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An efficient multiple-path routing protocol for ad hoc networks

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Abstract

An ad hoc network is a cooperative engagement of a collection of mobile hosts that requires no intervening of any centralized access point or existing infrastructure. Each mobile host, operating as a specialized router, forwards packets from other mobile hosts. The possibility of fast movement of mobile hosts means network topologies may change frequently. Thus, applying traditional routing schemes to ad hoc networks is inappropriate. In this paper, we present an efficient routing protocol called the multiple next hops (MNH) routing protocol, which is based on the ad hoc on-demand distance vector (AODV) routing protocol for ad hoc networks. The proposed MNH protocol establishes multiple paths for a route discovery procedure, thus conserving network bandwidth and reducing route reconstruction times when routing paths fail. Numerical experiments are given to show the effectiveness of the MNH routing protocol. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Ad hoc networking; Dynamic routing; Mobile networking

1. Introduction

The rapid development of the Internet enables people to get the required information easily and quickly. In particular, the emergence of *world wide web* makes the Internet a colorful and interesting world. The number of Internet users is growing dramatically. Since wireless networks emerged in the 1970s, they have become more and more popular on the Internet, mainly because they enable mobility. People can access information from the Internet and remain on-line. Technology has also made wireless device smaller, less expensive, and more powerful. Communication anytime and anywhere is no longer just a dream.

There are currently two varieties of mobile wireless networks, infrastructure mobile networks (i.e. networks with fixed and wired bridges) and infrastructureless mobile networks, commonly known as ad hoc networks. The bridges in infrastructure mobile networks are known as base stations. When a mobile host wants to communicate with another, it must find the nearest base station within its communication radius and then connect to the wired network through this base station in a single hop. An ad hoc network is a cooperative engagement of a collection of mobile hosts that requires no intervening centralized access point or existing infrastructure. In such a network, each mobile host must operate as a specialized router in order to maintain information about connectivity and to forward packets for other mobile hosts.

Some applications of ad hoc networks are as follows: (1) Military (tactical) communications for establishing communication infrastructures quickly during deployment of forces in foreign terrains, (2) rescue missions for communicating in areas without adequate wireless coverage, and (3) commercial use for setting up communication at exhibitions, conference, or sale presentations.

The three main challenges [1] in designing and operating ad hoc networks come from:

1. The lack of centralized entities: Ad hoc networks are unlike other cellular wireless networks (infrastructures) that have centralized entities, such as base stations, mobile switch centers, HLRs, VLRs, etc. Therefore, they require more complicated distributed algorithms that perform the functions of these centralized entities.
2. The possibility of rapid platform movement: In ad hoc networks, mobile hosts are likely to move in arbitrary fashion. This mobility causes network topology changes that result in connection lifetimes between hosts to vary greatly.
3. All communication is carried by the wireless medium: Wireless communication is easily interfered with, and the

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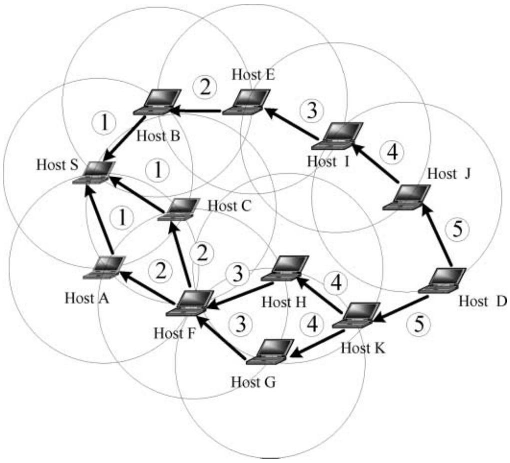


Fig. 1. An example of a route-request procedure.

connectivity between network nodes is not guaranteed, making intermittent and sporadic connectivity quite common.

Bandwidth and battery power are limited in wireless networks, and given the high mobility of mobile hosts and frequent link failures in wireless environments, conventional routing schemes for wired networks, such as distance Bellman–Ford (DBF) [2] or link state [3], are not appropriate because these conventional routing methods assume that networks are mostly stable and the routing overhead is negligible. Thus, they may lack the ability to reflect quickly the topology change that occur in ad hoc networks, or may incur excessive overhead that degrades network performance.

