

# Performance Behavior of Unmanned Vehicle Aided Mobile Backbone Based Wireless Ad Hoc Networks

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*Abstract*—We introduce Unmanned Vehicles (UVs) to aid the operation of the mobile backbone based wireless ad hoc networks, and serve to significantly enhance the construction of a capable backbone network. We consider two types of UVs: Unmanned Airborne Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs). The UAVs may orbit at different layers (and altitudes), communicating to ground access stations. They serve to connect distant isolated sub-networks and may act as relays for non-time-sensitive traffic flows. We position fixed UGVs in the operational area at advantageous positions to offer both high coverage of mobile units as well as to contribute to the formation of a capable high capacity backbone. Their location is selected based on observed mobility behavior (over the operational area of interest) statistics of the system's mobile stations. They also serve to maintain the network connectivity, mobile unit coverage and add need capacity and spatial connectivity needed to provide Quality of Service (QoS) guarantees and to support real-time streams and critical messaging flows. In this paper, we present extensive performance results concerning the operation of a dynamic backbone based ad hoc wireless network that employs UVs. We also study three different node movement models that affect the performance of such network.

## I. INTRODUCTION

We have introduced and studied mobile backbone based wireless ad hoc networks [1]. These networks employ some better-equipped mobile stations, identified as backbone capable nodes (BCNs), which have higher capabilities (such as higher transmission power and processing capacity). BCNs can operate at multiple power levels while the rest of the nodes (identified as regular nodes, or RNs) operate at a single lower power level. When elected as a backbone node (BN), the BN forms high power links with other BNs that are in communications range. In this manner, the BNs form a backbone network (Bnet). Depending upon the location of the elected BNs, the backbone network may consist of a number of disconnected Bnet components. To access the network, each RN or BCN must associate itself with a BN that is in communications range (employing their lower power links). In this manner, a BN and the nodes that are associated with it form an Access Network (Anet). This BN serves as the communications resource and admission manager of its Anet. At the MAC layer [2], it assigns TDMA time slots (and possibly also CDMA codes or FDMA frequency bands) to the members of its Anet. Our protocol dynamically initiates and maintains the configuration and association functions of such a network under nodal mobility and topological changes.

In [3], we have presented the performance features of this

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protocol, evaluated the number of nodes that are activated as BNs, characterized the extent to which the system covers its client mobile stations using its prescribed BCNs, and presented the rate of various protocol interactions as a function of the mobility speed of nodal users.

In this paper, we introduce Unmanned Vehicles (UVs) to aid the operation of the mobile backbone network (MBN) described above, and serve to significantly enhance the construction of a capable backbone network. We present extensive performance results concerning the operation of a dynamic backbone based ad hoc wireless network that employs Unmanned Airborne Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs).

The remaining of the paper is structured as follows. A brief introduction to Mobile Backbone Network and the relevant elements of the MBN protocol (MBNP) are presented in Section II. In Section III we showed three different movement models that have different performance results obtained through our simulation runs. We also display and evaluate performance results when we put UVs into the network. Conclusions are presented in Section IV.

## II. THE MOBILE BACKBONE NETWORK AND MBNP

### A. Description of Mobile Backbone Network

We construct an MBN structure through the following steps:[1] (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. (5) Network and MAC layer configuration of the networking operation across the Bnet. The above steps are identified as Mobile Backbone Network Protocol (MBNP). The purpose of the MBNP 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 in-

duced 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[1].

We introduce Unmanned Vehicles (UVs) to aid the operation of the mobile backbone based wireless ad hoc networks, and serve to significantly enhance the construction of a capable backbone network. We consider two types of UVs: Unmanned Airborne Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs). The UAVs may orbit at different layers (and altitudes), communicating to ground access stations. They serve to connect distant isolated Bnets and may act as relays for non-time-sensitive traffic flows. Certain UAVs may also be able to be interconnected by using inter-UAV (such as inter-satellite) communications links, if they are located within communications range. The higher is the UAV's altitude, the larger footprint it will have on the ground. A higher altitude UAV may, however, induce longer message delay latencies and provide lower communications capacity levels. We adjust the position of the access stations in accordance with the altitude of the underlying employed UAVs. UGVs may be outfitted with radio systems that provide them with the same or higher capability than that of BCNs. As is the case for BCNs, they can also operate at multiple power levels (including the lower level one that allows them to communicate with RNs). For the synthesis of the MBN, UGVs act as permanent BNs. In this way, they automatically and dynamically get associated with (uncovered) RNs and BCNs. They also form higher power links with other BNs to form and maintain a robust Bnet. We position fixed UGVs in the operational area at advantageous positions to offer both high coverage of mobile units as well as to contribute to the formation of a capable high capacity backbone. Their location is selected based on observed mobility behavior (over the operational area of interest) statistics of the system's mobile stations. They also serve to maintain the Bnet connectivity, mobile unit coverage and add need capacity and spatial connectivity needed to provide Quality of Service (QoS) guarantees and to support realtime streams and critical messaging flows. The operation of a UGV is constrained in the same manner as that of a BN by the overall network state information that it can gather in a short period of time. Its location adaptation is constrained by its speed and accelerations limitations.

