An Ad Hoc Network with Mobile Backbones*

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***Abstract*- A Mobile Ad Hoc Network (MANET) is usually assumed to be homogeneous, where each mobile node shares the same radio capacity. However, a homogeneous ad hoc network suffers from poor scalability. Recent research has demonstrated its performance bottleneck both theoretically and through simulation experiments and testbed measurement. Building a physically hierarchical ad hoc network is a very promising way to achieve good scalability. In this paper, we present a design methodology to build a hierarchical large-scale ad hoc network using different types of radio capabilities at different layers. In such a structure, nodes are first dynamically grouped into multi-hop clusters. Each group elects a cluster-head to be a backbone node (BN). Then higher-level links are established to connect the BNs into a backbone network. Following this method recursively, a multilevel hierarchical network can be established. Three critical issues are addressed in this paper. We first analyze the optimal number of BNs for a layer in theory. Then, we propose a new stable clustering scheme to deploy the BNs. Finally LANMAR routing is extended to operate the physical hierarchy efficiently. Simulation results using GloMoSim show that our proposed schemes achieve good performance.**

I. Introduction

The ad hoc wireless networking technology shows great potential and importance in many situations because of its independence of a fixed infrastructure and its instant deployment and easy reconfiguration capabilities. Usually, a mobile ad hoc network (MANET) is assumed to be homogeneous. However, a flat ad hoc network has poor scalability[1][2][11]. In [1], theoretical analysis implies that even under the optimal circumstances, the throughput for each node declines rapidly toward zero while the number of nodes is increased. This is proved in an experimental study of scaling laws in ad hoc networks employing IEEE 802.11 radios presented in [2]. The measured per node throughput declines much faster in the real testbed than in theory. Simulation results in [10] also demonstrated that while routing protocols are applied, their control overhead would consume most available bandwidth when the traffic is heavy. Besides limitation of available bandwidth, the "many hop" paths in large-scale network are prone to break and cause many packet drops. Packet drops can be treated as waste of bandwidth and worsen network performance. All these issues prevent the flat ad hoc network from scaling to large-scale. Thus, a new methodology is needed for building a large-scale ad hoc network. An emerging promising solution is to build a physically hierarchical ad hoc network and mobile wireless backbones.

Our proposed hierarchical ad hoc network structure is called an ad hoc network with mobile backbones (MBN). A general picture of a two level MBN is illustrated in Fig. 1. Among the mobile nodes, some nodes, named backbone

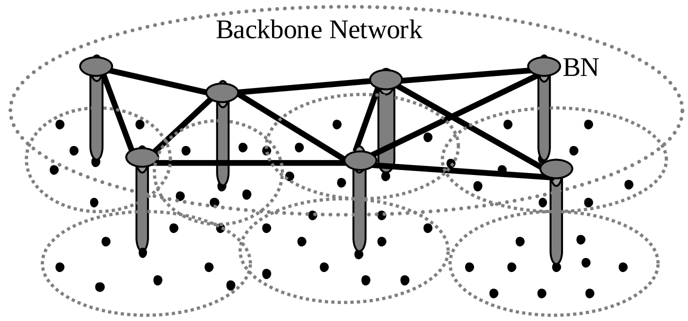

Fig. 1. General model of a two-level MBN

nodes (BNs), have an additional powerful radio to establish wireless links among themselves. Thus, they form a higher-level network called a backbone network. Since the backbone nodes are also moving and join or leave the backbone network dynamically, the backbone network is exactly an ad hoc network running in a different radio level. Multilevel MBNs can be formed recursively in the same way.

Three critical issues are involved in building such a MBN, the optimal number of BNs, BN deployment and routing. Since the backbone network is also a typical ad hoc network, its capacity follows the same scaling law mentioned above. In theory, multi-level MBNs can solve this problem. However, MBNs with too many levels are not easy to operate and suffer from hardware limitations (e.g. BNs need an additional powerful radio for each layer.). Thus, for a MBN with a few levels, we need to decide how many BNs are optimal for both the backbone network and the lower level cluster. In this paper, we give a simple theoretical analysis.

