Multi-Tier Mobile Ad Hoc Routing

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***Abstract*—We present a new approach for routing in multi-tier heterogeneous wireless mobile ad hoc networks. This protocol, namely multi-virtual backbone protocol (MVP), naturally addresses key challenges arising from multi-tier wireless networks such as the coverage asymmetry and node heterogeneity. It also supports various QoS needs by constructing and maintaining QoS-specific virtual backbone infrastructure. A detailed algorithm will be presented, and preliminary simulation results will be discussed.**

Keywords-mobile ad hoc networks; MANET; virtual dynamic backbone; multi-tier networks; Airborne Communication Node..

I. INTRODUCTION

Future battlefield networks will consist of various heterogeneous networking systems and tiers with disparate capabilities and characteristics, ranging from ground ad hoc mobile and sensor networks to airborne-rich sky networks to satellite networks; see Figure 1. It is an enormous challenge to create a suite of novel networking technologies that efficiently *glue* these disparate systems. By doing so, the resulting network must offer unprecedented capacity, flexibility, connectivity, reliability, and scalability for meeting even the most challenging needs of the future warfighters.

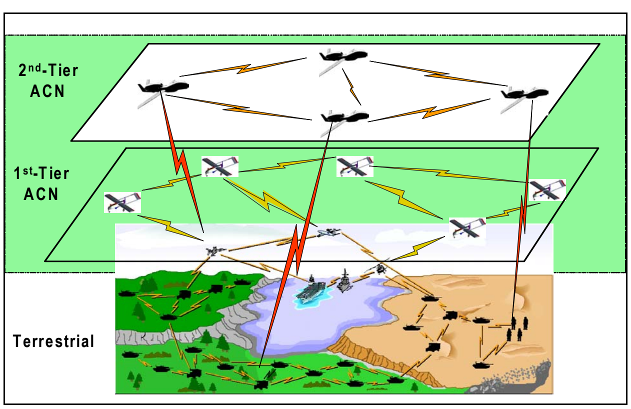

Figure 1: An illustration of 3-tier battlefield network.

This paper describes *multi virtual backbone protocol* (MVP), a new mobile ad hoc routing protocol designed for heterogeneous multi-tier mobile ad hoc networks such as battlefield networks. The primary goal of this protocol is to enable assured delivery of large volumes of critical data within a battlefield by ground nodes and airborne communication nodes (ACNs) at various altitudes. MVP is based on the concept of Virtual Dynamic Backbone (VDB). A VDB is an approximation to the Minimum Connected Dominating Set (MCDS) in a graph theory defined as a subset of the graph such that it is connected, reaches non-MCDS nodes within the graph with a single hop, and has the minimum size. By definition, VDB optimally carries broadcast traffic because it minimizes the number of forwarding actions by limiting it to only those in the MCDS. Details of this algorithm, along with its efficiency under various mobility scenarios, are presented in [1]. MVP operates by creating and maintaining multiple VDBs with minimum overlap among them. This concept utilizes the key strength of the original VDB algorithm in creating and maintaining a stable and small-size virtual backbone with a simple distributed algorithm. Note that the metric employed to compute a VDB is based on the combination of degree, frequency of neighbor changes, and a few other minor factors [1]. By replacing this metric with a QoS metric (instead of degree), the same algorithm can be seamlessly utilized to form different backbones. This approach enables the ACN (or even ground) tier to create and maintain multiple virtual backbones such as Delay-VDB for delay-sensitive traffic, Loss-VDB for loss-sensitive traffic, Energy-VDB for energy-conserving nodes, etc. We argue that this is an ideal structure for multi-tier heterogeneous ad hoc networks since MVP naturally provides multiple robust virtual backbones with distinctive QoS features, each via a separate tier, providing mobile nodes multiple choices of routes at any time depending on its QoS needs at that moment.