### B. Movement Patterns

We prescribe three different movement patterns (random walk, random movement and random destination [4]) to characterize the mobility of the nodes.

In 'random walk' movement pattern, every node moves towards possible directions with equal probability and speed ranging from zero to  $v_{max}$ .

Any node in 'Random movement' pattern has a speed

and angle that describes its current velocity. For each simulation step, the speed of that node cannot exceed  $v_{max}$  while the change of the speed (acceleration) cannot be higher than  $a_{max}$ . Its direction change is also limited by  $\theta_{max}$ .

In 'Random destination' movement pattern, every node goes to its destination for a certain (non-constant) speed (limited by  $v_{max}$ ). Once it reaches the destination, it stays there for a certain period of time, chooses a new destination and moves on.

These three movement patterns will have different impacts on system performance. In the later section, we calculate the fraction of time that the Bnet is connected. To determine the extent of backbone access that the network offers, we compute fractional number of RNs that are provided access to the backbone (or can be managed by a BN, being within communications distance from a BN). We also assess the number of BNs elected by our protocol as a function of the number of BCNs and permanent BN (including UVs) that are available in the network, under different movement patterns. We demonstrate that different movement patterns can yield distinct differences in the realized levels of the above-mentioned performance measures.

### C. Unmanned Vehicles

In [3], we studied the performances (mobile units coverage, fraction time of a connected Backbone network, etc.) as a function of the number of BCNs in the network. In order to make a connected Backbone network and cover as many mobile units as possible, we need to have enough BCNs in the network. (Excessive BCNs will be automatically turned off by our protocol). However, the BCNs are moving and may causes instability of the network (which includes link failure, route failure and network traffic congestion). If we know the topological information, we are able to get much better performances by introducing the UGVs and UAVs in the network.

We study the impact of static UGVs on system performance. We investigate the performance gains that can be attained when we replace some BCNs with UGVs that are properly positioned. Performance measures include: extent of mobile unit coverage (i.e., provision of access to the backbone net); the probability of a connected network; the level of control overhead experienced; and the topological configuration changes occurring in the network due to mobility. We study the positioning of UGVs for the construction of a robust and high performance wireless ad hoc networks. In [5], the network is first clustered and then UGVs are placed to form a connected disk covering backbone. In our system, it may not be possible to form full coverage (and clustering) of the network using available UGVs.

We study the placement of UAVs to enhance the synthesis of a capable backbone network. Ground access stations are placed to direct traffic to UAVs. The higher the altitude of the UAV, the wider is the terrestrial footprint that it creates. We use UAVs to interconnect distant backbone sub-networks (or components) by placing access station(s) in these separate networks. Given a set of access stations,

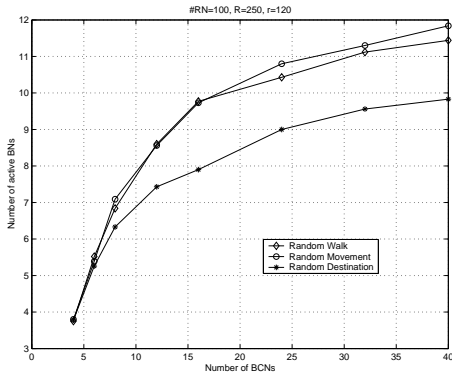


Fig. 1. Number of Active BNs as a function of number of BCNs

once their locations have been determined, we employ one or more UAVs, and place them in proper (one or more) orbits (at proper altitudes) to provide desirable coverage. We investigate the performance behavior of the resulting mobile backbone network under the use of such UAV elements.

### III. PERFORMANCE RESULTS

Our simulation area is a  $L \times L$  square ( $L = 500m$ ). The high power links that connect BNs to BNs to form a Bnet have cover range  $R$ . The low power links that connect BNs to RNs and inactive BCNs to form Anets provide communications over range  $r$ . The number of BN is between 4 to 40. The number of RNs is set to be 100. For all three movement models, the maximum speed is  $4m/s$ . Under the ‘random movement’ model, the maximum acceleration is  $2m/s^2$  and the maximum change of angle in a second is 90 degrees. For the ‘random destination’ model, the time that a node stays once it reaches its destination follows an Exponential distribution with average of 10 seconds.