After the number of BNs is decided, the second important issue is how to deploy them around the whole terrain. The main difficulties are mobility and BN failures. Using clustering schemes to elect the BNs would be a natural choice since clustering has already been widely used to form logically hierarchical networks [6][7]. It is ideal for partitioning the large-scale network into small groups. However, a big drawback of current clustering schemes is the instability of clusters, as indicated in many papers such as [6]. Conventional clustering schemes work effectively only in networks with very low mobility, such as the sensor network. Instability of clusters would make the hierarchy too dynamic to be operated successfully. Frequent change of BN position will waste most routing information. In this paper, we will present a new fully distributed clustering scheme to achieve good stability.

Routing is another critical issue to effectively and efficiently operate such a hierarchical ad hoc network. The

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key idea is to utilize the wireless backbone links efficiently. The main challenge of our problem with respect to the general Internet routing problem is mobility: address prefixes would need to be continuously changed as nodes move! The ensuing address management problem is very complex and would offset the hierarchy advantages. In this paper, we extend the Landmark Ad Hoc Routing (LANMAR) [17][18], a scalable ad hoc routing scheme, into the MBN. As we will show, our mobile backbone routing scheme retains the simplicity of conventional ad hoc networks. In spite of the simple routing scheme, many of the typical backbone strategy benefits (such as short paths to remote nodes, small end-to-end delay, high quality link, enlarged network capacity, and QoS support etc.) can be successfully achieved. Backbone links can help reduce the "many hop" paths. By adapting the hierarchical structure, our routing scheme is also capable to reduce control overhead and propagate routing information promptly.

Rest of this paper is organized as follows. In section II, we analyze the optimal number of BNs in theory. In section III, we briefly explain why dynamic BN election is required to build a MBN, and introduce our new stable clustering scheme. We compare our clustering scheme with other popular ones regarding stability in section IV. In section V, we show how LANMAR routing is extended into a MBN. In section VI, our routing scheme is evaluated in a large-scale ad hoc network. Related work is given in section VII and we conclude our paper in section VIII.

II. Optimal Number of Backbone Nodes

According to [1], per node throughput under optimal circumstance of an ad hoc network with n mobile nodes is given as $\Theta(\frac{W}{\sqrt{n}})$ bits/sec, where W is the channel bandwidth and θ is the Knuth notation theta. Apparently, it declines rapidly while the number of nodes is increased. Thus, to improve the throughput, we should keep the number of mobile nodes small enough (e.g. fewer than 100 nodes). However, in large-scale networks, hundreds or even thousands of nodes are desired. The possible solution is to partition the mobile nodes into clusters. Each cluster elects a cluster head to carry traffic cross clusters. All cluster members only communicate with other nodes within the same cluster. Each local cluster now can be considered as a small ad hoc network. Since the number of nodes in a cluster is small, per node throughput can be greatly improved. In a MBN, the cluster heads are connected using powerful radios to form a higher-level backbone network. This backbone network is again an ad hoc network. Thus, per node throughput of a BN is also constrained by the number of BNs. To achieve good throughput in the local clusters, we would like to reduce the cluster size as small as we can. However, small cluster size means large number of BNs, which implies the poor throughput of the backbone network. Per node throughput of local clusters and that of backbone network are related at the BNs. A BN has per node throughput in both its local cluster and backbone network since it is equipped with multiple radios (These radios use separate spectrum and can work in parallel). They handle traffic in and out of the local clusters. In the best situation, each BN should have optimal throughput in both its local cluster and the backbone network to handle traffic across clusters.

