Available at
www.ComputerScienceWeb.com
POWERED BY SCIENCE DIRECT•

J. Parallel Distrib. Comput. 63 (2003) 110–122

Journal of
Parallel and
Distributed
Computing

http://www.elsevier.com/locate/jpdc

Landmark routing in ad hoc networks with mobile backbones[☆]

Kaixin Xu,* Xiaoyan Hong, and Mario Gerla

Computer Science Department, University of California, Los Angeles, 3803B Boelter Hall, Los Angeles, CA 90095, USA

Received 17 October 2002

Abstract

A mobile ad hoc network 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 through both theoretical analysis and simulation experiments and testbed measurements. This is further exacerbated by heavy routing overhead of ad hoc routing protocols when the network size is large. 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 stable and light overhead clustering scheme to deploy the BNs. Finally landmark ad hoc routing (LANMAR) is extended to operate the physical hierarchy efficiently. We show that the hierarchical LANMAR can incorporate and efficiently utilize backbone links to reach remote destinations (thus reducing the hop distance). Simulation results using GloMoSim confirm that our proposed schemes achieve good performance.

Keywords: Ad hoc network; Scalability; Mobile backbone network; LANMAR routing; Hierarchical ad hoc network

---

1. Introduction

The ad hoc wireless networking technology shows great potential and importance in many situations due to its independence of a fixed infrastructure, its instant deployment and easy reconfiguration capabilities. Usually, a mobile ad hoc network (MANET) is assumed to be homogeneous, i.e., all mobile nodes in the network share the same random access wireless channel with a single omnidirectional radio. However, a flat ad hoc network has poor scalability [8,15,16]. In [16], theoretical analysis implies that even under optimal network layout conditions, the throughput for each node declines rapidly towards 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 [15]. The measured per node throughput declines much faster in the real testbed than in theory. These results reflect that a "flat" ad hoc network has an inherent scalability problem. Besides the capacity limitation, ad hoc routing protocols also pose a heavy burden to the network. Flooding is usually adopted by routing protocols to search a path or propagate routing information. In large-scale network with mobility, routing overhead will consume a major fraction of the available bandwidth. This further limits the scalability of "flat" ad hoc networks.

Recognizing the performance limitations in large-scale ad hoc networks, in this paper, we propose a wireless hierarchy solution for ad hoc networks using mobile backbones. Applications of this kind of network will be very useful in disaster recovery and military applications, e.g., automated battlefields. The main challenge of such hierarchical network architecture with respect to the general Internet is routing under 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. As we will show, our mobile backbone

---

[☆] This work is partly supported by ONR "MINUTEMAN" project under contract N00014-01-C-0016 and TRW under a Graduate Student Fellowship award.

*Corresponding author. Fax: +1-310-825-7578.
E-mail addresses: xkx@cs.ucla.edu (K. Xu), hxy@cs.ucla.edu (X. Hong), gerla@cs.ucla.edu (M. Gerla).

0743-7315/03/$ - see front matter © 2003 Elsevier Science (USA). All rights reserved.
doi:10.1016/S0743-7315(02)00058-8

routing scheme retains the simplicity of traditional 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, QoS support, etc.) can be successfully achieved. In our proposed hierarchical network architecture, only a portion of the nodes with multiple radio capacities is required. These nodes are equipped with powerful radios in addition to general radios, which are supported by all the network nodes. The powerful radios will form higher-level backbone links, which can help reduce the "long hop" paths by adapting the hierarchical structure.

One may argue that using long-range radios at all nodes (not only the backbone nodes (BNs)) would reduce the number of hops. However, the ensuing spatial reuse constraint would dramatically reduce the network capacity as discussed in [16]. Thus, increasing the transmission range of all mobile nodes is not a cost-effective solution. The use of different frequencies (and different ranges) at different levels is a must for a scalable multilevel architecture. In this paper, we will consider only the two-level architecture case. While the proposed scheme extends to arbitrary level hierarchies, in practice a two-level solution is amply adequate for all ad hoc network applications one can envision in the near future (say, several thousands of mobile nodes). The two-level networks will require installation of dual mode radios (short and long range) in some nodes. Multiple radios are common practice in the military. Moreover, they are emerging also in commercial mobile devices. For example, future personal data assistants (PDAs) will have three radios—cellular, wireless LAN and Bluetooth. In our backbone strategy, however, we will notice that only a relatively small fraction of the nodes are elected to be "BNs". Thus, cost savings are possible by assuming that only a small pool of mobiles have two radios and thus are eligible backbone candidates. This actually happens in practice in large battlefield networks where only armored vehicles and unmanned airborne vehicles (UAVs) are backbone candidates—dismounted infantry cannot serve as BNs. The key requirement is that the fraction of candidates is large enough to assure an efficient backbone solution.

The main contributions of this paper are in two areas. The first area is the construction of the hierarchical network. A simple analytic model was developed to determine the optimal number of BNs as a function of system parameters. Then, a stable clustering scheme was developed to dynamically select BNs. Based on this dynamic election, a reconfigurable hierarchical network can be established and maintained in the face of mobility and BN changes/failures. The second area is "hierarchical" addressing and routing. We have developed a scheme that can take advantage of the "physical" network hierarchy and at the same time is robust to mobility. Consequently, our hierarchical routing scheme retains the simplicity of traditional ad hoc, flat routing, and at the same time, achieves all of the benefits (e.g., short paths to remote nodes, small end-to-end delay, high-quality link, enhanced network capacity, QoS support, etc.) offered by a physical hierarchy. In our proposed hierarchical network architecture, some nodes are equipped with multiple radios, with different ranges, and operate in different frequency spectra. The longer-range radios will form higher-level backbone links, which can help reduce the "long hop" paths.

The paper is organized as follows. In Section 2, we review the scalability problem of ad hoc routing protocols. The proposed hierarchical ad hoc network structure is presented in Section 3. In Section 4, an analytic model is used to derive the optimal number of BNs as a function of system parameters. In Section 5, we present our backbone election and deployment algorithm, and we evaluate it in Section 6. The landmark ad hoc routing (LANMAR) scheme is introduced and applied to the hierarchical structure in Section 7. In Section 8, we report simulation results evaluating the performance of the proposed hierarchical structure and compare it to other solutions. We review related work in Section 9 and conclude our paper in Section 10.

