classes of key events and the corresponding TBONE protocol reaction(s) to their occurrences. Reactions triggered by these events include modifications to Bnet topology, to underlying Anet associations, and/or to MAC allocation of resources.

A. ALGORITHMS

The TBONE protocol consists of four algorithms: the Anet association algorithm, the BN election algorithm, the BN-BCN conversion algorithm, and the time slot allocation algorithm. In the following, we describe each of these algorithms.

A.1. THE Anet ASSOCIATION ALGORITHM

This algorithm provides a mechanism that associates an unassociated low power node with exactly one BN in a manner that considers both the QoS requirements of the unassociated low power node as well as the efficient allocation of MAC-layer resources. The Anet association algorithm pre-selection of a high capacity node by an unassociated RN (A.1.1) or by an unassociated BCN (A.1.2), is followed by admission of the unassociated low power node by a BN to its Anet (A.1.3). Every unassociated low power node instigates the Anet association algorithm by sending a "join request" message to a BN or associated BCN. The join request message consists of the unassociated low power node's ID, the destination of the join request (intended BN or BCN), the low power node's known low and high power link neighboring list, and the low power node's traffic/QoS list (that consists of the requested service class, traffic descriptor and specified QoS level, for each application). An optional parameter that may be included in the join request is the number of slots per time frame that the unassociated low power node requires to support its current application(s). If the low power node has sufficient processing capability, it will calculate such required time slot value as a function of its traffic/QoS list and include it in the join request. Note that if as a result of the admission process (A.1.3) a BCN is selected to admit an unassociated node, the BCN first converts itself into a BN for the sake of creating a new Anet to support the unassociated node.

A.1.1) Pre-selection by an unassociated RN: An unassociated RN needs only to come within a transmission range of at least one BN or associated BCN before it can begin the Anet association algorithm, hopefully resulting in association with a BN. When an unassociated RN hears multiple BNs and/or associated BCNs, it may determine that an associated BCN is a better alternative than any of its low power link BN neighbors, to be selected as an associated BN. If an unassociated RN receives information from at least a single node that is identified as a BN or associated BCN, it will react as follows:

1.) If the unassociated RN has sufficient processing capability, it selects one of the BNs or associated BCNs that it can hear according to their advertised dynamic weighted labels, and waits for a predefined period of time. Otherwise,

it randomly selects one of the high capacity nodes that it hears, and executes step 3.

2.) While waiting, if the unassociated RN receives a nodal status packet from another BN or associated BCN with a dynamic weighted label that is at least D units greater than the dynamic weighted label of the currently selected high capacity node, it will select the latter new node as a substitute for the previously selected high capacity node. The values of the threshold (D) and the waiting period are determined to provide algorithmic robustness, while ensuring sufficiently short reaction times.

3.) The unassociated RN synchronizes to the frame process of the selected high capacity node. It then transmits a join request to the selected high capacity node during the first available random access period embedded in the advertised time frame structure of the selected node.

4.) If the join request is sent to an associated BCN, the BCN will relay it to its associated BN.

5.) Upon receiving the join request directly from an unassociated RN or indirectly through an associated BCN, the BN proceeds with the admission process (A.1.3).

A.1.2) Pre-Selection by an Unassociated BCN: If an unassociated BCN can hear at least one BN using its low power radio module, it reacts in a manner that is similar to that followed by an unassociated RN (A.1.1) with the following distinctions:

- For simplicity, an unassociated BCN does not transmit a join request to any associated BCN.

- All unassociated BCNs have the processing capability to select a low power link BN neighbor based on comparing the advertised dynamic weighted labels. Also, all unassociated BCNs have sufficient processing capability to calculate the number of slots per time frame that they require to support their current traffic application(s).

A.1.3) Admission Process: In this part of the Anet association algorithm, two cases are considered: the BN receives a join request either directly or indirectly (in the latter case, the BN receives the join request through an associated BCN). If the BN receives the join request directly from the unassociated low power node, it determines whether it should admit the unassociated node into its Anet. For this purpose, the BN initializes the time slot allocation algorithm (Algorithm A.4), which provides a mechanism for examining the sufficiency of its capacity to support the required QoS. In the second case, it considers itself (as for the direct reception case) as a candidate BN but it also examines other high capacity nodes. If the unassociated low power node is a BCN, a preadmission procedure must be followed prior to the initialization of the admission process (see step 1 below).