We use the MBNP protocol to implement the MBN topological layout, and employ its algorithms (as delineated in[1]) for RN election, RN association, BCN to/from BN conversions, as well as mobility and failure adaptations. We study the system’s performance behavior as we vary the number of BCNs in the network.

In Fig.1, we observe that the number of active BNs increases as the number of BCNs increases. It reaches an asymptotic value, as derived in [3]. Under the ‘random destination’ movement pattern, the system exhibits the lowest number of active BNs. This is due to the fact that under the ‘random destination’ movement model, the nodes are more likely to pass through the central region of the simulation area, and thus condensing the effective area in which nodes reside. Statistically, the nodes under the other two models tend to move around their original start neighborhood, so that nodes are more uniformly distributed across the area of operations.

Fig.2 shows the extent of coverage of mobile units achieved under each movement pattern. Fig.3 shows the fraction of time that the Backbone network is connected. We observe that the three movement models yield about the same coverage performance and Bnet connection prob-

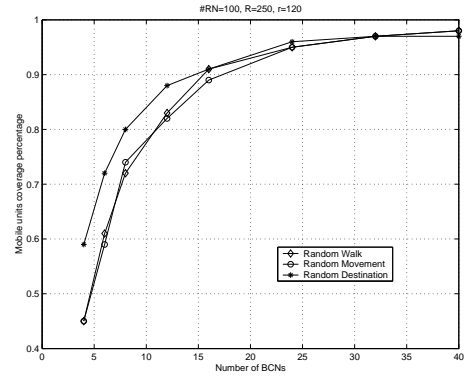


Fig. 2. Mobile units coverage as a function of number of BCNs

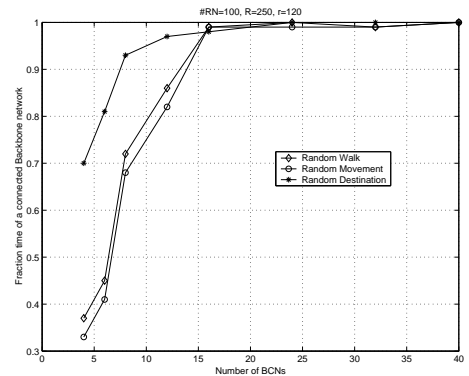


Fig. 3. Prob. of a connected BNet as a function of number of BCNs

ability when the number of BCNs is relatively large. In turn, the ‘random destination’ model provides the largest coverage and Bnet connection probability when the number of BCNs is small. Following the argument made in connection with Fig.1, for the same small number of BCNs, a reduced simulation area yields higher coverage and increased likelihood of a connected Backbone network. However, as the number of BCNs grows larger, this effect becomes less noticeable.

Fig.4 shows the BCN conversion rate as a function of the number of BCNs. When the number of BCNs is small, it is less likely to have many conversions, since most of the BCNs have been turned on to function as active BNs. On the other hand, when the number of BCNs is large, conversion transitions also tend to occur less often, as the activated nodes form a stable backbone network. We observe that the number of BCNs observed as the conversion rate reaches its maximum level, in all of the three models, is coincident with the corresponding asymptotic value shown in Fig.1. This shows that the optimum values of the number of BCNs given by the MBNP protocol (when one aims to minimize the number of active BNs while at the same time achieve a given connectivity level), may result with backbone network operation that experiences a higher conversion rate level.

Fig.5 demonstrates the RN re-association rate for the different movement models. The RNs re-associate with a BN when they find it to be more beneficial (e.g., when they are closer to that BN, or when the new BN has a higher resid-