We use Fig. 1 as a general model to analyze the optimal number of BNs. Let N denote the total number of mobile nodes (including BNs). In our analysis N is a constant. Variable m denotes the number of BNs. These N nodes are grouped into clusters around each BN. Under the optimal circumstance, if the network is partitioned equally, we can assume the average number of nodes in each cluster is N/m. Let W_1 and W_2 denote the channel bandwidth of the local cluster and the backbone network respectively. According to [1], the per node throughput of nodes within a cluster is given as (1).

$$R_{local} = \Theta(\frac{W_1}{\sqrt{N/m}}) \qquad (1)$$

The per node throughput of nodes in the backbone network is given as (2).

$$R_{backbone} = \Theta(\frac{W_2}{\sqrt{m}}) \qquad (2)$$

Since N is fixed, both R_{local} and $R_{backbone}$ are only functions of m. We now investigate a BN in detail. A BN has two interfaces, one for the local cluster and one for the backbone network. Traffic across clusters is switched at BN nodes from local interfaces to backbone interfaces, or vice versa. Assuming that network traffic is uniformly distributed, the portion of R_{local} of a BN used for traffic in/out to other clusters is (m-1)/m. This portion should be smaller or equal to $R_{backbone}$ of that BN. Otherwise, congestion will happen at that BN. Thus, we got the inequality (3).

$$\frac{m-1}{m} R_{local} \le R_{backbone} \qquad (3)$$

Now, our goal is to obtain the optimal $m=M^*$ under which $\frac{m-1}{m} R_{local}$ achieves the maximum throughput while still meeting inequality (3). We plot the curves of both $\frac{m-1}{m} R_{local}$ and $R_{backbone}$ in Fig. 2. Apparently, M^* is equal to the value of m where two curves intersect.

The meaning of M^* is that when $m < M^*$, the local clusters are congested and part of the bandwidth of the backbone network is wasted. While $m > M^*$, the backbone network is congested and unable to handle traffic at BNs.

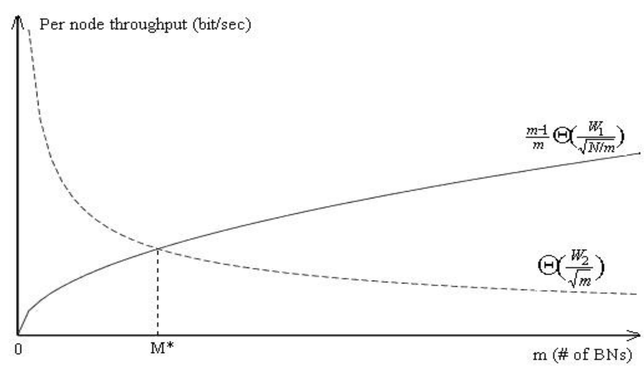


Fig. 2. Throughput as a function of # of BNs

Now, we calculate M^* using the upper bound of per node throughput. According to [1], the upper bounds of $\frac{m-1}{m} R_{local}$ and $R_{backbone}$ are given as $\frac{m-1}{m}\sqrt{\frac{8}{\pi}}\frac{W_1}{\Delta}\sqrt{\frac{N}{m}}$ and $\sqrt{\frac{8}{\pi}}\frac{W_2}{\Delta}\sqrt{m}$ respectively. Under $m=M^*$, they should be equal to each other. We get equation (4).

$$\frac{M^*-1}{M^*}\sqrt{\frac{8}{\pi}}\frac{W_1}{\Delta}\sqrt{\frac{N}{M^*}} = \sqrt{\frac{8}{\pi}}\frac{W_2}{\Delta}\sqrt{M^*} \qquad (4)$$

Solve (4), we get M^* as $\frac{W_2}{W_1}\sqrt{N}+1$. When N is large, which is usually true in large-scale networks, M^* is given as $\frac{W_2}{W_1}\sqrt{N}$.