1.) Preadmission: If the unassociated low power node is a BCN, before initiating the admission process, the intended BN checks whether the Bnet is connected. For this purpose,

when the intended BN receives the join request, it compares the high-power link neighboring list of the unassociated BCN to the set of its iso-component BNs and their local registration lists. If there is at least one BN (BCN) in the high-power link neighboring list of the unassociated BCN that is not in the list of its own iso-component BNs (the local registration lists of the iso-component BNs), the BN uses the opportunity to connect the underlying Bnet components by sending a convert command to the unassociated BCN. Upon receiving the convert command, the BCN converts into a BN and the algorithm stops.

2.) If the BN receives the join request directly from the unassociated low power node, the BN initiates the time slot allocation algorithm (Algorithm A.4). This will confirm whether there is sufficient capacity through the Anet of the BN, the Bnet, and the Anet of the destination node. If as a result of the time slot allocation algorithm, the BN is able to allocate time slots to the unassociated low power node, it transmits an admission message to the unassociated low power node. Once an unassociated low power node receives the admission message (assuming it to be received prior to a specified expiration period), it converts into an associated low power node and executes step 7.

3.) If the BN receives a join request indirectly through an associated BCN or determines that it does not have enough available time slots for a directly received join request, it attempts to select an appropriate iso-component MC-BN or associated BCN in its Anet that has been mentioned in the unassociated low power node's low power link neighboring list. Note that in parts A.1.1 and A.1.2 an unassociated low power node selects a high capacity node among such candidate nodes by comparing their dynamic weighted labels. However, in the present part, the BN performs the comparison based on high capacity nodes' metric lists, which results in a more comprehensive and detailed selection. This is due to the fact that BNs locally store all the required metric lists that they are able to process at sufficiently high speed.

4.) If as a result of step 3, a BN is selected to admit the unassociated low power node, it allocates the calculated number of access time slot(s) to the newly associated low power node based on the requested QoS and the current capacity available across its source Anet, transit Bnet and destination Anet. Then, it sends the newly associated low power node an admission message. Once the newly associated low power node receives (prior to the expiration period) the admission message, it converts into an associated low power node and executes step 7.

5.) If as a result of step 3, a BCN is selected to admit the unassociated low power node after receiving a convert command from its associated BN, it converts into a BN. Then, it allocates the calculated number of access time slot(s) to the newly associated low power node based on the requested QoS and the current capacity available across its source Anet, transit Bnet and destination Anet. It then sends the newly associated low power node an admission message. Once the newly associated low power node receives (prior to the

expiration period) the admission message, it converts into an associated low power node and executes step 7.

6.) If the unassociated low power node hears no response prior to the expiration period, it will select another low power link BN/BCN neighbor and return to A.1.1 or A.1.2.

7.) After the newly associated low power node receives an admission message, it transmits its association to all its low power link neighbors. Its low power link neighbors will disregard its previous association (if any).

Note: If as a result of step 1, the intended BN indeed sends a convert command to the unassociated BCN, we prove (see appendix A for the proof) that this decision would be independent of which low power link BN neighbor is selected as the intended BN. This proves that our quasi-distributed algorithm consistently supports connectivity across the Bnet topology.

A.2. THE BN ELECTION ALGORITHM

The purpose of this algorithm is to elect eligible BCNs and convert them into BNs in order to satisfy the covering requirement. The dynamic weighted labels of BCNs determine their eligibility. If an unassociated BCN utilizing its low power radio module cannot hear any BN for a predefined period of time, but hears from at least one unassociated BCN, it initiates the BN election algorithm. Rather than employing the commonly used procedure that makes selections according to nodal IDs, we synthesize a distinctly efficient backbone network by selecting BNs based on their (systematically-built) advertised dynamic weighted labels. The BN election algorithm proceeds as follows:

1. The unassociated BCN that initiates the BN election algorithm broadcasts its ID and dynamic weighted label request to all low power link unassociated BCN neighbors. Every unassociated BCN that receives this packet transmits its own ID and dynamic weighted label to the originating BCN.
2. The originating BCN waits for a certain period of time to gather relevant data. Then, it compares the dynamic weighted labels advertised by its low power link unassociated BCN neighbors with its own dynamic weighted label.
3. If its dynamic weighted label is the highest, it will convert itself into a BN. Otherwise, it waits for a predefined period of time.
4. If during the waiting period, the unassociated BCN utilizing its low power module hears at least one BN, it initiates the Anet association algorithm (A.1.2).
5. If during the waiting period, the unassociated BCN, utilizing its low power radio module, cannot hear any BN while hearing at least one other unassociated BCN, it returns to step 1.