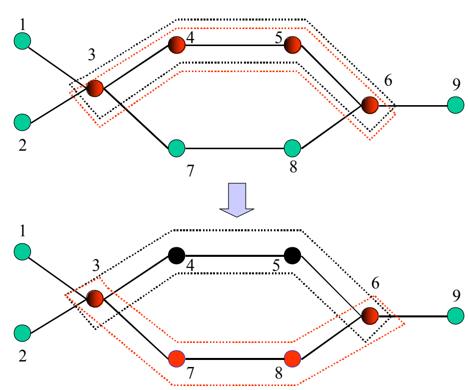

Figure 2: An illustration of Multiple VDBs

Figure 2 illustrates the concept of creating multiple backbones in response to traffic changes. Suppose that each node disseminates not only their degrees and stability, but also the observed queueing delays. Initially, the nodes 3,4,5, and 6 form a VDB based on the original algorithm utilizing only degree and stability. Since there will be little traffic across the network, the original VDB also serves as Delay-VDB. Now, suppose the traffic between nodes 4 and 5 have doubled due to sudden increase in traffic from lower-tier nodes under 4 and 5. This will delay the traffic from node 1 to 9, thus increasing queueing delay at nodes 3, 4, and 5. Based on measuring their own queueing delays, these nodes declare to be no longer Delay-VDB. Upon detecting this, the node 7 changes to RED (backbone node of Delay-VDB) following the same VDB selection algorithm since its delay value is locally minimum. Since the nodes 6 and 7 are now backbone nodes of Delay-VDB, the backbone connection process makes node 8 red as well. The node 3 later becomes part of the Delay-VDB upon the request of node 1, just like the backbone expansion process of the original algorithm. This example shows how the existing algorithm can be seamlessly used to form a QoS-specific virtual backbone by pushing QoS-sensitive traffic outside the original VDB whenever it needs to. Figure 3 illustrates this concept applied to 3-tier ACN ad hoc network.

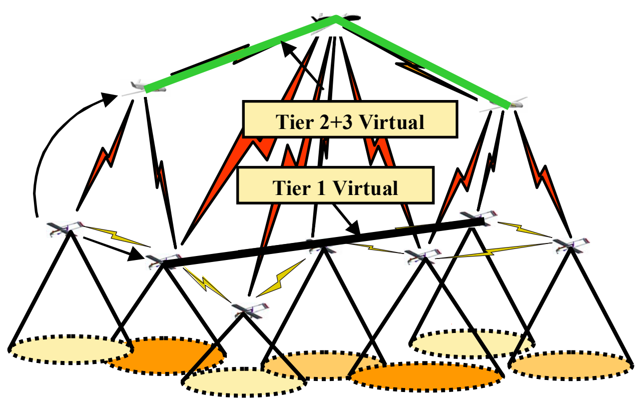

Figure 3: MVP in a 3-tier ACN network

II. MULTI-VIRTUAL BACKBONE PROTOCOL (MVP)

Similar to its predecessor VDBP, the MVP algorithm consists of three major processes: the Backbone Selection Process (BSP), the Virtual Access Point (VAP) Selection Process (VSP), and the Backbone Connection Process (BCP). Each non-backbone node designates one of its backbone neighbors as its VAP, indicating that the selected VAP node provides "connection" to the backbone. This is used to maintain the minimum size of the backbones. These processes are facilitated by two kinds of broadcast packets: the Hello message which serves as a beacon to a node's neighbors, and the General Broadcast Message (GBM) which broadcasts to the entire network and also provides routing information. GBMs are forwarded by backbone nodes only. Two tables are maintained at each node: a Neighbor Information Table (NIT) which contains data on neighbors' colors, degree, VAPs, etc. and a routing table.

A. Backbone Selection Process (BSP)

The BSP is a procedure that occurs only at the establishment of a backbone, when none yet exists. Consider node *N*, a node with several neighbors, in the case of the first backbone (or only backbone in the case of VDBP). At the moment, node *N* is white, meaning it has no VAP and is not part of any backbone. Let us assume that node *N* has no black or green neighbors, only white ones. A node is colored black if it is part of the first backbone, and green if it has a black neighbor. In this case node *N* will examine its NIT, which by this time has been filled with information concerning all of node *N*'s neighbors. It then compares its degree, meaning the number of neighbors it has, with the degrees of all its neighbors. If node *N* has the highest degree of all its neighbors, it will turn black, if not it will wait until the neighbor with the highest degree turns black or green and then chose it as a VAP, allowing it to turn green. In the case where node *N* does not have all white neighbors, the VSP will be initiated.