2. Scalability problem of ad hoc routing protocols

A considerable body of literature has addressed research on ad hoc routing protocols [5,10,17,18,19,20,23,24,27,29,30,32,33]. Most research is based on a "flat" ad hoc network model. Research has proven that many routing protocols work well in the "flat" network structure while the network size is small (with no more than one hundred nodes, say, in most situations). However, much larger ad hoc networks emerge in several application scenarios, such as in military or disaster recovery situations. Directly using the current "flat" ad hoc routing protocols in a large-scale setting will cause performance degradation [9,10,25,30]. Several reasons exist for this performance degradation. The first reason is longer paths from sources to destinations, which naturally occur in a large-scale network. In a typical case with existing radio power ranges and hundreds of nodes spread over a large terrain, the average number of hops between source and destination can easily exceed ten. A breakage of any single link on the path will cause failure. Even without failure, the average end-to-end delay and delay variance may be too large to be acceptable by time-critical applications. The second reason is heavy line overhead generated by routing protocols. Proactive routing protocols, such as DSDV [32], Fisheye [29] and OLSR [19], relying on periodic exchanges of routing information, cannot scale well because they propagate routing information throughout the whole network periodically. With mobility present, more frequent updates are required to keep the information accurate, thus producing a large amount of control overhead. In a large-scale mobile environment, the on-demand routing protocols such as AODV [33] and DSR [20], etc., which generate routing overhead only when there is data traffic to send, and thus have been traditionally considered more suitable for ad hoc wireless network, also tend to cause heavy overhead due to the large-scale flood search. The "long hop" paths are more prone to break due to mobility and expiration of cached routes, which in turn, cause new flood searches for new routes. In a mobile network example based on 100 nodes and 40 sources, the results in [9] illustrate that on-demand routing protocols will generate so much routing overhead that they alone will consume most network capacity. A similar study presented in [25] shows that DSR does not scale well to a large network size. The third drawback of "flat" routing in large, mobile networks is inaccurate routing information about remote nodes. With a large network size, routing information needs a long time to reach remote nodes. When it arrives, it may be already out of date. The stale paths lead to data packet drops on their way.

To overcome the above limitations, several techniques have been proposed to make ad hoc routing protocols more scalable [1,2,5–7,10,19,21,23,29,30]. For example, Fisheye [29] propagates link state packets with different frequencies to nodes inside vs. outside its Fisheye scope, respectively. OLSR [19] reduces the control packets by selecting only part of the neighbor nodes for packet broadcasting. TBRBF [5] reduces the LS update overhead in a Link State routing scheme by maintaining and sharing a tree for update broadcast. R-DSDV [6] introduces congestion control to the original DSDV [32] routing, thus limiting control overhead. LANMAR [10,30] uses a landmark node to represent a group of mobile nodes. The control overhead of on-demand routing protocols can also be reduced by repairing a broken route locally at the node, which experiences the link breakage, as is done in WAR [1,2]. Geographical information assisted routing such as LAR [23], GPSR [21] and GZRP [7] try to use the geographic information (typically from GPS) to achieve scalability. All of these schemes provide scalability improvements in the routing protocols themselves. However, the performance problems intrinsic of the "flat" ad hoc network structure (e.g., paths with many hops, etc.) still remain.

3. Mobile backbone network

The proposed mobile backbone network (MBN) is a hierarchical network in which a set of nodes functionally more capable than the ordinary nodes form the backbone. The basic scenario consists of a large number of mobile nodes deployed over a large area. Among these, the BNs have the ability of forming multilevel backbone networks using long-range radios. Usually, radios at each backbone level use some form of channel separation (e.g., antenna directivity, different codes, different frequencies, or combinations thereof) in order to minimize interference across levels. Radios in the same level share the same frequency and channel resources. Unlike the wired network, the nodes in the MBN are also moving, thus the backbone topology is dynamically changing. In many scenarios such as the battlefield, the hierarchical structure is an inherent feature of the application. Different units have different communication devices and capacities. For example, the wireless radios installed in military vehicles have a more ample energy supply and thus are more powerful than those carried by the dismounted soldiers. UAVs and even satellites can be used for providing higher level and broader reach connections. Fig. 1 illustrates a three-level hierarchy where the first level supports ground communications among soldiers; and the second and third levels are implemented using tanks and UAVs, respectively. In this paper, most of our discussions and simulations are based on a two-level hierarchical architecture. However, the routing and clustering algorithms and protocols can be easily extended to multilevel hierarchical networks.

Hierarchical ad hoc networks have great potential in real-time constrained applications, especially in the digitized battlefield. However, the backbone design is quite challenging if the nodes are mobile. Three critical issues are involved in building such an MBN, namely, optimal number of BNs, BN deployment and routing. In theory, a multilevel MBN can solve the scaling law problem observed in flat networks. However, MBNs with too many levels are not easy to operate and suffer from hardware limitations (e.g., each level requires an additional radio). Thus, one generally opts for an MBN with a few levels (say, two) and must decide the number of BNs.

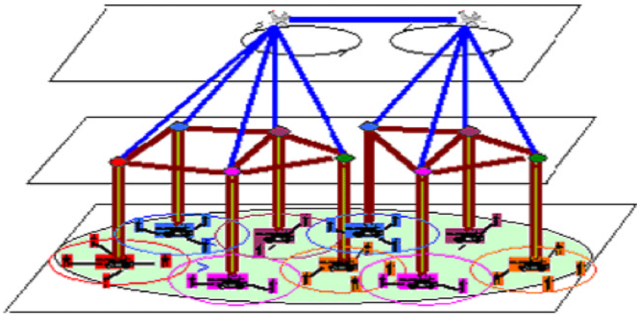


Fig. 1. Illustration of an ad hoc network with multilevel mobile backbones.

After the number of BNs is decided, the second issue is how to deploy them. The main difficulties are mobility and BN failures. Using a clustering scheme to elect the BNs is a natural choice. Clustering has been widely used to form logically hierarchical networks [3,35] and to partition a large-scale network into small groups. However, a drawback of current clustering schemes is cluster instability, as indicated in many papers such as [3]. Conventional clustering schemes work effectively only in networks with very low mobility or no mobility at all, such as the sensor networks. Instability of the clusters and frequent changes of BNs introduce high routing O/H and make the hierarchy difficult to operate. In this paper, we will present a new clustering scheme to achieve good stability.

Routing is the third critical issue: The main requirement is to utilize the wireless backbone links efficiently and in a robust way. The main challenge of MBN routing 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 would be very complex and would offset the hierarchy advantages.

In the following sections we will focus on addressing each one of these issues and then we will present our proposed schemes.

4. Optimal number of BNs

According to [16], per node throughput under optimal conditions in an ad hoc network with N mobile nodes is given as $\Theta(W/\sqrt{N})$ bits/s, where W is the channel bandwidth and Θ is the Knuth notation theta representing the order of complexity (i.e. $f(x)=\Theta(g(x))$ means that $f(x)=O(g(x))$ and $g(x)=O(f(x))$). This result assumes a uniform traffic pattern, while in most practical situations (and especially in large networks) traffic pattern exhibits strong locality. Thus, the above result is very conservative. Nevertheless, per node throughput declines rapidly when the number of nodes is increased, more so in wireless networks than in wired networks [16]. Thus, for efficient throughput performance, we should keep the number of mobile nodes small enough (e.g., fewer than 100 nodes). However, some important ad hoc applications (e.g., battlefield) have several thousand of node. A possible solution is to partition the mobile nodes into clusters. Each cluster elects a cluster head to carry traffic across 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. At a higher level, the cluster heads are connected using long-range radios to form a higher-level backbone network. This backbone network is again an ad hoc network. Thus, per node throughput decreases as the number of BNs increases. There is clearly a tradeoff. To achieve good throughput in the local clusters, we need to reduce cluster size. However, small cluster size means large number of BNs, which implies poor backbone throughput. The per node throughput of local clusters and that of the backbone network are interrelated and both depend on the number of BNs. We must find the number of BNs that optimizes total throughput.