A.3. THE BN-BCN CONVERSION ALGORITHM

The purpose of the BN-BCN conversion algorithm is to provide a mechanism to determine redundant BNs and convert them into BCNs in order to support minimality. Every BN periodically compares its local registration list to the local registration list of its iso-component MC-BNs. If a BN determines that (1) each of the nodes in its Anet has at least one low power link BN neighbor and (2) all its high power link BN neighbors would remain in the same component if it converts into a BCN, it will perform the following:

- 1.) If the BN, as a result of coordination with its iso-component MC-BNs, realizes that there is a more appropriate BN that may be converted into a BCN, it terminates the algorithm. Otherwise, it proceeds to step two.
- 2.) By examining the metric list of all its iso-component MC-BNs, the BN selects a subset of BNs that are able to admit itself and all its associated low power nodes. If it can select such a subset of iso-component MC-BNs, it proceeds to the next step. Otherwise, it terminates this algorithm.
- 3.) The BN transmits a join request on behalf of each of the nodes in its Anet to exactly one of the selected iso-component MC-BNs.
- 4.) Each of the selected BNs that receive a join request will initiate the time slot allocation algorithm. As a result, it allocates the calculated access time slot(s) to each new associated node and sends it an admission message.
- 5.) After the completion of the admission procedure for all the associated low power nodes, and after receiving an admission message for itself, the BN converts into a BCN.

Note that a conversion of a BCN into a BN is triggered to provide connectivity and covering support and/or to supplement insufficient capacity resources. These causes are considered prior to any BN to BCN conversion. Hence, the BN-BCN conversion algorithm does not lead to BN to/from BCN oscillations.

A.4 THE TIME SLOT ALLOCATION ALGORITHM

The purpose of this algorithm is to provide a mechanism for allocation of time slots by BNs among their associated low power nodes, based on received reservation requests and on available capacity resources. Also, it is used as a subroutine for the Anet association algorithm to determine whether a new node should be admitted or not. The general steps involved are described as follows:

- 1.) A BN receives a new slot request or a join request.
- 2.) If an associated low power node (such as a power-limited sensor) does not have a sufficient level of processing capability, the BN itself has to calculate the required number of time slots as a function of the requested service class, the provided traffic descriptor and the specified QoS performance

level. The low power node includes these parameters in its traffic/QoS list.

3.) The BN examines the current slot allocation list for its Anet. It also uses information it has received concerning the availability of capacity for outbound flows across the destination Anet. In addition, it employs the information it has concerning the availability of communications resources across the Bnet. It also checks with its neighboring MC-BNs for the possibility of coordinating the allocation of slots to the requesting node to prevent interferences. Based on these availability checks, it determines whether the underlying request can be admitted, or must be denied (blocked).

4.) If the BN has sufficient available time slots to satisfy the request, it assigns time slots to the node and notifies its iso-component MC-BNs about its allocations. Otherwise, no action is required.

B. KEY EVENT CLASSES

To dynamically adapt the selected MBN to variations in network conditions, we identify the key changes to which our scheme must react. These changes include modifications that are topologically based (induced by initialization, mobility, activation or deactivation processes) and/or changes triggered by traffic flow fluctuations (due to variabilities in application oriented service requirements or induced by certain network failures). Such changes lead to violation of one (or more) of the scheme's targeted attributes, causing our protocol to take action in adapting to the newly sensed scenario. We define these events as key events. In the following, we classify the set of key events into eight classes and describe their involved identification, triggered algorithm reaction, and induced implication.

Key event class 1 (connectivity)- Every associated BCN periodically transmits its high-power link neighboring list to its associated BN. As soon as a BN receives this list from one of its associated BCNs, it compares it with the list of its iso-component BNs and their local registration lists. If there is at least one BN (BCN) in the received list that is not included in the list of its iso-component BNs, the BN concludes that the Bnet is not connected. Consequently, it sends a convert command to this BCN. As a BCN receives a convert command, it converts itself into a BN. The occurrence of any key event in this class is a sufficient condition for existence of a disconnected Bnet.

Key event class 2 (minimality)- Every BN periodically compares its local registration list to the local registration list of its iso-component BNs. If a BN determines that (1) each of the nodes in its Anet has at least one low power link BN neighbor and (2) all its high power link BN neighbors would remain in the same component if it converts itself into a BCN, it initiates the BN-BCN conversion algorithm. The occurrence of any key event in this class is a necessary condition for existence of a redundant BN.

Key event class 3 (efficiency)- If, as a result of changes taking place in network topology and/or the traffic/application scenario, an associated low power node with a sufficient processing capability is in the scope of a BN with dynamic weighted label that is at least D units greater than the dynamic weighted label of its current associated BN, it "considers" itself as an unassociated low power node and initiates the Anet association algorithm. The occurrence of any key event in this class is an indication that an associated low power node might be able to associate with a more appropriate BN.

Key event class 4 (RN covering)- If an unassociated RN hears at least a single node that is identified as a BN or an associated BCN, it initiates the Anet association algorithm. The occurrence of any key event in this class indicates that an unassociated RN may associate with a BN.