In the case of MVP's second backbone, the algorithm is much the same save that only the degrees of non-black neighbors are considered in order to avoid overlap of the two backbones. And if node N itself is already black it will defer to a lower degree neighbor.

B. VAP Selection Process (VSP)

The selection of VAPs occurs every time the NIT is updated or a node changes color once the BSP has occurred. Consider again node N and assume that at the moment it is not black and is searching for the best neighbor to use as its black VAP. The first kind of neighbor node N will search for is the black neighbor with the highest degree. If such a node is not available, the node will choose the neighbor with the highest degree that is not black. Node N's VAP V will establish a timer once it receives a Hello or GBM from N recognizing it as a VAP. This timer will be renewed after every broadcast packet received in which V is a VAP to any of its neighbors. Once this timer runs out, barring certain special cases discussed below, V will turn green. The selection of red VAPs is slightly more complex. The most desirable red VAP is one that is not black but is red and has the highest degree of all such neighbors. If that is not available, node N will choose the non-black neighbor with the highest degree, and lastly, failing that, it will choose the neighbor with the highest degree. However, the latter choice means that some overlap of the backbones will occur and is highly undesirable.

C. Backbone Connection Process

The most complex of the three processes is the BCP in which backbone fragments are connected through two kinds of procedures which occur in two separate circumstances. The first circumstance is when a backbone node realizes that it has no route to the VAP of one of its neighbors. This means that this neighbor sits in-between two backbone nodes but is not a member of the backbone itself. This is called the BGB case because a green node exists in between two backbone nodes. The second circumstance is when a non-backbone node realizes that it has no route to the VAP of one of its non-backbone neighbors. This means that two green nodes exist between two backbone nodes and is called the BGGB case.

The BGB case is the simpler of the two. Consider the situation B1 —- G2 —- B3, in which G2 has B3 as a VAP. Once B1 detects that it has no route to B3, it sends a unicast message to G2 or to one with higher degree that also has B3 as a VAP if possible. Assuming G2 receives the message, it will then verify that B3 is still its VAP in case B1's data is obsolete and if so, G2 will turn black and connect B1 and B3. G2 will send an acknowledgement message back to B1 so that B1 can add B3 to its routing table. The node G2 will keep a record of the two nodes it connects so that, in the case of VAP timeouts or other situations where it would normally turn green it will stay part of the backbone. There are only three cases where this connection can be broken. The first being if the actually link is severed and the node removed from G2's NIT; the second being if B1 or B3 turns green, in which case G2 will turn back to green after a period of six seconds; the third one is if G2 is no longer necessary to connect the two nodes.

The BGGB case involves several unicast messages. Consider the case B1—- G2 —- G3 —- B4, in which G2 has B1 as a VAP and G3 has B4 as a VAP. Either G2 or G3 can detect the lack of a route to the other's VAP. Suppose G2 detects that it has no route to B4. In this case it will send a unicast message called a Connection Information Message (CIM) to its VAP providing the identities of G3 and B4. Once B1 receives this message, it will verify that the BGB case does not exist–meaning that a shorter connection might be made. If such is not the case and B1 has no route to G3 or B4, it will send a Connection Order Message (COM) back to G2 telling it to initiate the connection. The node G2 will, upon receiving the COM, send a Connection Relay Message (CRM) to G3 telling it to turn black and create a connection pair consisting of the two nodes G2 and B4. The node G3 will then return an acknowledgement message to G2 telling it to turn black and establish a second connection pair involving B1 and G3.