Let N denote the total number of mobile nodes (including BNs). In our analysis N is a constant. The variable m denotes the number of BNs. These N nodes are grouped into clusters around each BN. Under optimal conditions, if the network is uniformly partitioned, we can assume that the average number of nodes in each cluster is N/m. Let W_1 and W_2 denote the radio bandwidth of the local cluster and the backbone network, respectively. Then per node *Throughput Rate* of a local cluster is given by

$$R_{\text{local}}=\Theta(W_1/\sqrt{N/m}). \tag{1}$$

Per node *Throughput Rate* of the backbone network is then given by

$$R_{\text{backbone}}=\Theta(W_2/\sqrt{m}). \tag{2}$$

Since N is fixed, both R_{local} and R_{backbone} are only functions of m. We now investigate the traffic at a BN. 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 backbone interfaces to local interfaces, or vice versa. The total traffic entering the backbone network is bounded by $m * R_{\text{backbone}}$. The traffic switched from backbone network to the local cluster at each node is given as $(m * R_{\text{backbone}})/m = R_{\text{backbone}}$. This portion of traffic must be smaller than the achievable bandwidth of the BN in the local cluster. Otherwise, congestion will occur at that BN. Thus, we can write the following inequality:

$$R_{\text{backbone}} \leqslant R_{\text{local}}. \tag{3}$$

Our goal is to obtain the optimal $m=M^*$ under which the BN achieves the maximum throughput while still satisfying inequality (3). We plot the curves of both R_{local} and R_{backbone} in Fig. 2. The optimal number of BNs, M^* is equal to the value of m where the 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.

Now, we calculate M^* using the upper bound of per node throughput. According to [16], the upper bounds of R_{local} and R_{backbone} are given as $\left(\sqrt{8/\pi}\right)(W_1/\Delta)\sqrt{N/m}$ and $\left(\sqrt{8/\pi}\right)(W_2/\Delta)\sqrt{m}$, respectively. Under $m=M^*$, they should be equal to

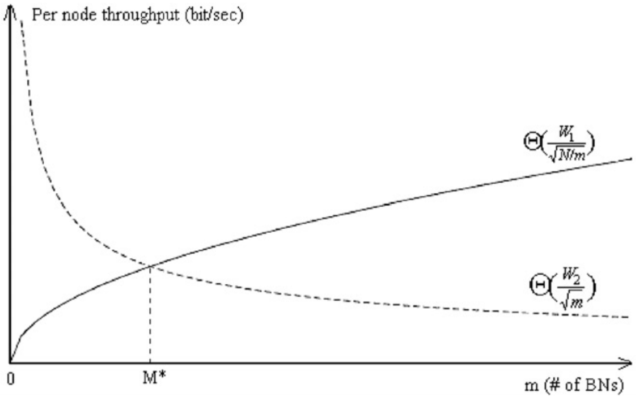


Fig. 2. Throughput as a function of number of BNs.

each other and get

$$\sqrt{\frac{8}{\pi}}\frac{W_1}{\Delta}\sqrt{\frac{N}{M^*}} = \sqrt{\frac{8}{\pi}}\frac{W_2}{\Delta}\sqrt{M^*}. \tag{4}$$

Solving (4), we get M^* as $(W_2/W_1)\sqrt{N}$. Note, above derivation assumes uniform distribution of traffic. If a traffic distribution other than uniform distribution is given, it needs some minor modifications.

5. BN deployment and clustering

After identifying the optimal number of BNs as a function of the number of nodes and channel bandwidths, the second critical issue is how to achieve an optimal BN deployment. The simplest way is to pre-assign BNs and scatter them uniformly across the field at initialization. However, such a static deployment has two main problems. First, the BNs are constantly moving. Thus after some time, some BNs may congregate in small geographical areas, creating congestion; while other areas may be depleted of BNs altogether. This certainly is not a good scenario. The second concern is fault tolerance. BNs may fail or even be destroyed (a likely event considering the emergency applications envisioned for MANETs). New BNs should be deployed to replace the defunct ones. Static deployment cannot fulfill these requirements. Our solution is to deploy some redundant backbone capable nodes (i.e., nodes with long-range radios) and to dynamically elect a proper subset to BNs. When one BN is destroyed or moves out of a certain area, a new BN will be selected from the backbone capable node pool. If two BNs move near to each other, one of them will give up its backbone role. The *BN election* is completely distributed and dynamic. It must result in a BN distribution that reflects the distribution of ordinary nodes. A *Distributed Clustering* algorithm is the most common approach to this problem [3,35]. In the next section we introduce a clustering algorithm that achieves these objectives.

5.1. *Random competition-based clustering*

Many clustering schemes have been proposed in the literature [3,12,24,26]. Among them, the lowest ID (LID) and highest degree (HD) algorithms are widely used due to their simplicity. The details of the two algorithms can be found in [12,26]. Previous research in clustering mainly focused on how to form clusters with good geographic properties such as minimum overlap of clusters etc. However, stability is probably the most critical property in applications involving mobility. This is because clustering is often used to support hierarchical routing. In particular, for the hierarchical structure, the stability of the BNs is important, and it directly depends on the stability of the clustering algorithm that elects them.

Targeting stability, simplicity and light overhead, we designed a new clustering scheme called random competition-based clustering (RCC). The main idea is that any node that does not belong to any cluster, can initiate a cluster formation by broadcasting a packet to claim itself as a cluster head. The first node, which broadcasts such a packet, will be elected as the cluster head by its neighbors. All the neighbors, 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" (CHCP) to maintain their role. Since there is a delay between CHCP broadcast and reception by neighbors, several neighbor nodes may simultaneously broadcast CHCPs. To reduce such concurrent broadcasts, we introduce a random timer. Each node defers by a random time before its cluster head claim. If it hears another cluster head claim during this random time, it gives up its broadcast. The idea of "first claim node wins" was first proposed in the passive clustering scheme in [11]. Due to the specific limitations imposed by "passive clustering" no timers were used in [11]. However, our scheme is "active clustering"; so, we introduce an explicit random timer to reduce conflicts. Of course, the random timer reduces, but cannot completely eliminate concurrent broadcasts. When a concurrent broadcast is detected, node ID resolves the conflict. The node with lower ID becomes the cluster head.

Our 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 gives up its cluster head position only 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 LID and HD clustering schemes, each node has to have complete neighbor information. In our scheme, only the cluster heads need to broadcast a small control packet periodically. All other nodes just keep silent.

5.2. *Multi-hop clustering*

Usually clustering schemes are single hop based that is the cluster head can reach all members in one hop. This is not suitable for BN election. We want to control the number of elected BNs and make it approximately equal to the optimal number we derived in Section 4. 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 control the number of elected cluster heads.