III. Backbone Node Deployment and Clustering

After knowing optimal number of BNs, the second critical issue is how to deploy them. The simplest way is to pre-assign backbone nodes and scatters them around the terrain at the initialization. However, such a static deployment has two main problems. First, the BNs are also moving, thus after sometime, some BNs may move together (interfering to each other) while some areas may lack of BNs. This certainly is not a good scenario. The second problem is fault tolerance. BNs may fail or even be destroyed (considering the proposed application environment of the MANET). New BNs should be deployed to replace the defunct ones. Static deployment cannot fulfill these requirements. To solve these problems, our solution is to deploy redundant backbone capable nodes. Here, backbone capable nodes mean those mobile nodes, which have the physical radio capacity to communicate with other backbone nodes and join the backbone network. Since backbone capable nodes are in more ample supply than strictly needed, only parts of them become BNs. Others are kept as spare nodes. When one BN is destroyed or moves out of a certain area, a new BN will be selected from the backbone capable nodes to replace the old one. If two backbone nodes move near to each other, one of them will give up its backbone position. The way to select backbone nodes from capable nodes is called backbone election. It should be dynamically performed and the elected backbone nodes should disperse around the area. Clearly performing clustering among the backbone capable nodes is a good solution, as it has been widely used to form logically hierarchical ad hoc networks [6][7].

A. Random Competition based Clustering (RCC)

Many clustering schemes have been proposed in the literature, such as in [3][4][5][6]. Among them, the Lowest ID (LID) and Highest Degree (HD) algorithms are widely used due to their simplicity. The detail of the two algorithms can be found in [3][4]. Previous research in clustering mainly focuses on how to form clusters with a good shape such as minimum overlap of clusters etc. However, stability is also a serious problem to real application of the clustering schemes, especially when clustering is used to support routing. For the hierarchical structure, stability of backbone nodes is highly preferred. Existing schemes cannot meet such a requirement.

Targeting stability and simplicity, we designed a new Random Competition based Clustering (RCC) scheme. The main idea is that any node, which doesn't belong to any cluster, can initiate a cluster formation by broadcasting a packet to claim itself as a cluster head. The first node, which broadcast such a packet, will be elected as the cluster head by its neighbors. All its neighbor nodes, after hearing such a broadcast, give up their right to be a cluster head and become members of this cluster. Cluster heads have to periodically broadcast a cluster head claim packet to maintain their clusters. Since there is a delay from when one node broadcast its cluster head claim packet to when this packet is heard by its neighbors, several neighbor nodes may broadcast during this period. To reduce such concurrent broadcasts, we introduce a random timer. Each node defers a random time before its cluster head claim. If it hears a cluster head claim during this random time, it then gives up its broadcast. The idea of "first claim node wins" was first proposed in the passive clustering scheme in [8]. However, our scheme is active clustering and we introduce an explicit random timer to reduce conflicts. Of course, the random timer cannot completely solve the concurrent broadcast problem. When the concurrent broadcasts happen, we use node ID to solve the conflict. The node with lower ID becomes the cluster head.

Our Random Competition based Clustering (RCC) scheme is more stable than conventional clustering schemes such as LID and HD. In the LID scheme, when the cluster head hears a node with a lower ID, it will give up its cluster head role. Similarly, in the HD scheme, when a node with more neighbors appears, the cluster will also be reformed. Due to node mobility, such things may happen very frequently. In RCC, one node only gives up its cluster head position when another cluster head moves near to it. Since cluster heads are usually at least two hops away, clusters formed by RCC are much more stable.

The low control overhead of our scheme is clear. In the lowest ID and highest degree clustering schemes, each node has to know the complete information of neighbor nodes. In our scheme, only the cluster heads need to broadcast a small control packet periodically. All other nodes just keep silent.

B. Multihop Clustering

Usually the clustering schemes are one hop based, that is the cluster head can reach all members in one hop. This is not suitable for backbone node election. We want to control the number of elected BNs and make it approximate to the optimal number we got in section II. To achieve this, we extend clustering schemes to form K-hop clusters. Here, K-hop means that a cluster head can reach its members in at most K hops. By adjusting the parameter K, we can approximately control the number of cluster head. Bigger K means fewer cluster heads, thus fewer BNs. Note, only backbone capable nodes take part in the election.