Key event class 5 (BCN covering)- If an unassociated BCN hears at least a single node that is identified as a BN, it initiates the Anet association algorithm. The occurrence of any key event in this class indicates that an unassociated BCN may associate with a BN.

Key event class 6 (BCN covering)- If an unassociated BCN utilizing its low power radio module cannot hear any BN for a predefined period of time, but receives information from at least one unassociated BCN, it initiates the BN election algorithm. The occurrence of any key event in this class indicates that by selecting a BCN among a certain set of nodes and converting it into a BN, a necessary condition for associating an unassociated BCN to a BN is provided.

Key event class 7 (BCN covering)- If an unassociated BCN only hears RNs and/or associated BCNs or it cannot hear any node for a predefined period of time, it initiates the BN election algorithm. Note that this is a "degenerate" BN election algorithm, since there is only one unassociated BN under consideration. Clearly, as a result of this algorithm, the

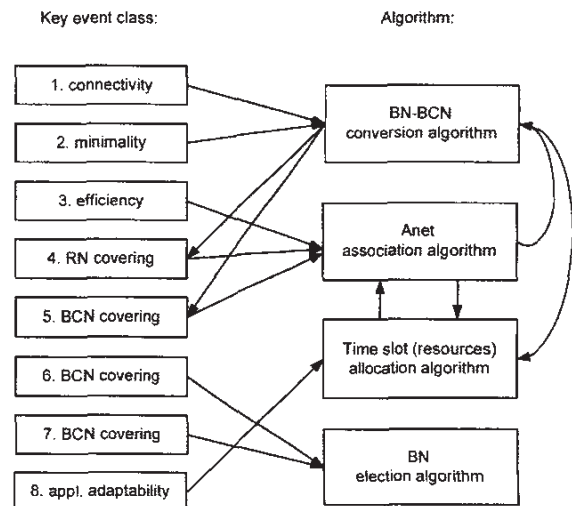


Fig. 7 - The TBONE protocol diagram

unassociated BCN converts into a BN. The occurrence of any key event in this class indicates that the most appropriate way of covering an unassociated BCN is to convert it into a BN.

Key event class 8 (application adaptability)- If a new application is generated, or fluctuations in the current mixture of applications takes place, an associated low power node sends out to its associated BN its traffic/QoS list, and possibly its calculated number of required number of slots per time frame.

The relationships between the key events and the protocol algorithms are depicted in Fig. 7.

IV. ILLUSTRATIVE EXAMPLES

In this section, we present four illustrative examples. In Example 1, we demonstrate the reaction of the TBONE protocol to various changes in topology. In Example 2, we illustrate the performance advantages of our algorithm in incorporating capacity and performance factors in the construction of Anet clusters. In Examples 3 & 4, the effect of our algorithm on spatial reuse is shown. In subsequent figures, large and small solid circles represent BNs and low power node, respectively. Also, thick and thin solid lines denote high and low power links, respectively.

A. Example 1:

In this example, the reaction of the TBONE protocol to changes in topology is illustrated. Figure 8 shows the original topology of the network. Some changes in the network are demonstrated in Figure 9. Note that RN1 and RN8 have moved out of the transmission range of BN2 and BN5, respectively, and the high power link between BN2 and BN3 has failed. Two new nodes, BCN 7 and BCN 6, show up in the network.

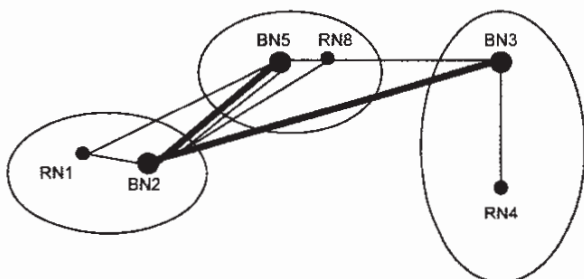


Fig. 8 - A network with 6 nodes before topology changes

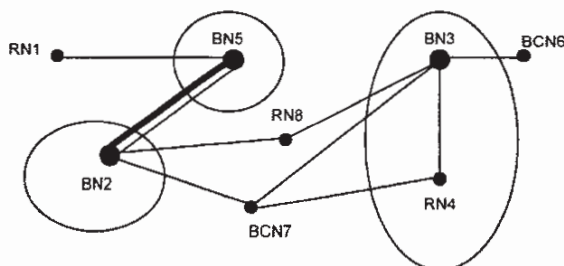


Fig.9 - The network after some topology changes

The protocol associates the unassociated low power nodes with Anets (Figure 9): RN1 hears BN5 and initiates the Anet association algorithm, based on key event class 4. RN8 hears both BN2 and BN3 and it also initiates the Anet association algorithm based on key event class 4. BCN6 and BCN7 hear at least one BN and based on key event class 5, they initiate the Anet association algorithm. RN1, RN8, BCN6, and BCN7 are now associated with their corresponding Anets (Figure 10).