Many routing protocols have been proposed for ad hoc networks. These routing protocols can be divided into two types, table-driven and on-demand (source-initiated) [5].

Table-driven routing protocols are based on the DBF routing protocol. They attempt to use large number of control messages to get the latest and the most complete routing information. These routing protocols require that each mobile node stores up-to-date routing information in its routing table and responds to network topology changes by propagating update messages to all hosts in the network to maintain a consistent routing table. Typical table-driven routing protocols are destination-sequenced distance-vector routing [6], wireless routing protocol [7] and cluster-head gateway switch routing [8].

On-demand routing protocols create routes only when they are needed. When a node wants to communicate with another node, it initiates a route-discovery procedure. Once a route has been created, it is maintained by route-maintain procedure until either the route is no longer needed or the destination is gone. Typical on-demand routing protocols are dynamic source routing [9,10], ad hoc on-demand distance-vector routing (AODV) [4], associativity based routing [11], signal stability-based adaptive routing [12], the zone routing protocol [13] and the temporally ordered routing algorithm [14].

In this paper we present an efficient on-demand routing protocol, called the multiple next hops (MNH) routing protocol for ad hoc networks. We apply the concept of forward link and reverse link used in the AODV protocol. The main ideas of MNH are as follows.

1. Each mobile node maintains MNH in its routing table for a destination. Thus, MNH can provide multiple paths for a source–destination pair while AODV provides only a single path.
2. Each intermediate host maintains the routes and so it can reconstruct the routing if link failure occurs. This can reduce the number of route reconstructions and control messages required for the source to re-initiate a route.

The remainder of this paper is organized as follows. Section 2 describes the MNH routing method in detail. Section 3 presents simulation results, and the conclusions are given in Section 4.

2. Multiple next hops routing protocol

In ad hoc networks, each mobile host is free to move, so the topology of the network may change frequently. The goal of the MNH protocol is to provide up-to-date and real-time routing paths suitable for ad hoc networks. AODV provides only a single path and when links break due to mobility, AODV informs the source to initiate a new route using a route-request procedure. This leads to waste bandwidth and route searching time in finding a new route. Thus, if intermediate nodes maintain alternate routes instead of waiting for re-initiation, connections can be recovered much faster, which means network bandwidth consumption and the numbers of route request procedures invoked can be reduced.

In order to provide multiple paths, for a given destination each mobile host must have more than one next-hop field in its routing table. When a link fails due to movement, the intermediate nodes that detect the broken link are responsible for finding other routes using their routing tables. This is the main idea of the MNH protocol. In addition, we borrow the concept of destination sequence number from AODV to maintain the most recent routing information between nodes and ensure loop-free routing [4]. That is, each node maintains an increasing sequence number counter. The routing paths are labeled with destination sequence number whenever they are established. Below, we describe the operation of the MNH protocol.

2.1. Route request procedure

When a source node wants to communicate with a destination node and has no routing information about this destination, it initiates a *route-request procedure* to find a route

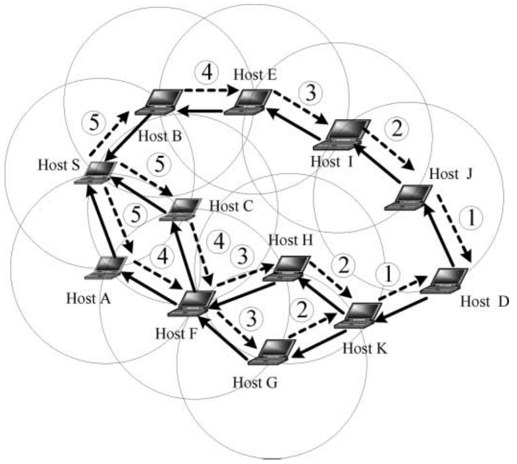


Fig. 2. An example of a route-reply procedure.

to the destination by broadcasting a route-request (RREQ) message to its neighbors as shown in Fig. 1 and sets a *route discovery expiration timer*. The purpose of this timer is to detect whether the destination is reachable or not. The route discovery expiration time depends on the size of the ad hoc network. The RREQ message contains the following fields: source address, destination address, source sequence number, destination sequence number, message identifier, hop limit and hop count. The message identifier is incremented whenever the source node issues a new RREQ message. The intermediate node uses the pair (source address, message identifier) to identify a RREQ message. When duplicate copies of RREQ arrive and their hop counts are greater than the hop count value recorded in routing table, they are discarded. The source sequence number is used to maintain freshness information about the reverse route to source, and destination sequence number specifies the most recent routing information of the route to destination maintained in source node.