To extend our clustering scheme to be multihop, each node now has to forward the cluster head claim packet from its cluster head. A mobile node will select the nearest cluster head within its K-hop scope to be its cluster head. When there is no any cluster head within its K-hop scope, it claims itself as a cluster head after deferring random time. In multihop clustering, the probability of concurrent cluster head claim is high due to the longer time for propagating cluster head claim packet K-hop away. The random time delay plays a very important role here.

IV. Simulation Evaluation of Clustering Algorithm

We use GloMoSim [16], a packet level network simulator for ad hoc networks, to evaluate our Random Competition based Clustering (RCC) algorithm. We first compare the stability of our algorithm with the Lowest ID (LID) and Highest Degree (HD) algorithms. Then, we study the relationship between number of elected BNs by RCC and the optimal number of BNs in theory. Since we are targeting large-scale networks, 1000 mobile nodes are deployed. The terrain size is as large as 3200mX3200m. Each mobile node has an IEEE 802.11 wireless radio with transmission range as 175m. The DCF mode of IEEE 802.11 is used and channel bandwidth is set to 2 Mbps, following the standard. Node mobility model is random waypoint mobility [14]. In our simulation, the pause time is kept as 30 seconds and we vary the mobility speed to observe the stability of clusters. Simulation time of each run is 6 minutes.

The stability of clusters includes two parts, stability of cluster head and stability of cluster members. We define two metrics, average lifetime of a cluster head and average membership time of a cluster member, to measure both kinds of stability. The average lifetime of a cluster head is defined as the average time period during which one node plays the role as a cluster head continuously. The average membership time is the average time that one mobile node remains in a cluster. These two metrics fully reflect the stability of clusters. In a MBN, average lifetime of a cluster head is exactly the average lifetime of a BN. In our simulation, we only implement the basic clustering scheme without considering the "gateway" node selection as in [3][4] etc.

A. *Cluster Stability*

Usually, clustering is performed to form one hop clusters. Thus, here we compare the stability of one-hop clusters. Simulation results are given in Fig. 3 and Fig. 4.

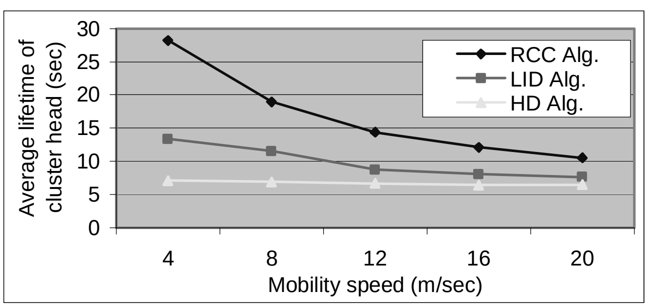


Fig. 3. Average lieftime of a cluster head

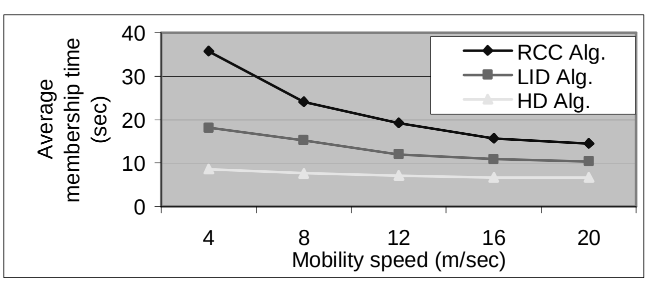


Fig. 4. Average membership time

From Fig. 3 and Fig. 4, we can see our clustering algorithm is more stable than the LID and HD algorithms under both low mobility and high mobility. Stability of the HD algorithm is the worst. This is due to the fact that the degree of one node is changing frequently under mobility.