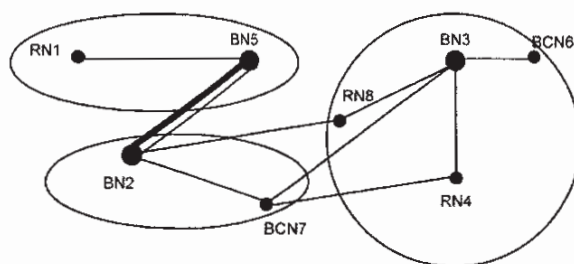


Fig. 10- The reaction of the algorithm due to key event classes 4 and 5

Based on the topology of Figure 10, the protocol reacts to support the Bnet connectivity: As BN2 receives the BCN7's high power link neighboring list (consisting of only BN3), it compares that with the list of its iso-component BNs and their local registration lists (consisting of BN2, BN5, BCN7, and RN1). Since BN3 is not a member of the latter lists, BN2 will conclude that the Bnet is disconnected and based on the key event class 1, it sends a convert command to BCN7. Then, BCN7 converts into BN7 and establishes the high power link to BN2, BN3 and BN5 (Figure 11).

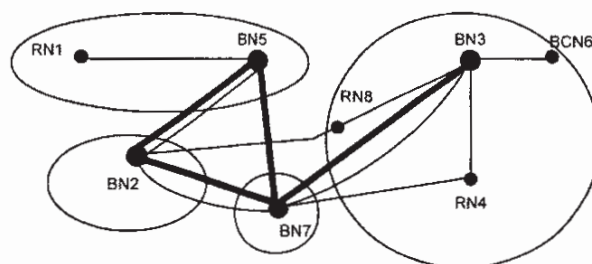


Fig. 11 - The reaction of the algorithm due to key event class 1

To maintain minimality in the topology of Figure 11, BN2 shuts off its high power link: Since the only node in BN2's Anet (BN2) is connected by low power links to BN5 and BN7, and conversion of BN2 into BCN2 does not have any effect on the connectivity of the Bnet, BN2 will convert into BCN2 (based on key event class 2). At the same time, due to new traffic generation, RN4 needs more capacity, which BN3 is unable to provide it. According to the dynamic weighted label of BN7 and based on key event class 3, RN4 initiates the Anet association algorithm. As a result, RN4 joins BN7 (Figure 12).

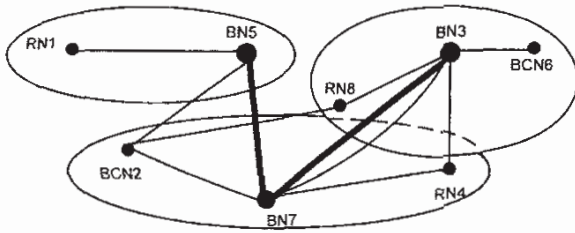


Fig. 12 - The final topology presented by the algorithm, based on the key event classes 2 and 3

B. Example 2:

In this example, the effects of different clustering algorithms on the efficient utilization of MAC layer resources are explored. Figure 13 presents node 6 as a new unassociated low power node that requires two slots per time frame, and can hear both BN1 and BN2. We next note that though BN1 does not have available time slots for node 6 (Figure 13), if we have employed the lowest ID algorithm, or the highest connectivity algorithm, either one will never-the-less assign node 6 to BN1 (Figure 14). In contrast, our algorithm, by using the distributed dynamic weighted labels, dedicates special attention to the current state of the MAC layer. Assuming node 6 to be an RN, according to the reactions prescribed by the occurrence of key event class 4, it initiates the Anet association algorithm. Subsequently, it initiates the

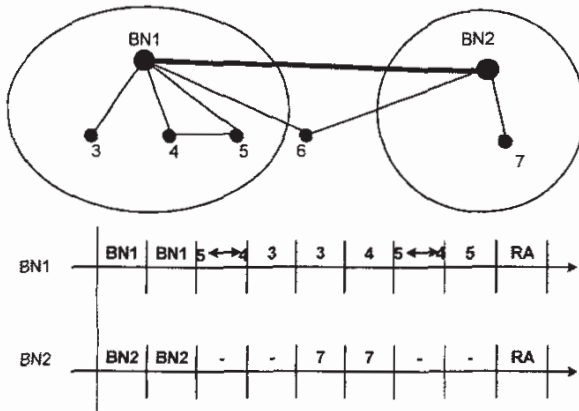


Fig. 13 - Time frame for cluster 1 and cluster 2 before appearance of node 6.