When a node receives a RREQ message, it performs one of the following steps:

1. If the receiving node knows a route to the destination node, it checks to see if the route is current by comparing the destination sequence number in its own route entry to the destination sequence number in RREQ. If the destination sequence number in RREQ is not greater than that recorded in its own route entry, the intermediate node sends back a route reply (RREP) message.
2. If the receiving node does not know a route to the destination node or the destination sequence number in RREQ is greater than that recorded in its own route entry, it decreases the hop limit in RREQ by one. If the hop limit is zero, then discard the RREQ. Otherwise, the receiving node attempts to build reverse links to the nodes that sent the RREQ message and then re-broadcast the RREQ message to their neighbors.

Each intermediate node repeats above procedure until an intermediate node finds a route to the destination, or the destination is reached. When an intermediate node knows a route to the destination, or the destination node sends RREP message back along the reverse link, the route-request procedure is terminated.

In the example shown in Fig. 1, node S wants to communicate with node D, but it has no routing information about D in its routing table. It then initiates a route-request procedure to find the routes to D by first, S broadcasting RREQ message to its neighbors A, B and C. Initially A, B and C also have no routing information about D. So they build reverse links to S and send RREQ messages to their neighbors. That is, A and C send RREQ messages to F, and B sends an RREQ message to E. Note that F has two reverse links to A and C and will broadcast RREQ message to its neighbors once. (However, in AODV protocol, F only builds a reverse link to A or C and discards the RREQ message arriving later). Note that K builds two reverse links to G and H and ultimately an RREQ message will reach destination D.

2.2. Route reply procedure

After the route-request procedure, the RREQ message will arrive the destination or a node that possesses a route to the desired destination. Then the receiving node will send an RREP message to the source along the reverse links. The RREP message contains the following fields: source address, destination address, destination sequence number, message identifier, hop limit and hop count. Note that the message identifier is extracted from the RREQ message and the intermediate nodes use the pair (source address, message identifier) to identify a RREP message. As the RREP message travels to the source, each node along the reverse path will perform one of the following operations.

1. If the RREP message is a duplicate message from another neighbor, the receiving node will set up a forward link, update its routing table, and then discard the RREP message; otherwise, it will consider the message redundant and discard it.
2. If the RREP message is not a duplicate message and the receiving node is the source, then it will create a forward link, update its routing table and start communication.
3. If neither 1 nor 2 described above is true, the receiving nodes will create a forward link, update its routing table and send an RREP message back along the reverse link.

In MNH, each node may have more than one forward link while AODV each will have only one forward link. Hence, mobile nodes may have more than one next hop in their routing tables; we use this mechanism to provide multiple paths in our protocol. However, in MNH each node needs more memory space to keep multiple paths. Consider an ad hoc network of N nodes, which has m connections and assume that average length of the routing path is L. In the

Table 1
Routing table entries of mobile hosts to destination D

Source	Destination	Next hops
S	D	A, B, C
A	D	F
B	D	E
C	D	F
D	D	–
E	D	I
F	D	G, H
G	D	K
H	D	K
I	D	J
J	D	D
K	D	D

worst case, each node using MNH needs m routing entries and the network provides at least (N/L) paths for each connection. We can restrict the number of RREP messages replied by destination to at most k to reduce memory space needed for keeping multiple paths. In this case, the routing entries is reduced to $(k \times m \times L)/N$ and the network provides at least k paths for the connection. Similar, we can also restrict the number of next hops in each routing entry.