To extend our clustering scheme from single hop to multi-hop clustering, each node stamps hop distance (to its cluster head) in the CHCP and forwards it to its neighbors. A mobile node will select the nearest cluster head within its K-hop scope to be its cluster head. When there is no cluster head within its K-hop scope, a BN capable node (after deferring some random time) claims itself as a cluster head. In multi-hop clustering, the probability of concurrent cluster head claims is high due to the higher latency for propagating CHCP K-hop away. The random defer time plays an important role here.

6. Simulation evaluation of the clustering algorithm

6.1. *Simulation environment*

We use GloMoSim [37], a packet level simulator specifically designed for ad hoc networks, to evaluate the proposed RCC algorithm. We first compare its stability with that of the LID and HD algorithms. Then, we study the relationship between the number of elected BNs by RCC and the optimal number of BNs in theory. We also vary the fraction of backbone capable nodes among the total nodes to see its effect. Since we are targeting large-scale networks, 1000 mobile nodes are deployed. The field is a 3200 m × 3200 m square. Each mobile node has an IEEE 802.11b wireless radio with transmission range of 175 m. The DCF mode of IEEE 802.11 MAC is used and channel bandwidth is set to 2 Mbps. Node mobility model is random waypoint mobility [20]. Simulation time of each run is 6 min.

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. 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 uninterrupted. 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 an MBN, average lifetime of a cluster head is exactly the average lifetime of a BN. In our simulations, we only implement the basic clustering scheme without considering the “gateway” node selection feature as in [12,26], etc.

6.2. *Stability of clusters*

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

From Figs. 3 and 4, we can see that 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 very frequently under mobility. In our experiments, we have assumed that every node has capability to be a cluster head. In reality, only a small fraction (e.g., 10–25%) of

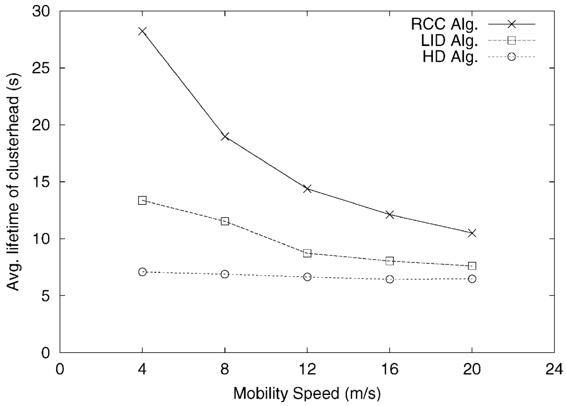


Fig. 3. Average lifetime of cluster heads.

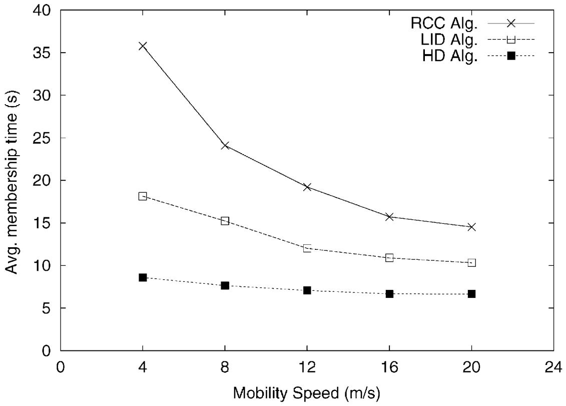


Fig. 4. Average membership time of cluster members.

the total mobile nodes are backbone capable. Thus, we expect clusters to be more stable as an established cluster head has fewer challengers.

6.3. Multi-hop BN election and optimal number of BNs

In this experiment, we show how the number of BNs elected by RCC can be made to closely approximate the optimal number predicted by theory. To this end, we run RCC with different values of scope K and monitor the number of elected BNs. We repeat this experiment for different fractions of backbone capable nodes. The total number of mobile nodes is 1000. Recall, that the optimal number of BNs M^* is given as $(W_2/W_1)\sqrt{N}$. Usually we have $W_2 \geqslant W_1$. Thus for $(W_2/W_1) = 1$ and $(W_2/W_1) = 2$ M^* takes the values 32 and 63, respectively, as shown in Fig. 5.

The X-axis in Fig. 5 is the scope K in terms of number of hops and the Y-axis is the number of elected BNs for different fractions of backbone capable nodes. The two horizontal lines represent the optimal number of BNs when W_2/W_1 is equal to 1 and 2, respectively. By adjusting the scope K of backbone election, we can control the number of elected BNs to achieve the optimal value. As the scope increases, the number of elected BNs decreases as expected. In the sequel, we wish to establish an approximate estimate of the number of BNs elected by the clustering algorithm as a function of the scope K. Based on the systems' characteristics (1000 nodes on a 3.2 km × 3.2 km square) and assuming for simplicity that nodes are placed on a grid, where each node has exactly 100 m distance to the neighbors in the grid, one easily finds the following upper bound on the average number of BNs as a function of scope K, as shown in Table 1.

To understand the above results, note first that the "upper bound" on number of BNs is obtained by seeking the "lower bound" on the cluster size. The smallest cluster occurs when the distance between two cluster heads is $K+1$. Then, a cluster with scope K includes all the members at hop distance $\leqslant (K+1)/2$. Finally, the number of backbone nodes BN is given by BN = 1000/cluster size. The number of BNs we get with this model is an upper bound on the real number, since our clusters are smaller than the actual average. The RCC algorithm with 100% BN capable nodes (see no. of BN elected by RCC in Table 1) comes very close to the analytic estimate developed above. Thus, when $(W_2/W_1) = 2$ and density is approximately 3–6 neighbors, the optimal scope K is around 2. If W_1 is equal to W_2, the scope should be $K = 4$. When the node density is changed, corresponding optimal scope K can be found in the same way.

Table 1
Upper bound on average number of BNs as a function of scope K

K (no. of hops)	1	2	3	4	5	6
Cluster Size (lower bound)	5	9	13	25	49	65
No. of BNs (upper bound)	200	111	76	40	20	15
No. of BNs elected by RCC	199	80	47	33	18	14

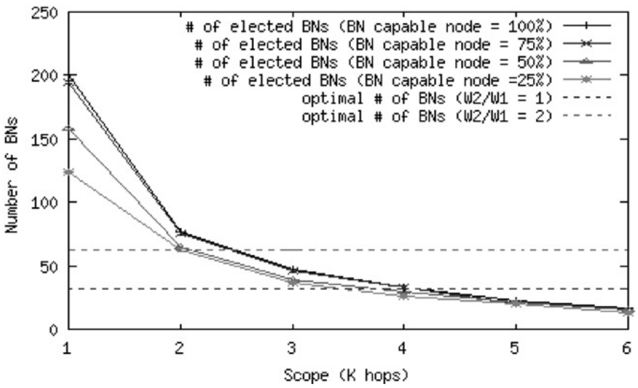


Fig. 5. Number of elected BNs as a function of scope K and the fraction of backbone capable nodes.