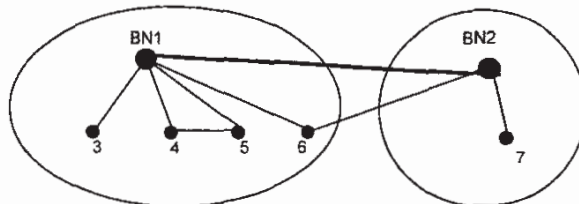


Fig. 14 - A clustering according to the lowest ID and highest connectivity algorithms.

time slot allocation algorithm. As a result, BN2 admits node 6 as its associated low power node and assigns it two slots per frame (Figure 15). Note that any transmission from node 6 in any of its allocated slots will result in an "allowed" collision (occurring at BN1).

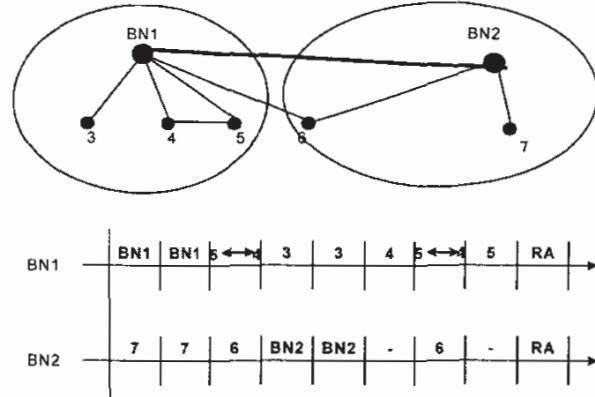


Fig. 15 - Clustering according to the topology synthesis algorithm and the associate time slot allocation.

C. Example 3:

In this example, the effect of our algorithm on spatial reuse, while a BN is transmitting to its associated low power node is illustrated. If the associations in Figure 16 are in place, whereby two Anets are displayed, messages arriving and destined to node 4 must go through BN2 (We assume the source node to not be a low power link neighbor of node 4.) While relaying such transmissions from BN2 to node 4, no other transmissions in either of these two Anets can take place. In our algorithm, invoking key event class 4 (and 5), triggering the Anet association algorithm and the time slot allocation algorithm, BN1 would then admit node 4 to its Anet. This would bring about the associations in Figure 17,

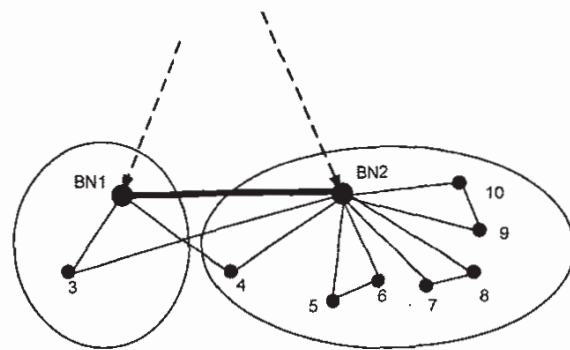


Fig. 16 - Node 4 associates to access net 2

whereby all transmissions from a third Anet to node 4 must now go through BN1 (provided the source node and node 4 are not low power link neighbors). This selection also leads to a distinctive spatial reuse gain. While transmissions from

BN1 to node 4 take place, nodes 5 - 10 can (simultaneously in time) send their messages to any other node in their Anet.

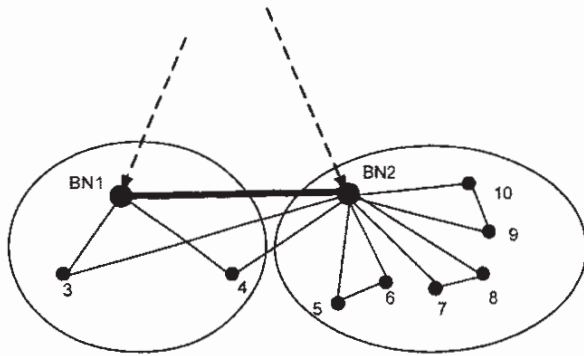


Fig. 17- Node 4 associates to access net 1.

D. Example 4:

In this example, the effect of the TBONE protocol on spatial reuse, while a low power node is transmitting to its associated BN, is illustrated.

