Topological Performance of Mobile Backbone Based Wireless Ad Hoc Network with Unmanned Vehicles

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***Abstract*— We have recently introduced a hierarchical structure for ad hoc wireless networks that classifies nodes into two categories: Backbone Capable Nodes (BCNs) and Regular Nodes (RNs). BCNs are better equipped, have higher capacities, and have the ability to operate at multiple power levels and employ multiple radio modules. Under our protocol, identified as TBONE, when a BCN is elected to function as a Backbone Node (BN), it uses its high power link to communicate with other BNs, thus forming a Backbone Network (Bnet). To access the network, each RN or BCN must associate itself with a nearby BN (if any). The BN manages transmissions across its access network (Anet), whereby messages are transmitted to/from the BN and among Anet members at lower power levels. Our protocol dynamically initiates and maintains the configuration and association functions of such a Mobile Backbone Network (MBN) under nodal mobility, topological changes and traffic flow variations. We further employ Unmanned Vehicles (UVs) to aid in maintaining the connectivity of the MBN as well as to upgrade the network capacity when required to sustain real-time and messaging flows that demand Quality-of-Service (QoS) performance assurance. In this paper, we present the performance features of this protocol, evaluating the number of nodes that are activated as BNs, characterizing the extent to which the system covers its client mobile stations using its prescribed BCNs, and presenting the rate of various protocol interactions as a function of the mobility speed of nodal users. We also evaluate the impact of employed UVs on the system's connectivity and coverage features.**

I. INTRODUCTION

We have recently been investigating the operation of mobile ad hoc wireless networks through the embedded establishment of a Mobile Backbone Network (MBN). In [1], we have defined the structure and elements of mobile backbone based ad hoc wireless networks. We have presented there a protocol, TBONE, for the synthesis of MBNs. In [2][3], we have presented approaches to the topological synthesis of mobile backbone networks. 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 Fig.1. 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 (possibly in a single hop) at least a single Backbone Node (BN).

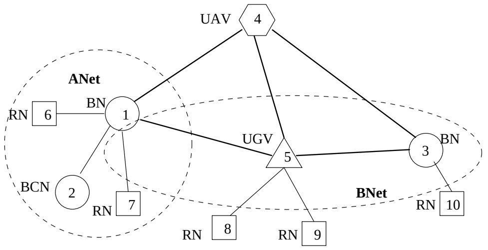

Fig. 1. Structure of Mobile Backbone Network

In the MBN system under consideration, we classify nodes into two categories: Backbone Capable Nodes (BCNs) and Regular Nodes (RNs). BCNs are better equipped, have higher capacities, and have the ability to operate at multiple power levels and employ multiple radio modules. Under our protocol, identified as TBONE, when a BCN is elected to function as a BN, it uses its high power link to communicate with other BNs, thus forming a Bnet. Assume transmissions by backbone nodes of message transported across a Bnet to use a backbone frequency band, while message transmissions made (at typically lower power levels) to access the backbone to occupy a distinct access frequency band. BCNs (that have radio modules allowing them to access both bands) continuously and simultaneously listen for messages transmitted in their reception range across the two frequency bands. However, BCNs are restricted to using their high power radio module for only receiving and transmitting the control packets that are used to establish the connectivity of the Bnet. Low capacity nodes act merely as RNs. They are limited in their power, storage, and processing capabilities; they employ just a single low power radio module. To access the network, each RN or BCN must associate itself with a nearby BN (if any). The BN manages transmissions across its Anet, whereby messages are transmitted to/from the BN and among Anet members at lower power levels. Our protocol dynamically initiates and maintains the configuration and association functions of such a network under nodal mobility and topological changes.

In this paper, we present performance features of this protocol, evaluating the number of nodes that are activated as BNs, characterizing the extent to which the system covers its client mobile stations using its prescribed BCNs, and presenting the rate of various protocol interactions as a function of the mobility speed of nodal users. We also

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evaluate the impact of employed UVs on the system's connectivity and coverage features.

The remaining of the paper is structured as follows. The Mobile Backbone Network and the relevant elements of the TBONE protocol are presented in Section II. In Section III, we obtain basic performance equations that can be readily used for basic network sizing and analysis purposes under the MBN protocol (MBNP). In Section IV, we display and evaluate performance results obtained though our simulation runs. Conclusions are presented in Section V.