Fig. 2 shows an example of the route-reply procedure. As shown in Fig. 2, when J and K receive an RREP message from destination D, they create forward links to D and update routing their tables. J sends an RREP message back to I and K sends an RREP message to G and H. When G, H and I receive the RREP messages, they perform the same operations (e.g. create forward links, update their routing tables and send RREP messages back along the reverse links) until source node S receives the RREP message. S can then start communication. Reverse links, not on the RREP message path, will time out after their link validation times expired. Note that F has two next-hop fields, G and H, in its routing table. Thus, S has more than one route to D, e.g. S → A → F → G → K → D, S → B → E → I → J → D, and S → C → F → H → K → D. Table 1 shows a summary of the routing table entries of each mobile host to destination D.

2.3. Route maintenance procedure

Once a next hop becomes unreachable, upstream nodes must perform appropriate operations to recover the routing path. In the AODV routing protocol, an upstream node sends an error message to notify the source node when a link failure occurs. The source node then decides whether to re-initiate a *route-request procedure* or not. This is inefficient because the source node needs much time and many control messages to find a new route. If a new route can be found immediately, without initiating a route request procedure, then the network resources are saved and reconstruction times are reduced.

In the MNH routing protocol, intermediate nodes are responsible for finding new routes when the next hops become unreachable. This is done by maintaining multiple next-hops in each mobile host. When link failures occur during communication, upstream nodes detect the failures and eliminate invalid routes. Note that since mobile hosts send ‘hello’ messages periodically, they know the existence of their neighbors. Thus, broken links will be detected promptly by upstream nodes. If these upstream nodes have more than one next hop in their routing tables, they select new ones, otherwise they inform their upstream nodes along the reverse links. These upstream nodes then become responsible for reconstructing new routes. Thus, the number of new route reconstructions is reduced.

For example in Fig. 2, S has many routes to D, such as S → A → F → G → K → D, S → B → E → I → J → D, and S → C → F → H → K → D. If F detects a link failure, it will then find it has two next hops to D, G and H, and will immediately eliminate the invalid hop to G and choose another next hop to D. If (F,G) and (F,H) both break, F will eliminate the invalid routes and inform its upstream neighbors A and C. Since neither A nor C has a route to D, they will inform S of this so S can choose another route (e.g. S → B → E → I → J → D) to destination D and will not need to initiate a route-request procedure.

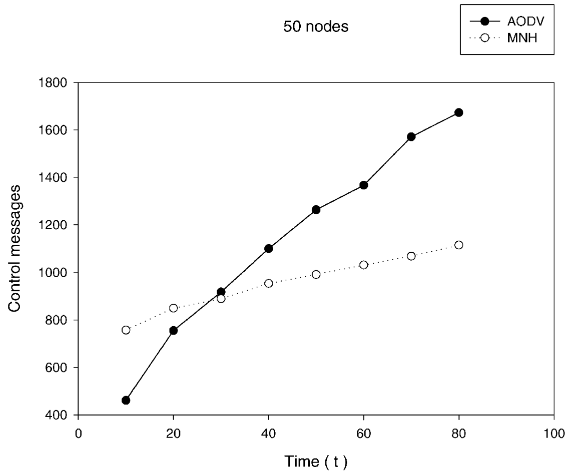
3. Simulation results

The performance of the MNH routing protocol is studied in this section. We first describe the simulation environment and mobility model, and then compare the performance of MNH and AODV.

3.1. Simulation environment

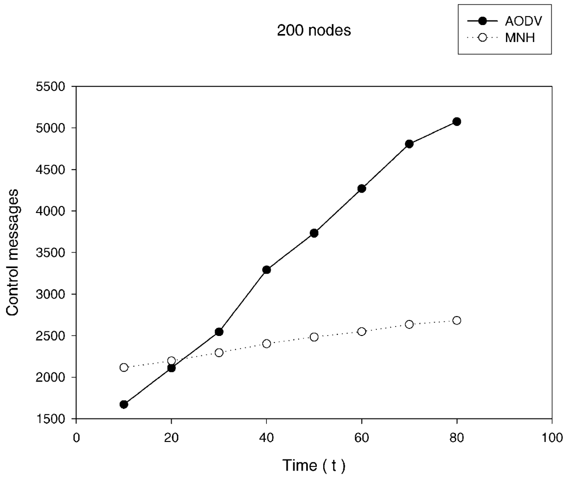
A simulator called PARSEC [15], which was developed at UCLA as the successor to Maisie [16], was used to simulate the AODV and MNH routing protocols. The PARSEC language is well suited for the simulation of dynamic topologies and routing algorithms. Our simulation ran on networks of 50, 100, and 200 nodes in room sizes of 30 m × 30 m, 50 m × 50 m and 100 m × 100 m, respectively. During the simulation, nodes were free to move anywhere within these areas according to the mobility model described below. Each mobile host could choose a speed from a uniform distribution between 0 and 2 m/s. Mobile hosts that reached the borders of their areas were turned back in the opposite direction. The inter-connection patterns of ad hoc networks were determined by the transmission ranges of the mobile hosts. In our simulation, we hold the transmission ranges constant at 8 m. The number of next hops for each routing entry was restricted to at most three. We also made the following assumptions:

1. Packets could be sent as long as links existed, and all errors were due to link failures.
2. The transmission ranges of all mobile hosts were the



$$\frac{AODV\_Average\_Control\_Message}{MNH\_Average\_Control\_Message}=1.19$$

Fig. 3. Control message comparison for 50 nodes (10 connections).



$$\frac{AODV\_Average\_Control\_Message}{MNH\_Average\_Control\_Message}=1.35$$

Fig. 5. Control message comparison for 200 nodes (10 connections).

same and they could hear each other when within their communication ranges.

3.2. Mobility model

The mobiles distributed in the coverage area could roam anywhere according to the following mobility model [17].

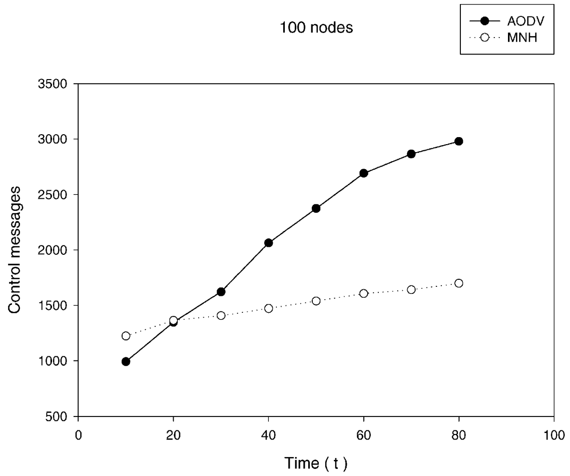
$$V(t+\Delta t)=\min\{\max\{V(t)+\Delta V,0\},V_{\max}\}$$

$$\theta(t+\Delta t)=\theta(t)+\Delta\theta$$

$$X(t+\Delta t)=X(t)+V(t)\cos\theta(t)$$

$$Y(t+\Delta t)=Y(t)+V(t)\sin\theta(t)$$

The movement of each mobile host is determined by its velocity vector (V, θ), where V is the mobile host's speed and θ is its direction, measured with respect to the positive x-axis. $V_{\max}$ is the maximum mobile velocity (i.e. 2 m/s). ΔV is the velocity change and is uniformly distributed within $(-A\times\Delta t, A\times\Delta t)$, where A is the maximum acceleration/deceleration of the mobile (i.e. 0.5 m/s^2). $\Delta\theta$ is the direction change and is a uniform distribution within $(-\alpha\times\Delta t, \alpha\times\Delta t)$ where α is the angular change of the mobile's direction per unit of time (i.e. 1). The position of each mobile host, (x, y) and its velocity (V, θ) were updated every Δt time interval (here, 1 s).



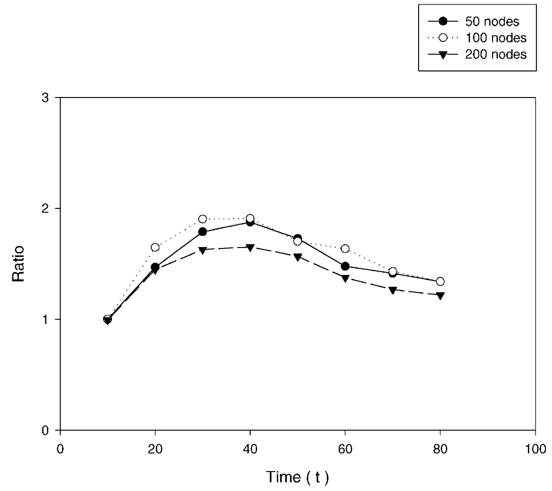
$$\frac{AODV\_Average\_Control\_Message}{MNH\_Average\_Control\_Message}=1.41$$

Fig. 4. Control message comparison for 100 nodes (10 connections).