The fraction of BN capable nodes also affects the results, especially if the scope is small. With large scope, however, there is almost no difference. This is expected since when the scope is large, clusters are large, and there is a very good chance that a backbone capable node can be found in a large cluster, no matter how small the backbone capable fraction is. These results give us guidelines for deploying backbone capable nodes. For example, a 25% fraction seems to be more than adequate to support any scope larger than $K = 1$. Even smaller fractions will be adequate for larger scopes. This validates our argument that the proposed hierarchical structure is practical and does not require extensive node retrofitting. Only a small fraction of nodes needs a hardware upgrade.

7. Ad hoc routing with mobile backbones

Once elected, the BNs establish connections among each other using the long-range radios. The next issue is routing. The routing scheme in the MBN has some requirements: it must be able to exploit the high-level backbone links, enhancing throughput and delay with respect to scheme without a backbone. It must do so without compromising (in fact, possibly enhancing) scalability and fault tolerance. In fact, considering the emergency recovery, unfriendly or even hostile environments where ad hoc networks are deployed, the BNs can very possibly become disabled or may fail to operate. Maintaining connectivity in the face of BN failures is a strong requirement. Thus, the addressing and routing scheme cannot be totally "dependent" on the health of the backbone. For this reason, a cellular network like addressing and routing scheme will not work here. In a cellular network, the Home Location Register/Visiting Location Register (HLR/VLR) scheme will properly route the call request packet to the area where the roaming user has now registered. This requires that the Home Location of the user is up, and has a pointer to the Visited Location. In our MBN where BNs disappear and come up frequently, there is no reliable Home Location for any mobile. Redundant, robust Name Server schemes have been recently proposed [36], but they are not appropriate for our application, as their complexity would offset the advantages reaped by the hierarchical routing. To meet the challenges of our extremely volatile environment, we extend the LANMAR [10,30] to operate in the MBN. We call this solution hierarchical LANMAR routing (H-LANMAR). The details of H-LANMAR are presented in the following subsections.

7.1. LANMAR overview

LANMAR [10,30] is an efficient routing protocol designed for ad hoc networks that exhibit group mobility. Namely, one can identify logical subnets in which the members have a commonality of interests and are likely to move as a "group". The logical grouping is reflected in the address used within the ad hoc network, namely the two field address ⟨Group ID, Host ID⟩. One may notice a similarity between the group address and the IP address. In the group address the "network ID" is replaced by the "group ID." The Internet uses network IDs to drive the packet to its final destination. In the Internet, the networks have a temporal and geographical permanency. In a mobile ad hoc system, there are no permanent, geographically meaningful subnetworks. There are, instead, groups of nodes moving together. It is thus natural to exploit these temporally persistent groups to support the type of hierarchical routing used in the Internet. The Internet uses Link State or Distance Vector routing schemes. Instead, LANMAR uses the notion of landmarks to keep track of such logical groups. It uses an approach similar to the landmark hierarchical routing proposed in [38] for wired networks. Each logical group has one node serving as a "landmark". The landmark node is dynamically elected. The routes to landmarks are propagated throughout the network using a distance vector mechanism (in this study, we assume DSDV). In addition to landmark distance vector propagation, LANMAR relies also on a local, myopic routing algorithm (in this paper, we use Fisheye state routing (FSR) [29], with limited scope; but, any other proactive routing scheme could work, for example, OLSR [19], TBRBF [5], DSDV [32] etc). Within the Fisheye scope, LANMAR thus runs link state routing. For nodes outside of the Fisheye scope, only landmark distance vectors are broadcast. In local FSR routing, each node periodically exchanges in-scope topology information with its immediate neighbors. Updates carry the sequence numbers assigned by the sources. To the Fisheye update, the source also piggybacks a distance vector of all landmarks. Thus, in LANMAR each node has detailed topology information about nodes within its scope and has a distance and routing vector to all landmarks.

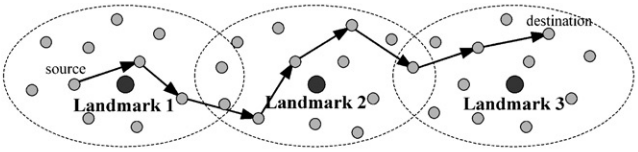
When a node needs to relay a packet to a destination that is within its Fisheye scope, it uses accurate routing information available from the Fisheye routing tables. The packet will be forwarded directly. Otherwise, the packet will be routed towards the landmark corresponding to the destination's logical subnet, carried in the packet header. When the packet arrives within the scope of the destination, it is routed to it directly (possibly without going through the landmark).

LANMAR reduces the control overhead largely through the truncation (i.e., scoping) of local routing tables and the "summarization" of routing information to remote groups of nodes. The above features reduce line and processing O/H and thus greatly improve routing scalability to large, mobile ad hoc networks. As a final note, we must stress that the LANMAR addressing and routing scheme has significance only within the ad hoc network (e.g., battlefield). Each node has also an IP address, which is distinct from the LANMAR address. Moreover, Mobile IP can be used to route packets from remote Hosts (in the internet) to the mobile user that happens to roam in an ad hoc network. If IPv6 is used, the LANMAR address can be stored in the local subnet address field. This way, the same IPv6 address can be used within the ad hoc network, and across wired and ad hoc networks [4].

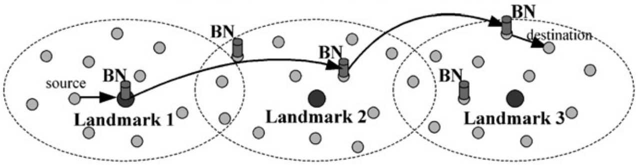
7.2. Hierarchical landmark ad hoc routing

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 towards the corresponding remote landmark along a long multi-hop path. In the hierarchical MBN, we can route the packet to the nearest BN, which then forwards it through a chain of MBN links to a remote BN near the remote landmark. Finally, the remote BN sends the packet to the remote landmark or directly to the destination if it is within its scope. This will greatly reduce the number of hops. The procedure is illustrated in Fig. 6. We can see that by utilizing the backbone links, the 8-hop path is reduced to be 4 hops long, a great improvement!

We extend the LANMAR routing protocol so that it can take the "short cut" described above. First, all



LANMAR Routing in an Ad Hoc Network without Backbones



H-LANMAR Routing in an Ad Hoc Network with Backbones

Fig. 6. Illustration of H-LANMAR routing in an MBN.

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 the higher-level paths are usually shorter, they will win over (and thus replace) the long multi-hop path in the level 1 network. From landmark updates the ordinary nodes thus learn the best path to the remote landmarks, including the paths that utilize the backbone links.

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 indirectly learned via BN routing broadcasts. Now, suppose a BN of one group is destroyed by enemies, the shorter paths via this BN will 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 level 1 LANMAR routing, which can still provide connectivity, yet at lower performance.

8. Performance evaluation

In this section, we present simulation results to compare the H-LANMAR in the MBN with the original LANMAR routing and AODV routing [33] in a "flat" ad hoc network. The purpose of these experiments is to show that how H-LANMAR running on top of MBN can improve the network performance effectively. Same network scenario as in previous experiments is used and channel bandwidths of the "short-range" and "long-range" radios are set to 2 and 4 Mbps (e.g., $W_2/W_1 = 2$), respectively. The scope of backbone election is fixed to be two, as under which number of elected BNs is approximate to the optimal value. To generate traffic 30 randomly selected CBR pairs are used. We increase the node mobility from 0 to 10 m/s to compare the performance. Results are given from Figs. 7–10.