III. Performance of MVP: A Preliminary Study

Despite the fact that the multi-tier network is 3-D in nature, simulation tools such as OPNET and ns2 provide little support to develop, test, and visualize the protocols under realistic multi-tier ACN network dynamics. The lack of 3-D support while designing and evaluating protocols for the 3-D ACN network has been a major obstacle to the full understanding of the interaction between protocol behaviors and topology dynamics. Realizing this challenge, we have developed an extension of ns2 and nam to add 3-D ACN network simulation and visualization capabilities. Details of these tools are described in [2]. These new capabilities have enabled us to develop the MVP and analyze its performance in a realistic 3-D multi-tier mobile ad hoc network environment.

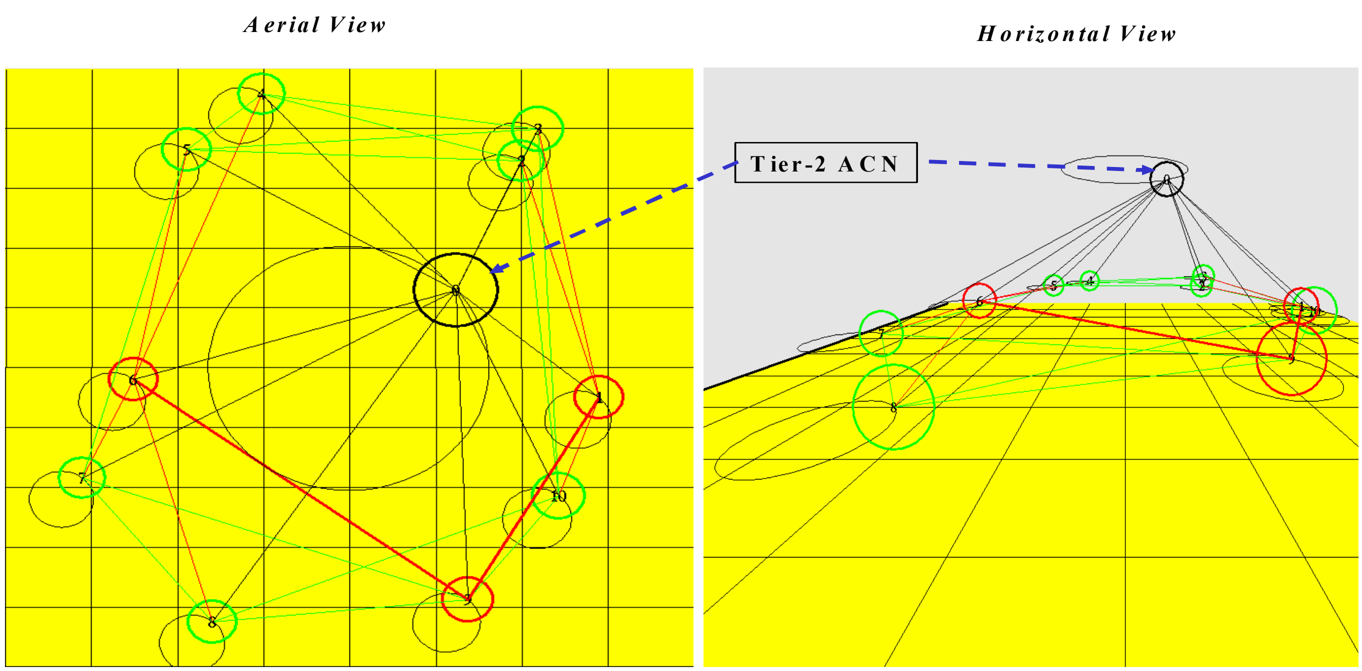

Figure 4: 3-D visualization of 2-tier ACN network with MVP.

The key benefit of MVP is that it naturally supports the multi-tier structure of the ACN network. As illustrates in Figure 4, the MVP forms the first virtual backbone (represented as black color) with the tier-2 ACN only since it can "see" all the nodes under it. The second virtual backbone is formed solely by lower-tier ACNs (represented as red color). The nodes that are green represent the ACNs that are connected to both backbones.

Before investigating the routing performance of MVP, one must ensure that MVP indeed yields multiple VDBs as expected. In this paper, we examine *normalized backbone ratio* (NBR) as an indication of how much of a network is comprised of backbone nodes while fully connected. The size of backbones must be kept as small as possible in order to minimize the flooding overhead, while ensuring full connectivity.