In Figure 18, all transmissions from node 9 to a node in a third Anet, which is not a low-power link neighbor of node 9, must pass through BN2. All other transmissions in these two Anets that occur simultaneously with a transmission initiated by node 9 would result in a non-allowed collision. In our algorithm, triggered by key event class 4 (or 5), the Anet association algorithm and the time slot allocation algorithm are invoked. BN1 then admits node 9 into its Anet. This presents the configuration shown in Figure 19 whereby all transmissions from node 9 to a node residing in a third Anet are relayed through BN1. Now, simultaneously with the latter transmission, nodes 4 and 6 as well as nodes 10 and 11 are allowed to transmit to each other. Note that these transmissions result in allowed collisions at BN2. This example illustrates that by selecting the proper association, one can increase the system's throughput rate.

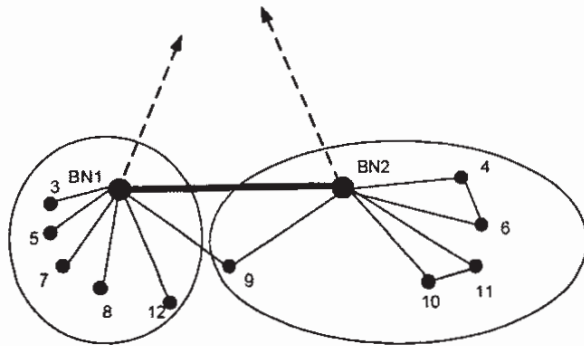


Fig. 18 - Node 9 associates to access net 2.

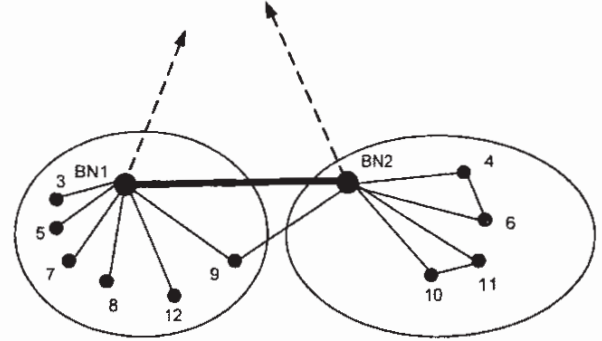


Fig. 19 - Node 9 associates to access net 1.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed a mobile backbone based algorithm for wireless ad hoc networking, which supports h-covering, k-connectivity, minimality and QoS objectives for the transport of multimedia traffic. We have decomposed the set of all changes in topology and/or traffic processes into eight classes of key events and defined the reaction of our protocol (and its related algorithms) to each of these events. By carefully integrating the allocation of MAC layer resources and the synthesis of the Bnet, our protocol provides a scalable and spatial-reuse based solution for wireless ad hoc networks that employ multiple node types (including UVs). We have illustrated our protocol to implement a clustering scheme that is able to dynamically incorporate current system capacity availabilities and congestion occurrences.

As part of our on-going investigations, additional capabilities are being introduced into the system. For example, we also manage and control the power of the BN radios, adjusting the range of each of these radios. Also, we have been studying extensions to the protocol presented here to accommodate longer access (multi-hop) scope in the Anets, as well as utilizing directional antennas in the Bnet.

APPENDIX A

Theorem: The conversion of an unassociated BCN to a BN status during the Anet association algorithm is independent of the intended BN that the BCN selects.

Proof. Let $SI(BN_i)$ represents the set of iso-component BNs of BN_i and their associated low power nodes. Moreover, let $SN(BCN_j)$ be the set of high power link neighbors of unassociated BCN_j . Consider the case under which an unassociated BCN, say BCN_k , sends a join request to a low power link BN neighbor (BN_r). Assume, as a result of the Anet association algorithm, BCN_k converts into a BN. Clearly, this happens if and only if

$$SN(BCN_k) \not\subset SI(BN_r). \quad (1)$$

Now, we prove that for any other low power link BN neighbor of BCN_k such as BN_p , we have

$$SN(BCN_k) \not\subset SI(BN_p).^2$$

If BN_p and BN_r are in the same component, the proof is trivial. Let BN_p belong to a different component. Then,

$$SI(BN_p) \cap SI(BN_r) = \emptyset \quad (2)$$

and

$$BN_r \subset SI(BN_r). \quad (3)$$

Now, assume

$$SN(BCN_k) \subset SI(BN_p). \quad (4)$$

Since,

$$BN_r \subset [SN(BCN_k) \cap SI(BN_r)], \quad (5)$$

then, by (4) we have,

$$BN_r \subset SI(BN_p). \quad (6)$$

But, conditions (3) and (6) contradict relation (2).

Therefore,

$$SN(BCN_k) \not\subset SI(BN_p), \quad (7)$$

and the proof is complete. ■

APPENDIX B

In the following, we describe the key control messages employed in the TBONE protocol.