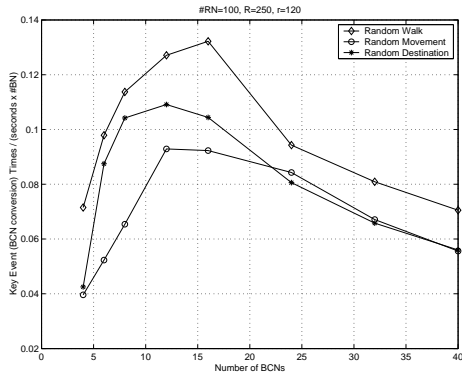


Fig. 4. BCN conversion rate as a function of number of BCNs

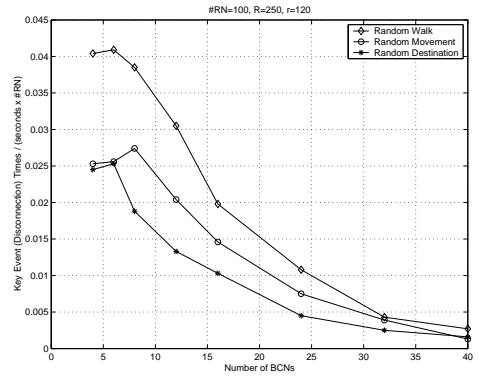


Fig. 6. RN disconnection rate as a function of number of BCNs

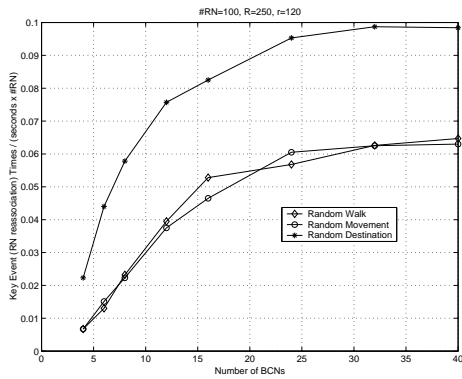


Fig. 5. RN reassociation as a function of number of BCNs

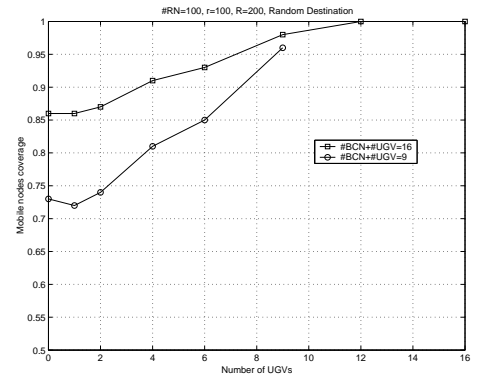


Fig. 7. Mobile units coverage as a function of number of UGVs

ual capacity) to make that re-association. As mentioned in Fig.1, the ‘random destination’ model tends to yield a more dynamic movement while the nodes in the other two models tend to stay in their neighborhood. Hence, the ‘random destination’ model results in higher RN re-association rate, as more dynamic the nodes are, the better chance the RNs have to associate with a preferred BN. demonstrates the RN re-association rate for the different movement models. The RNs re-associate with a BN when they find it to be more beneficial (e.g., when they are closer to that BN, or when the new BN has a higher residual capacity) to make that re-association. As mentioned in Fig.1, the ‘random destination’ model tends to yield a more dynamic movement while the nodes in the other two models tend to stay in their neighborhood. Hence, the ‘random destination’ model results in higher RN re-association rate, as more dynamic the nodes are, the better chance the RNs have to associate with a preferred BN.

Lastly, Fig.6 shows the rate of link failure (association break) in the network. This can be regarded as another evaluation measure of nodal coverage. Following the same arguments made for Fig.2, the ‘random destination’ model exhibits the least RN disconnection rate as it attains the widest mobile units coverage.

To study the advantages of introducing UGVs into the network, we substitute some of the BCNs in the network with *stationary* UGVs (which are employed as permanent BNs), placing the UGVs symmetrically over the operational area. We assume the high power link of UGVs offers

the same communication range as that provided by regular BCNs.

We consider two scenarios. Under both scenarios we have 100 RNs with high power link  $R = 200m$  and low power link  $r = 100m$ . The mobile units follow the ‘random destination’ movement model with maximum speed of  $4m/s$  and an average of 10 seconds staying time. In scenario 1, the total number of high power nodes is 16; that is, the sum of the number of BCNs and the number of UGVs is 16. We vary the number of UGVs from 0 to 16. In scenario 2, the total number of high power nodes is equal to 9.

In Fig.7, we see that by substituting BCNs with UGVs we have a major impact on the coverage scope of mobile units. In both scenarios, the higher we set the fraction of placed UGVs, the larger is the mobile unit coverage level attained. The fractional coverage level is raised by about 14% and 25% under the first and second scenarios, respectively.

In Fig.8, the results show that as we increase the fraction of placed UGVs, we also raise the likelihood of a connected backbone topology. In Figs.9-10, we exhibit the variation of the rates of two key control (RN re-associate and RN disconnection) flows vs. the number of employed UGVs. We note the rates of these control flows to decrease as we increase the number of statically placed and BN-tasked UGVs.