3.3. Numerical results

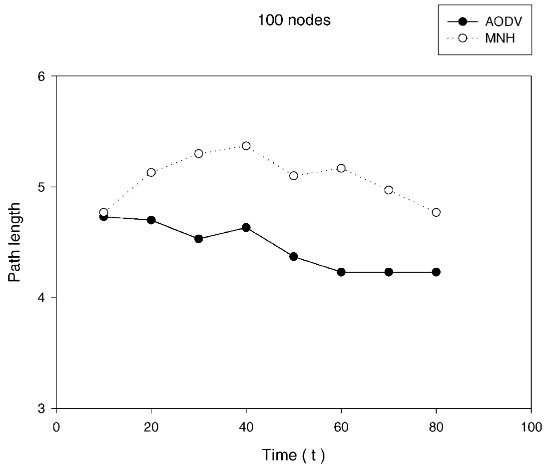
A comparison between the control messages used in MNH and AODV was made. Figs. 3–5 show the numbers of control messages used for 10 connections in networks with 50, 100 and 200 nodes, respectively. These figures show that the MNH routing protocol required fewer control messages than AODV. From Figs. 3–5, we note that initially, the MNH routing protocol requires more control messages to set up connections than the AODV because MNH routing protocol stored more information. As time went by, the control messages required by the MNH and AODV routing protocols increased, but AODV needed more control messages than MNH. In the AODV routing protocol, upstream nodes that detected the link failures notified the source node to initiate route-request procedures. While in the MNH protocol the upstream nodes that detected link failures only had to choose other routes from the next-hop field (if they existed) in their routing tables. Only in the worst cases when all upstream nodes did not have other routes to destinations will cause the MNH routing protocol to initiate route-request procedures. This explains why MNH needed fewer control messages than AODV over the long term.

Next, the route search times between MNH and AODV



$$Ratio_{avg} = \frac{AODV\_Route\_Search\_Time}{MNH\_Route\_Search\_Time} = 1.493$$

Fig. 6. Time-ratio comparison.



$$\frac{AODV\_Average\_path\_length}{MNH\_Average\_path\_length} = 1.138$$

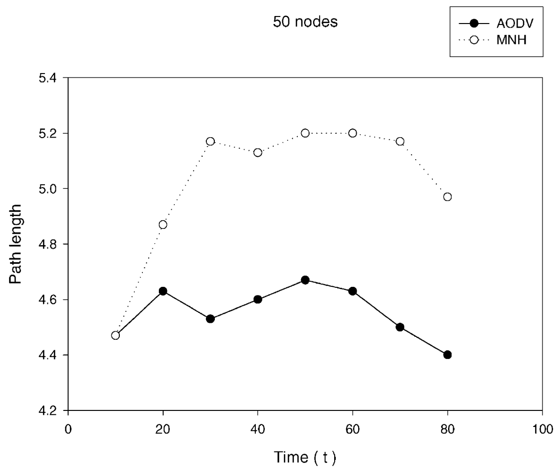
Fig. 8. Path-length comparison for 100 nodes.

were compared. Here, the route search-time is defined as the number of hops spent before a new route is found. For example, we have two routes from S to D in Fig. 2, S → A → F → G → K → D or S → C → F → H → K → D. If link (F,G) fails, the MNH routing protocol F need to select only H as its next hop to D, but the AODV routing protocol, require F to notify S via the path F → A → S, requiring 2 hops. Source S would then initiate a route-request procedure to find a new route, assuming the route is S → C → F → H → K → D, 10 hops (5 forward links and 5 reverse links) would be required. Thus, AODV would require 12 hops to find a new route vs. the 2 hops required by MNH. Fig. 6 shows the route-search time ratios of the AODV and MNH routing protocols.