Nodal status packet 1: Every BN and unassociated BCN periodically broadcast this nodal status packet by using the low power radio module. Also, every BCN periodically broadcasts this nodal status packet by its high power radio module. This packet contains the node's ID, dynamic weighted label, associated BN (if any), and frame structure field.

Nodal status packet 2: Every non-isolated BN periodically broadcasts this nodal status packet using its high power radio module. It includes the node's ID, and its high power link neighboring list.

Nodal status packet 3: Every associated BCN periodically broadcasts this nodal status packet using its low power radio module. It includes the node's ID, low and high power link neighboring list, metric list, dynamic weighted label, associated BN, and frame structure field.

Nodal status packet 4: Every non-isolated BN periodically transmits this nodal status packet to all its iso-component MC-BNs, using its high power radio module. It contains

node's ID, local registration list, metric list, and frame structure.

Nodal status packet 5: Every non-isolated BN periodically transmits this nodal status packet to all its iso-component BNs, using its high power radio module. It contains node's ID and local registration list.

Nodal status packet 6: Every isolated BN periodically broadcasts this nodal status packet using its high power radio module. It contains node's ID, and frame structure field.

Nodal status packet 7: Every associated RN periodically transmits this nodal status packet to its associated BN. It includes node's ID, associated BN, and low power link neighboring list.

Note that an RN transmits only nodal status packet 7, while a BCN transmits at most two nodal status packet types. In turn, a BN may have to transmit up to four different types of nodal status packets.

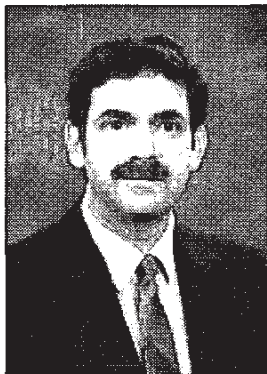
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² This proof is independent of the fact that $SN(BCN_k)$ is only the set of high power link neighbors of BCN_k that it has identified during the waiting period and not necessarily the set of all high power link neighbors.

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Izhak Rubin received the B.Sc. and M.Sc. from the Technion - Israel Institute of Technology, Haifa, Israel, and the Ph.D. degree from Princeton University, Princeton, NJ, all in Electrical Engineering. Since 1970, he has been on the faculty of the UCLA School of Engineering and Applied Science where he is currently a Professor in the Electrical Engineering Department.



Dr. Rubin has had extensive research, publications, consulting, and industrial experience in the design and analysis of commercial and military computer communications and telecommunications systems and networks. At UCLA, he is leading a large research group. He also serves as President of IRI Computer Communications Corporation, a leading team of computer communications and telecommunications experts engaged in software development and consulting services.

Professor Rubin served as co-chairman of the 1981 IEEE International Symposium on Information Theory; as program chairman of the 1984 NSF-UCLA workshop on Personal Communications; as program chairman for the 1987 IEEE INFOCOM conference; and as program co-chair of the IEEE 1993 workshop on Local and Metropolitan Area networks. Dr. Rubin has been elected as a Fellow of IEEE for his contributions to the analysis and design of computer communications networks. He has served as editor of the IEEE Transactions on Communications, of the ACM/Baltzer journal on Wireless Networks, of the Kluwer journal on Photonic Network Communications and of the Wiley InterScience International Journal on Communications Systems.

Arash Behzad received the B.Sc. degree in Industrial Engineering from Tehran Azad University, Tehran, Iran, in 1996. He received the M.Sc. degree in Industrial Engineering with an emphasis on optimization from Sharif University of Technology, Tehran, Iran, in 1998. He served as a lecturer in Tehran Azad University in 1999.



Since 2000 he has been working towards his Ph.D. degree in Electrical Engineering at UCLA. His research areas of interest include networking, optimization and combinatorics.

Runhe Zhang received the B.S.E.E from Jiaotong University, Shanghai, China, in 1998. After working as a member of the Technical Staff at Lucent Technologies for one and half year, he attended University of Minnesota, Twin Cities and earned his M.S.E.E in 2001. That same year he joined University of California, Los Angeles and is pursuing his doctoral degree in Electrical Engineering.



Huiyu Luo received his B.S. in Mechanical Engineering from University of Science and Technology of China in 1999. After finishing his M.S. in the M.E. department of University of California, Los Angeles in 2000, he joined professor Rubin's group to pursue a M.S. in Telecommunications. He is a student member of IEEE.

Eric Caballero earned a B.S. in Electrical Engineering from the University of California, Los Angeles (UCLA) in June 2000. He is currently a graduate student researcher at UCLA pursuing a M.S. in Electrical Engineering with a specialization in communications. His present studies are concentrated on hierarchical mobile ad hoc networks.