We next consider scenarios where the simulation area is fairly large:  $L \times L$  where  $L = 1000m$ ; we set  $R = 200m$  and  $r = 100m$ . The number of BCNs is equal to 20. Other

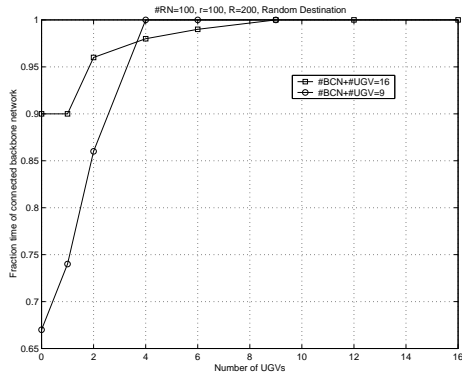


Fig. 8. Prob. of a connected BNet as a function of number of UGVs

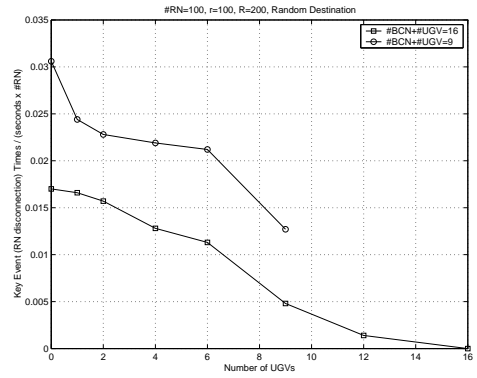


Fig. 10. RN disconnection rate as a function of number of UGVs

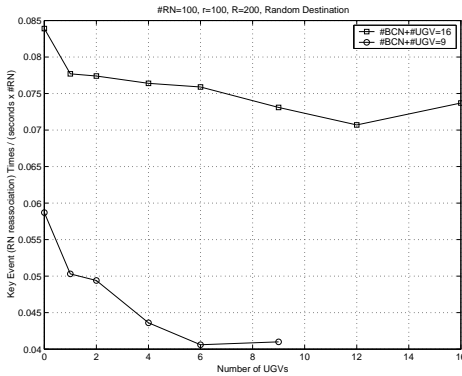


Fig. 9. RN reassociation rate as a function of number of UGVs

parameters remain the same. For this network, the relative number of BCNs is smaller in relation to the area that they need to cover. In addition, there is a higher likelihood here that BNs are unable to communicate with each other. We introduce UAVs to provide airborne communications relay support to the ground network established over the operational area. We employ four UAVs and eight ground based (stationary) Access Stations (ASs). Each UAV is connected to two Access Stations through corresponding ground-air communications links. They are deployed in orbits that place the access stations in the foot-prints of the corresponding UAVs. Obviously, the higher the UAV's altitude is, the larger is its footprint and its Access Stations will then yield wider cover. Our simulation results show that in this scenario, when there are no UAV or Access Stations present, the mobile unit coverage ratio is equal to only 66% and the probability that we have a connected Backbone network is only 28%. When a UAV is placed in orbit and 8 BCNs are replaced with 8 Access Stations, the mobile unit coverage ratio increases to 72% while the probability of a connected backbone network is upgraded to 89%.

#### IV. CONCLUSIONS

The Mobile Backbone Network Protocol (MBNP) configures dynamically wireless ad hoc networks into a robust hierarchical network architecture. Unmanned Vehicles (UVs) are employed when available to enhance the network's nodal coverage, improve backbone connectivity as

well as reduce control traffic rates. The employment of UVs is also highly beneficial for reducing routing complexity, for implementing simpler message multicasting schemes, and for the support of real-time traffic under Quality of Service (QoS) provisions. An effective network management structure is maintained by using a quasi-centralized management protocol, whereby each Anet is managed by its backbone node, while backbone nodes interact in a distributed fashion across the backbone network. Such an implementation tends to reduce the rates of overhead and control traffic in comparison with those generated under a flat hierarchy network operation.

The performance evaluations presented in the paper demonstrate the features of MBN topological layout protocol in providing for nodal coverage and in forming access and backbone nets. We have employed three distinct movement models: 'random walk', 'random move', 'random destination' and studied their impact on the network system behavior. We have demonstrated the potentially significant improvement that can be attained when UGVs are placed in the operational area under consideration. We have demonstrated the robustness and coverage properties of the network, and have illustrated the reduction in control flow rates that can be achieved. We exhibited the improvements that can be gained by deploying UAVs to connect distant, or potentially disconnected, areas of the network.

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