We have implemented MVP in QualNet 3.5, and estimated NBR under the following conditions. The networks were 20, 60, and 100 nodes. Each node had an antenna with a range of 167 meters, and the size of the domain was 640 by 640 meters for the 20 node network, 1110 by 1110 meters for the 60 node network, and 1430 by 1430 for the 100 meter network, which ensured a constant node density. The scenario consisted of a flat plane, two-dimensional situation with nodes distributed randomly and moving in random way-point fashion up to speeds of 50 m/s.

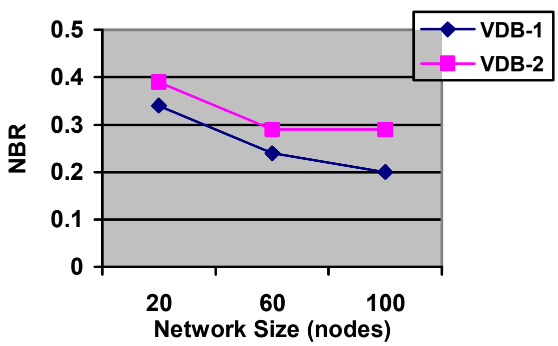

Figure 5: NBR for static networks

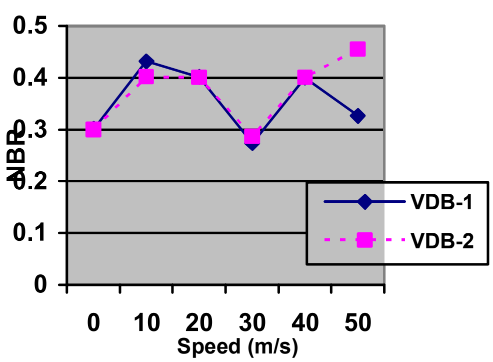

Figure 6: NBR for different motilities. Network size = 20.

Figures 5 and 6 show the measured NBR for both static and mobile ad hoc networks. For the static network case (Figure 5), we make the following observations:

- The size of the second backbone set is slightly larger than the first one. This is very important and as expected, since it indicates that the algorithm works correctly. Because the second backbone is created and maintained by excluding the first backbone nodes in order to minimize overlap between the two, the second backbone should be larger than the first. At the same time, the small difference indicates that the second backbone is also kept small.
- The size of backbones decrease as the network size increases. This is expected since larger network tend to have more dense connectivity, decreasing the size of MCDS.
- The number of backbone nodes being created and maintained for each backbone ranges between 20-40% of the entire network. This implies that having more than one backbone within the same tier may not be desired. However, we note that the size of the first backbone will be considerably smaller (only a few) if MVP is employed in a multi-tier network (e.g., Figure 4).

In the case of mobility (Figure 6), it appears the size of the backbones has little correlation with the increased mobility. More extensive simulation, with high-fidelity wireless channel model, is needed to fully characterize the behavior of MVP.

We have also implemented MVP in linux for testing and validation purpose. The HRL-developed mobile topology emulation tool, MobiEmu [3], was extensively used during the various processes of implementing and testing MVP. This implementation was used and demonstrated as part of DARPA's ACN program.

IV. CONCLUSION

In this paper, we have presented the concept and algorithm of a new MANET routing structure for multi-tier mobile ad hoc networks. Multi-tier networks are considerably more challenging than a traditional flat-plane MANET because they contain connectivity asymmetry (i.e., higher-tier nodes have much higher connectivity than lower-tier nodes) and node heterogeneity (in terms of mobility, range, battery power, etc.). We claim that MVP is an ideal approach for handling these challenges due to its attractive features such as:

- Small virtual backbone structures that are naturally obtained with higher-tier nodes that have considerably more connectivity than lower-tier nodes.
- Ability to create and maintain routing infrastructure with different QoS support.
- Efficient broadcast and multicast traffic delivery.

Further work is required in order to fully characterize its performance under various unicast and multicast traffic load conditions and realistic channel environment. This is under way, and the results will be reported elsewhere.

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