In Fig. 7, the delivery fraction of H-LANMAR clearly outperforms "flat" LANMAR and AODV as

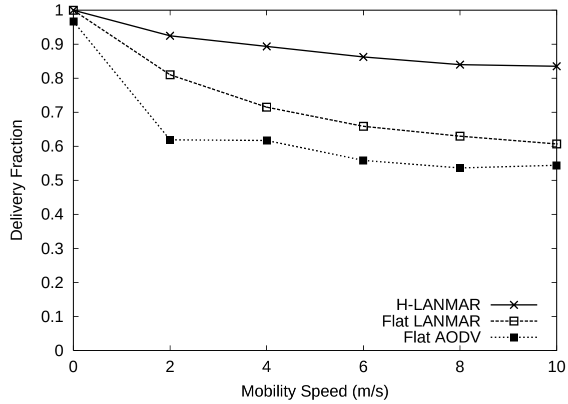


Fig. 7. Comparison of delivery fraction vs. mobility.

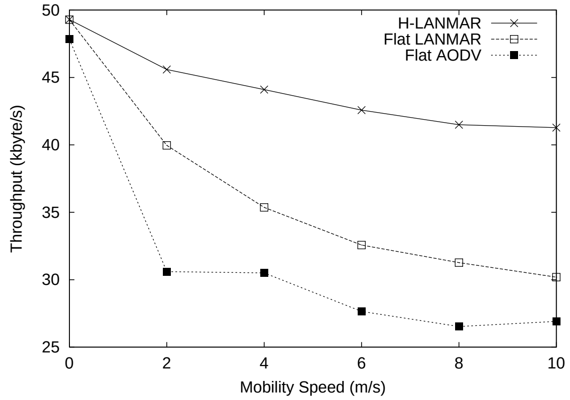


Fig. 8. Comparison of throughput vs. mobility.

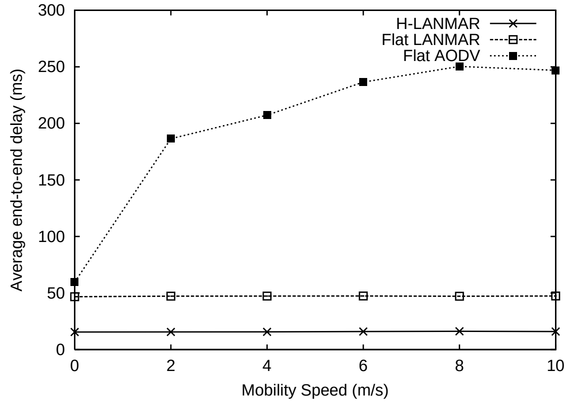


Fig. 9. Comparison of end-to-end delay vs. mobility.

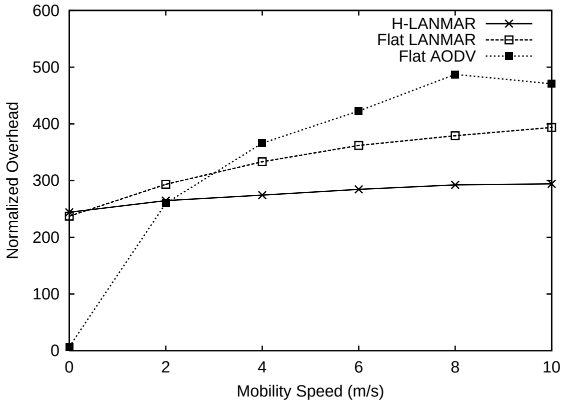


Fig. 10. Comparison of routing overhead vs. mobility.

mobility increases. Without mobility, all three protocols have delivery fraction nearly equal to 1. This is due to the fact that in a stationary network the routing information in the node routing table is always accurate. Only few packets are dropped on the way to destinations. Note that the CBR traffic load was chosen so as not to saturate the network. However, when the nodes are moving, routing information tends to become obsolete very rapidly. By utilizing the backbone links, H-LANMAR can propagate new routing information very quickly and efficiently and keep the routing table more up-to-date than the other schemes. This is the way H-LANMAR can achieve a high delivery fraction in high mobility while the other two degrade quickly. Similar results, this time in terms of network throughput, are reported in Fig. 8.

Fig. 9 shows average delay as a function of mobility speed. The average end-to-end delay of AODV increases rapidly with mobility speed. This is due to the on-demand routing maintenance feature of AODV. With increased mobility speed, path interruptions and expirations are more frequent. AODV delays packets in intermediate queues as it searches for new paths. In contrast, LANMAR and H-LANMAR are proactive and thus the average delay (of the packets that actually get delivered to destination) is not significantly affected by mobility speed. H-LANMAR further reduces the delay by using backbone links.

Fig. 10 gives the normalized routing overhead (NRO) of the three protocols. The NRO is defined as the number of routing packets used in order to route one data packet successfully. In low mobility or no mobility, the routing overhead of AODV is much smaller than LANMAR and H-LANMAR. In fact, AODV recomputes a route only when it expires because of lack of user traffic. Thus, its NRO is very small. However, with increasing mobility, the frequent link breaks and path expirations cause the overhead of AODV to increase sharply. As a result, the NRO increases very quickly. This is an indication that AODV has a scalability problem in large-scale, mobile ad hoc networks. Compared with AODV, the overhead of LANMAR and H-LANMAR is only minimally affected by mobility.

9. Related work

The use of clustering to self-organize the ad hoc network into some kind of hierarchy has been well studied in the past and several algorithms have appeared in the literature [12,24,26,28,31]. The clustering architecture can be recognized as a “logically hierarchical” structure. By utilizing the cluster information in routing schemes, the size of the routing tables and correspondingly routing control overhead is reduced. However, the “logical hierarchy” based routing protocols cannot completely solve the performance bottlenecks since they still face the challenges of space concurrency (between local and backbone transmissions), and of “long hop” paths and large end-to-end delays.

Some ad hoc network research results exploiting physical hierarchies have also been reported in the literature. In [34], a hierarchical structure for HDNet is presented. However, only the characteristics and qualitative advantages of the hierarchical structure are discussed. No detailed scheme for hierarchical routing is presented and evaluated. There are two schemes describing a physically hierarchical network and addressing routing in such a hierarchical structure. One is the UAV-based hierarchical structure with Extended Hierarchical State Routing (EHSR) in [13,14]. Another is the extension of on-demand routing schemes in physically hierarchical networks presented in [22]. We will discuss them in detail next.

9.1. Extended hierarchical state routing

EHSR [13,14] is an extension of hierarchical state routing (HSR) [31]. Like HSR, EHSR is a hierarchical “link state” routing protocol. Nodes are clustered into groups. The cluster heads at the lower level will become the members of the next higher level. Each node has a hierarchical ID (HID), which is defined as the sequence of the MAC addresses of the nodes on the path from the top hierarchy to the node itself. In terms of the hierarchical structure we described in this paper, EHSR has three levels, UAV network, backbone network and the ground ad hoc network. The HID of one node contains three parts, the UAV address, BN address and the address of the node itself. This HID is also a routing ID in that it completely defines the path within the hierarchy. The concept is similar to the prefix routing concept used in the Internet.