II. The Mobile Backbone Network and the TBONE Protocol

A. Description of Mobile Backbone Network

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 Anet 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 systems, each 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. [4] *(5)* Network and MAC layer configuration of the networking operation across the Bnet. In this paper, we focus on the features of the MBN topological layout process, so that steps *(4)* and *(5)* will not be discussed.

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 $h = 1$.

We use different frequencies for transmissions across high and low power links, so that no interferences take place between transmissions carried out across the Bnets and the Anets. We also assume in this paper 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.

B. 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. In this paper, we focus on the topological configuration features of this protocol.

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 protocol contains several key algorithms that are triggered by these events. We briefly discuss in the following two algorithms that are most relevant to the study carried out in this paper (see [1]): *1)* RN association and reassociation algorithm, *2)* BCN ↔ BN conversion algorithm.

1) RN Association and Reassociation Algorithm

Through the periodic transmission of 'hello' messages (at the proper power levels), the network connectivity matrix is formed. Each node determines its 'neighbors'. In an Anet, the BN learns from its clients the overall connectivity graph of its cluster. In the Bnet, BNs interact to exchange connectivity information.

An disassociated RN is always trying to get associated with a BN. If it hears from multiple BNs, it will try to get associated with a preferred one (based on the BNs excess MBN capacity, processing capability, and/or other attributes). For example, an RN can try to associate with its closest BN. (As is implemented in the simulation presented in a later section). If there are no BNs within its (low power) communications vicinity, but BCNs are identified within its range, it will request one of these BCNs to convert itself into a BN and it will then get associated with it.

An associated RN keeps trying to get re-associated with a better new BN, though it can still communicate with its older BN. Such an operation leads to power reductions and consequently energy conservation, as well as potentially higher spatial reuse gains attained by the MAC algorithm. In our simulation, we do so by permitting the node such a re-association only if it gets closer to a new BN by a preset distance difference level. The use of the latter level, identified also as a 'handover distance margin' prevents the occurrence of oscillations, under which an RN re-associates back and forth between two BNs.

2) BN $\leftrightarrow$ BCN Conversion Algorithm

A BCN will convert itself into a BN if there is an disassociated RN that requests it to do so. Alternatively, such a conversion also takes place if it leads to improved Bnet connectivity. For example, by reducing the number of the Bnet graph components; particularly, contributing to connecting a disconnected Bnet.

To reduce the number of redundant BNs (for example, to decrease energy consumption), in meeting the network's 'minimality' requirement, the protocol also acts to detect BNs that can be converted back into playing the role of BCNs. Note that BNs that are essential to ensuring RN covering and Bnet connectivity cannot be converted. Hence, a BN converts itself into BCN if and only if: *(1)* The conversion will not increase the number of iso-components or break a connected Bnet; and *(2)* Every RN currently associated with it, as well as itself, can successfully get connected to a new BN.

III. PERFORMANCE ANALYSIS

A. Number of Backbone Nodes

In general, we need a sufficiently large number of BNs in order to cover as many RNs as possible. However, the minimality feature of our protocol attempts to 'turn off' (i.e., convert back into BCN mode) redundant BNs, contributing to BN energy conservation, while guaranteeing coverage and connectivity features at the same time. The number of activated backbone nodes (i.e., number of BNs) at any time is thus dependent upon the actual locations of network nodes (including RNs, BCNs and BNs) at that time. It is a random variable that changes as nodes move and as communication (high and low power) link connectivities vary. In a later section, we study the size and variation of the average number of activated BNs through simulations. In the following, we provide a simple approximate analytical calculation for estimating this number.

We estimate the average number of BNs N_b in the network, given the number of BCNs n_c and RNs n_r. Let r and R denote the low and high power transmission range, respectively. They serve as key parameters for this calculation.

Using this calculated number of active BNs, various system design evaluations can be pursued. For example, one can determine the numbers of UGVs that should be introduced to supplement the currently allocated BCNs.