B. *Multihop Backbone Election*

In this experiment, we want to figure out the relationship between the number of BNs elected by RCC and the optimal number of BNs in theory. We adjust the scope parameter K of RCC and observe the change of the number of elected BNs. We also calculate the optimal number of BNs in theory. The total number of mobile nodes involved is still 1000. Recall, the optimal number of BNs M^* is given as $\frac{W_2}{W_1}\sqrt{N}$. Usually $W_2 \geq W_1$. Here, we only calculate the M^* with $\frac{W_2}{W_1}=1$ and $\frac{W_2}{W_1}=2$. Results are shown in Fig. 5. Along with the increase of scope parameter K, the number of elected BNs decreases. Apparently, when $\frac{W_2}{W_1}=2$, optimal scope K is 2. If W_1 is equal to W_2, selecting scope as 4 or 5 elects BNs approximate to the optimal value.

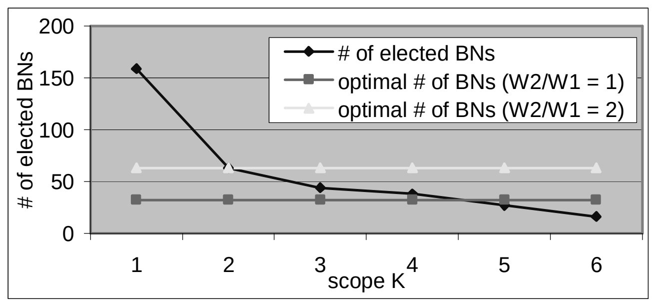


Fig. 5. # of elected BNs as a function of scope K

V. Routing Scheme

After number of BNs corresponding to the optimal value is elected, powerful radios are used to connect them and form the backbone network. The critical issue left is routing. The backbone links among BNs provide "short cut" and additional bandwidth. Routing schemes should be able to utilize them for remote destinations. Since BNs may fail or even be destroyed, fault tolerance and reliability are also important. In this section, we show how we extend the Landmark Ad Hoc Routing (LANMAR) [17][18] into a MBN.

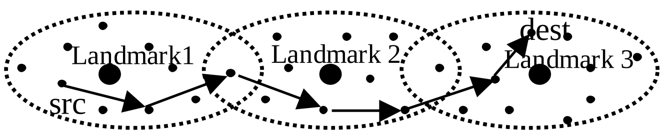
A. *Landmark Ad Hoc Routing (LANMAR)*

LANMAR is an efficient routing protocol in a "flat" ad hoc wireless network [17][18]. It assumes that the large-scale ad hoc network is grouped into logical subnets in which the members have a commonality of interests and are likely to move as a "group" (e.g., a team of co-workers at a convention). The existence of such logical group can be efficiently reflected in the addressing scheme. We assume that an IP like address is used consisting of a group ID (or subnet ID) and a host ID, i.e. <Group ID, Host ID>. The group ID may change from time to time as a node is reassigned to a different group (e.g. task force in a military scenario). The Host ID remains unchanged. LANMAR uses the notion of landmarks to keep track of such logical groups. Each logical group has one node serving as a "landmark". The route to a landmark is propagated throughout the network using a Distance Vector mechanism e.g. DSDV [15]. Further, the LANMAR routing scheme uses a local routing algorithm, e.g. Fisheye State Routing (FSR) [20] with the scope concept for local operation. That is, within the Fisheye scope, LANMAR runs link state routing. For nodes outside of the Fisheye scope, only landmark distance vectors are broadcasted. As a result, each node has detailed topology information about nodes within its Fisheye scope and has a distance and routing vector to all landmarks.