As a difference from the Internet, however, the nodes may move from one cluster to another. Thus the HID of a node needs to be dynamically updated. All other nodes must also be informed of such a change. To do so, a registration scheme similar to Mobile IP is used. Namely, each node has a permanent logical address and a home agent (HA) at which it registers its current HID. UAVs are ideal HAs for nodes within their areas. In order to form clusters, each BN broadcasts a beacon periodically. After hearing the beacon, a node can determine which cluster head it is closest to. Then, it can join that cluster. If the new cluster is different from the old cluster, the node updates its HID at the HA.

EHSR routing comes very naturally to the hierarchical network environment since it fully utilizes the higher-level links. However, it is fully dependent on the hierarchical structure and has several limitations, which can impact its performance. First, all traffic goes through BNs, even for communications between members of the same cluster. This will cause contention and congestion at the BNs. Secondly, strict EHSR routing requires that each node reach the BN in one hop. In other words, each group is actually a single hop cluster. This generates small size clusters. As a result, mobile nodes may frequently change clusters and trigger changes of HIDs. Third, the hierarchical nodes are vulnerable to attacks. Since the BNs must process all the local traffic, the destruction of a BN will break down the entire cluster. No packet forwarding can be done until a new cluster head is elected. This is in contrast with the automatic rerouting in H-LANMAR when a BN fails. HAs in EHSR are also critical points of failures. One can verify that most of the limitations of EHSR are solved by the HLANMAR scheme.

9.2. Extension of on-demand routing to hierarchical ad hoc networks

In [22], the traditional on-demand routing schemes are extended to operate on a physically hierarchical network. Nodes are divided into two types. One is Mini-mobile host (Mini-MH) with small transmit capacity and fast mobility speed. Another is Super-mobile host (Super-MH) with large transmit capacity and slow mobility speed. The Super-MH is similar to the BN in our architecture. However, the Super-MHs are connected via satellite links. Comparing with [22], our proposed scheme uses a multi-hop-based clustering algorithm to elect the BNs, which guarantees even distribution of BNs. Further, we also discussed the optimal number of BNs, thus presenting an optimal hierarchical structure. In [22] the BNs are pre-selected and the backbone topology selection is straightforward because of the use of the satellite links.

The routing scheme presented in [22] is basically on-demand routing. The route discovery procedure is divided into two parts. The Mini-MH first issues an Initial Route Discovery (IRD) packet to find a path to the nearest Super-MH. Then the Super-MH will take the responsibility to look for a route to the destination node by broadcasting a Remote Route Discovery (RRD) packet. The source nodes begin to send out the data packet just after discovering the presence of a nearby Super-MH. The routing scheme in [22] does provide reliability and fault tolerance. In the worst case, the whole network can turn into a "flat" ad hoc network running a traditional on-demand routing protocol. However, it still faces the same problems of on-demand routing schemes, such as excessive control overhead caused by broadcast-based route recovery and the long end-to-end delay caused by route discovery while the network is in large scale. Compared with it, H-LANMAR inherits advantages from LANMAR over on-demand routing protocols in "flat" ad hoc network. For example, hierarchical on-demand routing extension still delays data packets for path discovery, while H-LANMAR can provide a route immediately when a data session begins.

10. Conclusion

In this paper, we presented schemes to establish and operate a "physical" multilevel hierarchical ad hoc network with MBNs. The optimal numbers of BNs at each layer are derived through theoretical analysis. A stable multi-hop clustering scheme is also proposed to elect required BNs and organize the hierarchical network. For efficient routing in such a hierarchical structure, we proposed to use an extension of the LANMAR routing scheme. The LANMAR routing solution is the key to the feasibility and efficiency of the hierarchical structure. It is robust to mobility and yet reaps the benefits of the hierarchy. For example, backbone links are automatically selected by the routing scheme if they can reduce hop distance to remote destinations. Fault tolerance and system reliability of the proposed scheme have also been discussed. In essence, the proposed scheme combines the benefits of "flat" LANMAR routing and those of a physical network hierarchy. Simulation results using the Parsec/GloMoSim platform show that the proposed scheme significantly improves the performance of non-hierarchical schemes and that it is robust to failures.

References

[1] I.D. Aron, S.K.S. Gupta, A witness aided routing protocol for mobile ad hoc networks with unidirectional links, in: Proceedings of the First International Conference on Mobile Data Access, MDA '99, Hong Kong, December 1999, Lecture Notes in Computer Science, Vol. 1748, Springer, Berlin, 1999.

[2] I.D. Aron, S.K.S. Gupta, On the scalability of on-demand routing protocols for mobile ad hoc networks: an analytical study, J. Interconnect. Networks 2 (1) (2001) 5–30.

[3] S. Banerjee, S. Khuller, A clustering scheme for hierarchical control in multi-hop wireless networks, IEEE Infocom 2001, Anchorage, Alaska, April 2001.

[4] B.R. Bellur, M.G. Lewis, F.L. Templin, Tactical information operations for autonomous teams of unmanned aerial vehicles (UAVs), in: Proceedings of the IEEE Aerospace Conference, Big Sky, MT, March 2002.

[5] B. Bellur, R.G. Ogier, F.L. Templin, Topology broadcast based on reverse-path forwarding (TBRPF), draft-ietf-manet-tbrpf-02.txt INTERNET-DRAFT, MANET Working Group, September 2001.

[6] A. Boukerche, S.K. Das, A. Fabbri, Analysis of randomized congestion control with DSDV routing in ad hoc wireless networks, J. Parallel Distrib. Comput. (JPDC) 61 (2001) 967–995.

[7] A. Boukerche, S. Rogers, GPS Query optimization in mobile and wireless ad hoc networking, in: Proceedings of the Sixth IEEE Symposium on Computers and Communications, Hammamet, Tunisia, July 2001, pp. 198–203.

[8] M.S. Corson, Flat scalability—fact or fiction? in: ARO/DARPA Workshop on Mobile Ad Hoc Networking, College Park, MD, March 1997.

[9] S.R. Das, C.E. Perkins, E.M. Royer, Performance comparison of two on-demand routing protocols, in: Proceedings of the IEEE INFOCOM 2000, Tel Aviv, Israel, March 2000.

[10] M. Gerla, X. Hong, G. Pei, Landmark routing for large ad hoc wireless networks, in: Proceeding of the IEEE GLOBECOM 2000, San Francisco, CA, November 2000.

[11] M. Gerla, T.J. Kwon, G. Pei, On demand routing in large ad hoc wireless networks with passive clustering, in: Proceedings of the IEEE WCNC 2000, Chicago, IL, September 2000.

[12] M. Gerla, J.T. Tsai, Multicluster, mobile, multimedia radio network, ACM-Baltzer J. Wireless Networks 1 (3) (1995) 255–265.