We consider a mobile backbone network with BCNs and RNs randomly scattered in a plane with area S. We define $A(n)$ to denote the average area that n backbone nodes cover when operating at low-power to construct Anets , including overlapping covers and edge effects. Obviously, $A(n) \leq \min\{S, n\pi r^2\}$. Note that if currently N_b nodes are elected as BNs, then any un-elected BCN will be covered by the BNs with probability $\frac{A(n)}{S}$. Under the protocol, all BCNs are covered by BNs (for otherwise, a BCN is converted into a BN; redundant BNs that are converted to BCNs are guaranteed to be covered by BNs as well). We further note that while randomly allocated across the coverage area $A(n)$, it is possible for the n BNs to be batched across the area so that in fact some of them are converted into BCNs, so that the number of active BNs is lower than n. Disregarding RN coverage, we thus approximate the probability that n or less backbone nodes are elected by,

$$P(N_b \leq n) = \left(\frac{A(n)}{S}\right)^{n_c - n}. \tag{1}$$

Hence, an approximation for the probability that there are n BNs in the network (and that all the BCNs are covered, regardless of RN coverage), is given by,

$$P(N_b = n) = P(N_b \leq n) - P(N_b \leq n-1). \tag{2}$$

The average number of backbone nodes is,

$$\begin{aligned} \bar{N_b} &= \sum_{n=1}^{\min\{n_b^{max}, n_c\}} nP(N_b = n) \\ &= \min\{n_b^{max}, n_c\} - \sum_{n=1}^{\min\{n_b^{max}, n_c\}-1} \left(\frac{A(n)}{S}\right)^{n_c - n} \end{aligned} \tag{3}$$

where n_b^{max} is the least integer n that satisfies $A(n) \geq S$. When n_c is fairly large, we have $\bar{N_b} \simeq n_b^{max}$. This level represents the number of BNs that are required to cover the operational area S; it provides an upper bound on the average number of BNs in the network. As we will see in a later section, when the number of BCNs in the network is fairly large (e.g., when it is close to the maximal value mentioned above), the introduction of additional UGVs into the system does not contribute much to increased backbone connectivity.

B. Coverage of Regular Nodes

When the network employs a higher number of backbone nodes, a better coverage of RNs is expected. The fraction of regular nodes that are covered, denoted as P, is estimated as,

$$P = \sum_{n=1}^{\min\{n_b^{max}, n_c\}} P(N_b = n)\frac{A(n)}{S}. \tag{4}$$

IV. SIMULATION EVALUATIONS

Our simulation area is a $L \times L$ square ($L = 512m$). The high power links that connect BNs to form a Bnet have the range of R, which varies from $128m$ to $320m$. The low power links that connect BNs to RNs and inactive BCNs to form Anets have the range of r, which varies from $64m$ to $256m$. The number of BCNs n_c is between 4 and 64. The number of RNs n_r is set to be between 10 and 200. We use a random way-point mobility model [5]. Each node selects a random destination and moves with a random speed up to a maximum speed of $v_{max} = 4m/s$. Once its destination is reached, the node stays for a random waiting period at

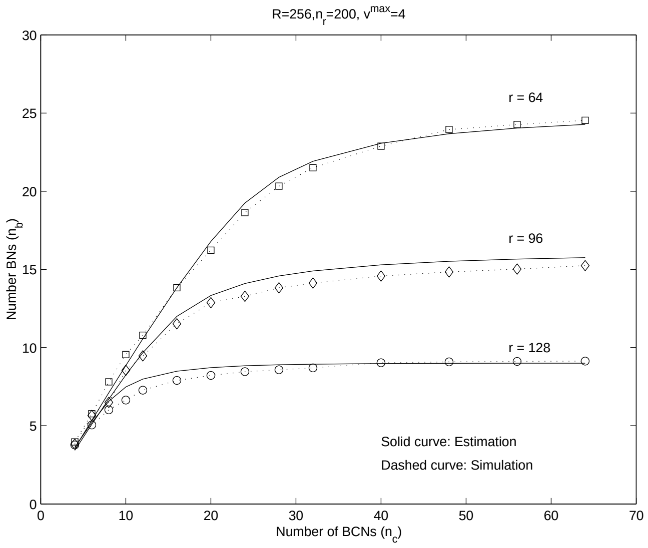

Fig. 2. Number of BNs as a function of Number of BCNs

the destination, and then resumes movement in the same fashion.

We use the TBONE protocol to implement the MBN topological layout, and employ its above described algorithms for: BN election, RN association, BCN to/from BN conversions, Bnet connectivity, as well as mobility and failure adaptations.