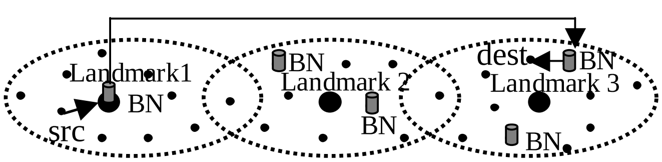
When a node needs to relay a packet, if the destination is within its Fisheye scope, accurate routing information is available from the Fisheye Routing Tables. The packet will be forwarded directly. Otherwise, the packet will be routed towards the landmark corresponding to the destination logical subnet, which is read from the logical address carried in the packet header. However, if the packet arrives within the scope of the destination before reaching the landmark, it is routed to it directly without going through landmarks.

B. LANMAR in the Mobile Backbone Network

LANMAR can be well integrated into the MBN by virtue of the fact that it is itself logically hierarchical. Routing information to remote nodes is summarized by landmarks. Now, we will extend such a logical hierarchical structure to utilize the physical hierarchy. In the original LANMAR scheme, we route the packet toward the corresponding remote landmark along a long multi-hop path. In the hierarchical MBN, we can route the packet to the nearest BN. It then forwards the packet to a remote BN near the remote landmark through the backbone links. Finally, the remote BN sends the packet to the remote landmark or directly to the destination if



LANMAR routing in ad hoc network without backbones



LANMAR routing in ad hoc network with backbones

it is within the BN's Fisheye scope. This will greatly reduce the number of hops. This procedure is illustrated in Fig. 6. We can see that by utilizing the backbone links, the 6 hop path is reduced to be 3 hops long, a great improvement!

Fig. 6. LANMAR routing in MBN

We extend the LANMAR routing protocol so that it can take the "short cut" described above. First, all mobile nodes, including ordinary nodes and BNs, are running the original LANMAR routing via the short-range radios. This is the foundation for falling back to "flat" multi-hop routing if BNs fail. Second, a BN will broadcast the landmark distance vectors to neighbor BNs via the backbone links. The neighbor BNs will treat this packet as a normal landmark update packet. Since this higher level path is usually shorter, it will replace the long multi-hop paths. From landmark updates the ordinary nodes thus learn the best path to the remote landmarks, including the paths that utilize the backbone links. Each BN needs to record the radio interface to the next hop on each path in order to route packets through the correct radios later.

One important feature of our routing scheme is reliability and fault tolerance. The ordinary nodes are prevented from knowing the backbone links explicitly. The backbone links are automatically learned via routing broadcasts of BNs. Now, suppose a BN of one group is destroyed by enemies, the shorter paths via this BN will soon expire. Then new landmark information broadcasted from other nodes will replace the expired information. Thus, in the worst case, routing in this group goes back to original landmark routing while other groups with BNs can still benefit from backbone links among themselves. When all backbone capable nodes are disabled, the whole network becomes a "flat" ad hoc network running the original LANMAR routing, which can still provide connectivity, yet at lower performance. So far, we have made no assumptions on MBN routing. In fact, we have assumed the simplest possible routing solution, with omnidirectional antennas, neighbor discovery, and distance vector routing support to landmarks. This scheme is sufficient to provide "short cut" benefits to LANMAR across the backbone. Clearly, more elaborate and efficient MBN configurations (e.g. point to point links) and routing schemes (e.g. Link State) can be proposed. We are currently investigating such directions.

VI. Performance Evaluation

In this section, we compare the LANMAR extension in MBN with the original LANMAR routing and AODV[13], a popular on-demand routing protocol, in the flat ad hoc network. The basic simulation environment is kept same as in section IV. 1000 mobile nodes are deployed. Each ordinary node has a small 802.11 wireless radio with power range 175m and channel bandwidth 2M as standard. The BNs have two 802.11 radios, one small radio same as the ordinary nodes and one powerful radio with power range 800m and channel bandwidth 5M. The mobility model is "group mobility" as presented in [19]. 30 CBR pairs on top of UDP are used to generate the traffic. The scope of backbone election is set to 2 according to the optimal value. We increase the node mobility from 0m/sec to 10m/sec to compare the performance. Results are shown in Fig. 7, 8.