[13] D.L. Gu, G. Pei, M. Gerla, X. Hong, Integrated hierarchical routing for heterogeneous multi-hop networks, in: Proceeding of the IEEE MILCOM 2000, Los Angeles, CA, October 2000.

[14] D.L. Gu, G. Pei, M. Gerla, X. Hong, UAV aided intelligent routing for ad hoc wireless networks, in: Proceeding of the IEEE WCNC 2000, Chicago, IL, September 2000.

[15] P. Gupta, R. Gray, P.R. Kumar, An experimental scaling law for ad hoc networks, May 16, 2001, http://black1.csl.uiuc.edu/~prkumar/

[16] P. Gupta, P.R. Kumar, The capacity of wireless networks, IEEE Trans. Inform. Theory IT-46 (2) (2000) 388–404.

[17] Z.J. Haas, M.R. Pearlman, P. Samar, The interzone routing protocol (IERP) for ad hoc networks, IETF Internet draft ⟨draft-ietf-manet-zone-ierp-01.txt⟩, June 2001.

[18] Z.J. Haas, M.R. Pearlman, P. Samar, The intrazone routing protocol (IARP) for ad hoc networks, IETF Internet draft ⟨draft-ietf-manet-zone-iarp-01.txt⟩, June 2001.

[19] P. Jacquet, P. Muhlethaler, et al., Optimized link state routing protocol, IETF Internet draft ⟨draft-ietf-manet-olsr-04.txt⟩, March 2001.

[20] D.B. Johnson, DA. Maltz, Dynamic source routing in ad hoc wireless networks, in: T. Imielinski, H. Korth (Eds.), Mobile Computing, 1996, Kluwer Academic, Dordrecht, pp. 153–181 (Chapter 5).

[21] B. Karp, H.T. Kung, GPSR: greedy perimeter stateless routing for wireless networks, in: Proceedings of the ACM MobiCom 2000, Boston, MA, August 2000.

[22] Y. Ko, N.H. Vaidya, A routing protocol for physically hierarchical ad hoc networks, Texas A&M University, Technical Report 97-010, September 1997.

[23] Y.B. Ko, N.H. Vaidya, Location-aided routing (LAR) in mobile ad hoc networks, in: Proceedings of the ACM/IEEE MOBICOM '98, Dallas, TX, October 1998.

[24] P. Krishna, N.H. Vaidya, M. Chatterjee, D.K. Pradhan, A cluster-based approach for routing in dynamic networks, in: ACM SIGCOMM Computer Communication Review, 1997, Vol. 27, No. 2, pp. 49–64, ACM Press, New York.

[25] J. Li, J. Jannotti, D.S.J. Couto, D.R. Karger, R. Morris, A scalable location service for geographic ad hoc routing, in: Proceedings of the ACM MobiCOM 2000, Boston, MA, August 2000.

[26] C.R. Lin, M. Gerla, Adaptive clustering for mobile networks, IEEE J. Select. Areas Comm. 15 (7) (1997) 1265–1275.

[27] V.D. Park, M.S. Corson, A highly adaptive distributed routing algorithm for mobile wireless networks, in: Proceedings of the IEEE INFOCOM '97, Kobe, Japan, April 1997.

[28] G. Pei, M. Gerla, Mobility management for hierarchical wireless networks, ACM Mobile Networks and Applications, 2001, Vol. 6, No. 4, pp. 331–337, ACM Press, New York.

[29] G. Pei, M. Gerla, T.W. Chen, Fisheye state routing in mobile ad hoc networks, in: Proceedings of the 2000 ICDCS workshops, Taipei, Taiwan, April 2000.

[30] G. Pei, M. Gerla, X. Hong, LANMAR: landmark routing for large scale wireless ad hoc networks with group mobility, in: Proceeding of the IEEE/ACM MobiHOC 2000, Boston, MA, August 2000.

[31] G. Pei, M. Gerla, X. Hong, C.C. Chiang, A wirelss hierarchical routing protocol with group mobility, in: Proceedings of the IEEE WCNC 1999, New Orleans, LA, September 1999.

[32] C. Perkins, P. Bhagwat, Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers, in: Proceeding of the ACM SIGCOMM, October 1994.

[33] C.E. Perkins, E.M. Royer, Ad-hoc on-demand distance vector routing, in: Proceedings of the IEEE WMCSA 1999, New Orleans, LA, February 1999.

[34] R. Sanchez, J. Evans, G. Minden, Networking on the battlefield: challenges in highly dynamic multi-hop wireless networks, in: Proceedings of the IEEE MILCOM '99, Atlantic City, NJ, October 1999.

[35] P. Sinha, R. Sivakumar, V. Bharghavan, Enhancing ad hoc routing with dynamic virtual infrastructures, IEEE Infocom 2001, Anchorage, AK, April 2001.

[36] I. Stoica, R. Morris, D. Karger, M.F. Kaashoek, H. Balakrishnan, Chord: a scalable peer-to-peer lookup service for internet applications, in: Proceedings of the ACM SIGCOMM '01, San Diego, CA, August 2001.

[37] M. Takai, L. Bajaj, R. Ahuja, R. Bagrodia, M. Gerla, GloMoSim: a scalable network simulation environment, Technical Report 990027, UCLA, Computer Science Department, 1999.

[38] P.F. Tsuchiya, The landmark hierarchy: a new hierarchy for routing in very large networks, Comput. Comm. Rev. 18 (4) (1988) 35–42.

Kaixin Xu is a Ph.D. student of the Computer Science department at UCLA. He joined the Network Research Lab. (NRL) of UCLA in 2000. His research focuses on the ad hoc wireless networking, especially protocols at MAC, Network and Transport layers. His recent work includes enhancing TCP performance in multi-hop ad hoc networks, TCP performance in IEEE 802.11 MAC based ad hoc networks, as well as MAC protocols for utilizing directional antennas and mobility track. He is also working on network protocols for building hierarchical ad hoc networks.

Xiaoyan Hong is a Ph.D. candidate at the Computer Science Department of the University of California at Los Angeles. She has been in the Wireless Adaptive Mobility Lab. since 1997. Her research is in the area of mobile computing and wireless networking, particularly ad hoc networks and energy concerned sensor networks. Her research interests include mobility issues, MAC protocols, unicast and multicast routing protocols, scalability, wireless network QoS support and adaptability.

Mario Gerla was born in Milan, Italy. He received a graduate degree in Engineering from the Politecnico di Milano, in 1966, and the M.S. and Ph.D. in Engineering from UCLA in 1970 and 1973, respectively. He joined the Faculty of the UCLA Computer Science Department in 1977. His research interests cover the performance evaluation, design and control of distributed computer communication systems, high-speed computer networks, wireless LANs (Bluetooth) and ad hoc wireless networks. He has been involved in the design, implementation and testing of wireless ad hoc network protocols (channel access, clustering, routing and transport) within the DARPA WAMIS, GloMo projects and most recently the ONR MINUTEMAN project. He has also carried out design and implementation of QoS routing, multicasting protocols and TCP transport for the Next Generation Internet. He is currently an Associate Editor for the IEEE Transactions on Networking.