A. Number of Backbone Nodes

To analytically estimate the number of BNs realized under different scenarios, we first estimate n_b^{max} as follows,

$$\tilde{n}_b^{max} = \begin{cases} \lceil \frac{L^2}{\pi r^2} \rceil & n_c \pi r^2 \ll L^2 \\ \lceil \frac{L}{\sqrt{3} r} \rceil^2 & \text{otherwise} \end{cases} \qquad (5)$$

Note that in the first case, where the area covered by BCNs is small compared to the total area, n_b^{max} is approximated by the ratio between the simulation area and the coverage area induced by a single backbone node. Otherwise, we assume the BN coverage area to assume the shape of an

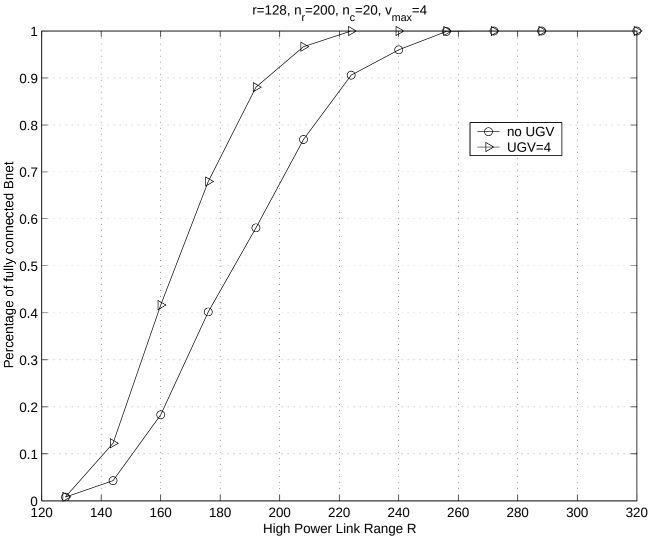

Fig. 4. Backbone Network connectivity as function of R

ing Bnet must be configured to be a connected network. This can be accomplished by either increasing the number of BCNs or increase the high power link transmission range. When the network contains an insufficient number of BCNs, the introduction of UGVs and their placement in advantageous locations, the probability of the backbone being connected can be substantially upgraded.

In this simulation, $n_r = 200, n_c = 20, v_{max} = 4, r = 128$ and we consider two cases: an MBN that employs UGVs as well as one that does not contain them. In Fig.4, we display the variation of the backbone network connectivity factor as a function of the high power transmission range parameter R, for both cases. As expected, the Bnet is more likely to be connected for longer communications ranges R. As we introduce UGVs into the network, we realize great improvement in connectivity. For example, when $R = 192$, when no UGVs are used, the connectivity factor (the probability that the backbone is connected) is equal to 58%, while when four UGVs are employed, the connectivity level is upgraded to 88%.

In the system discussed above, we employ UGVs that are positioned in permanent locations. However, if the UGVs are guided by the network management system into optimally selected positions, more significant performance improvements can be realized. Furthermore, a smaller number of UGVs may be employed. For a study of optimally located UVs that provide connected disk coverage of mobile nodes, see [6].

D. Key Events Rates

We have investigated the realized rates of three processes consisting of key events. These events correspond to topological and nodal association Changes that take place in the network. They are: (1) BCN ↔ BN conversions, (2) RN re-associations and (3) RN losses of connection.