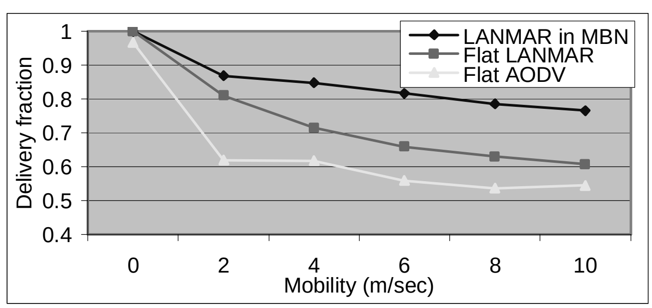


Fig. 7. Comparison of delivery fraction in mobility

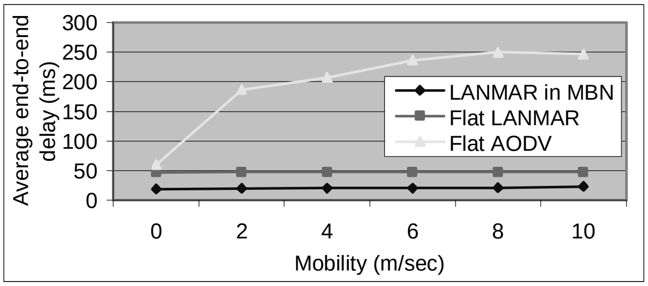


Fig. 8. Comparison of end-to-end delay in mobility

In Fig. 7 and Fig. 8, the performance of LANMAR in MBN apparently outperforms "flat" LANMAR and AODV, especially when nodes move. This is because it utilizes backbone links to reduce the number of hops of long hop paths. With mobility, the average end-to-end delay of AODV is greatly increased. This is due to the on-demand feature of AODV. While increasing the mobility speed, links break and path expirations are more frequent. AODV needs to delay packets as it searches new paths. In contrast, LANMAR and LANMAR extension in MBN are proactive, thus the average delay is not affected much by the mobility speed. LANMAR in MBN further reduce the delay using backbone links.

VII. Related Work

So far, we have not seen any related work on analyzing the network capacity of physically hierarchical ad hoc networks, BN election algorithms as well as the stability of BNs. Thus, our work on this part is novel. For routing in hierarchical structure, there is a considerable body of literature. In [12], routing in the UAV (Unmanned Aerial Vehicle) based hierarchical structure is investigated. In their scheme, clustering is also used to organize the network. However, it does not include multihop based algorithms. The routing scheme is fully folded on the hierarchical structure, which centralizes the traffic at the BNs and may cause congestions and single-point-failure problems. In contrast, our scheme of LANMAR extension in MBN shows advantages in terms of reliability and fault tolerance.

In [9], conventional on-demand routing schemes are extended into physically hierarchical networks. Their routing scheme does provide reliability and fault tolerance. Compared with it, our extension of LANMAR has some advantages since LANMAR has shown advantages over on-demand routing protocols in the flat ad hoc network [17][18]. These advantages still exist in the hierarchical structure. Specifically, their scheme inherits the long delay of the new path discovery, which certainly increases the end-to-end delay of data packets.

VIII. Conclusion

In this paper, we discussed major critical issues involved in building a hierarchical ad hoc network with mobile backbones (MBN). We first analyzed the optimal number of backbone node needed. Then, a new stable clustering scheme is proposed to deploy the BNs. We also proposed an extension of LANMAR routing to operate such a network efficiently. Backbone links are automatically selected by the routing scheme if they can reduce hop distance to remote destinations. Fault tolerance and system reliability are also considered and achieved. In essence, the proposed scheme combines the benefits of "flat" LANMAR routing and physical network hierarchy. Simulation results show that our proposed schemes can establish and operate a MBN effectively and efficiently. It can improve the network performance significantly and is robust to failures.

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