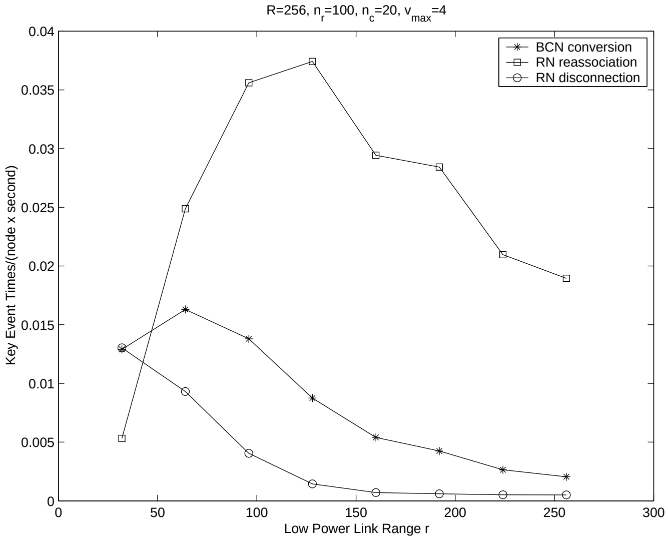

Fig. 5. Rate of key events as function of r

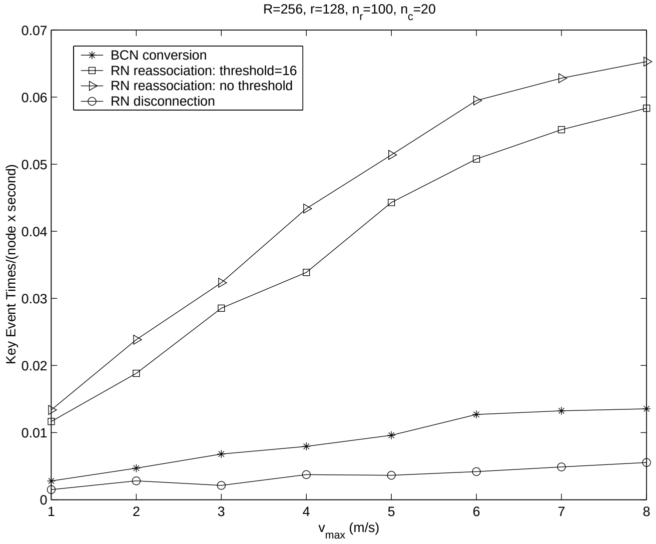

Fig. 6. Rate of key events as function of maximum speed

BCNs convert to become BNs to meet regular coverage or backbone network connectivity requirements. A BN becomes inactive, converting back to a BCN, under the protocol's minimality algorithm, as described in Section II. A regular node changes its association when it finds another backbone node that is closer (by at least the handover margin) than the current backbone node to which it is associated. A regular node loses its connection when it cannot find any backbone node (or BCN that can be converted into BN) in its transmission range in the network.

In this simulation we set: $R = 256, n_c = 20, n_r = 100$. We investigate the above-mentioned rates with respect to the low power transmission range r. As seen in Fig.5, the rate of BCN conversion as well as the rate at which RNs lose connection decrease as r increases. This is induced by the network configuration being more robust as the transmission range assumes a longer value.

The RN re-association rate, exhibits the following behavior. It reaches a maximum level at $r = 128m$ (equivalent to $R = 2r$), and then starts decreasing. This behavior is explained as follows: when the high power transmission range R is greater than $2r$, a RN is more likely to lose its current association before it is able to associate to another BN, so that its connection will be lost. In turn, when $R < 2r$, backbone nodes tend to be closer to each other (in relation to the transmission range of a regular node) and the RN is less likely to then to undergo re-association, noting that a handover margin threshold is implemented.

We now investigate the effect of mobility on the association rates. As seen in Fig.6, the rates of association, conversion and disconnection increase as the node's velocity increases. It is noted that the implementation of a handover margin threshold leads to reduction in the RN re-association rate.

V. Conclusion

The TBONE protocol configures dynamically wireless ad hoc networks into a robust hierarchical network architecture. A mobile backbone network (MBN) is configured, Unmanned vehicles (UVs) are employed when available to enhance the network nodal covering and to improve backbone connectivity. This is highly beneficial for reducing routing complexity, for multicasting messages, and for the support of realtime traffic under Quality of Service (QoS) provisions. An effective network management structure is maintained by using a quasi-centralized protocol, whereby each Anet is managed by its backbone nodes, while backbone nodes interact in a distributed fashion across the backbone network. Such an implementation tends to reduce the rate of overhead and control traffic required in comparison with those generated under a flat hierarchy network operation.

The performance evaluations presented in this paper demonstrate the features of our MBN topological layout protocol in providing for nodal coverage and in forming access and backbone nets. We demonstrate the topological layout features of the protocol. We examine the realized and required number of active backbone nodes. We exhibit the attained connectivity of the network when no UGVs are used, and demonstrate the potentially significant improvement that can be attained when UGVs are placed in the operational area under consideration. We demonstrate the robustness of the network, and assess the rates at which key protocol induced events occur as a function of nodal mobility speed. The latter rates are shown to decrease when UVs are employed.

The underlying simulations performed in this paper, assume a protocol operation under which nodes have required network status information without further constraints. In future studies, we will compare the results derived here with those obtained under a distributed protocol implementation that imposes constrains on the distribution of control messages. The results presented in this paper are essential in such an evaluation, in that they provide performance references and bounds that a distributed protocol implementation will strive to approach.

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