AODV's routing metric is the shortest path, however, in MNH the shortest path is not guaranteed. Figs. 7–9 show the average path length comparisons for the AODV and MNH routing protocols compared in term of hops. The results show that the average path-length of the MNH routing protocol is one hop longer than the average AODV path-length.

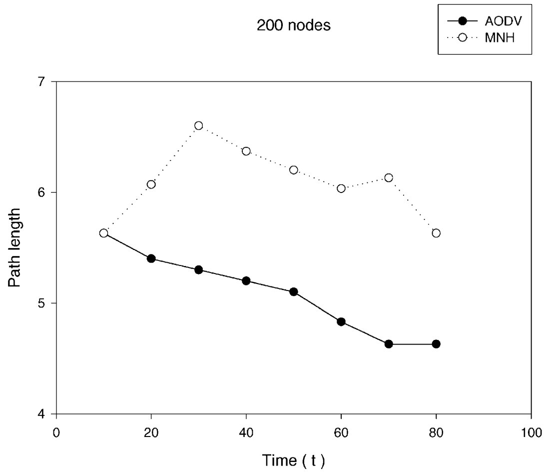
4. Conclusion

Ad hoc networks can be rapidly (ideally immediately) deployed without relying on pre-existing infrastructures. Because of possibly fast movement of nodes and rapidly changing propagation conditions, network information such as routing quickly becomes obsolete. Traditional



$$\frac{AODV\ \_Average\ \_Path\ \_Length}{MNH\ \_Average\ \_Path\ \_Length} = 1.104$$

Fig. 7. Path-length comparison for 50 nodes.



$$\frac{AODV\_Average\_path\_length}{MNH\_Average\_path\_length} = 1.195$$

Fig. 9. Path-length comparison for 200 nodes.

routing protocols such as distance-vector and link state rely on exchanging detailed routing information among nodes in networks and are not efficient in ad hoc networks.

In this paper, we have presented an efficient on-demand routing protocol, called as MNH protocol for the ad hoc networks. Compared to AODV, which only provides a single route to destination, MNH provides multiple alternate routes. These routes are maintained by intermediate nodes. This speeds up finding an alternate path when links fail. Using intermediate nodes to provide multiple alternate routes may need more memory space. However, the cost of semiconductor memory has been considerably reduced in nowadays.

Our simulation results show that the control messages and the route reconstruction times required to find an alternate route are reduced in MNH protocol. Therefore, we believe that MNH is an efficient routing protocol and is suitable for dynamic ad hoc networks.

Acknowledgements

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References

[1] Z.J. Haas, S. Tabrizi, On some challenges and design choices in ad hoc communications, IEEE MILCOM'98, pp. 187–192.

[2] D. Bertsekas, R. Gallager, Routing in Data Networks, 2nd ed, Prentice Hall, Englewood Cliffs, NJ, 1987 chapter 5.

[3] J.M. McQuillan, et al., The new routing algorithm for the ARPANET, IEEE Trans. Commun. (1980) 711–719.

[4] C.E. Perkins, E.M. Royer, Ad hoc on-demand distance vector routing, Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA'99. Second IEEE Workshop on, 1999, pp. 90–100.

[5] E.M. Royer, C.K. Toh, A review of current routing protocols for ad hoc mobile wireless networks, IEEE Personal Commun. April (1999) 46–55.

[6] C.E. Perkins, P. Bhagwat, Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers, SIGCOMM Conf. (1994) 234–244.

[7] S. Murthy, J.J. Garcia-Luna-Aceves, An efficient routing protocol for wireless networks, ACM Mobile Networks Appl. J. (1996) 183–197.

[8] C.C. Chiang, Routing in clustered multihop, mobile wireless networks with fading channel, IEEE SICON'97 (1997) 197–211.

[9] D.B. Johnson, D.A. Maltz, Protocols for adaptive wireless and mobile networking, IEEE Personal Commun. (1996) 34–42.

[10] D.B. Johnson, D.A. Maltz, Protocols for adaptive wireless and mobile networks, in: T. Lmielinski, H. Korth (Eds.), Mobile Computing, Kluwer, Dordrecht, 1996, pp. 153–181.

[11] C.K. Toh, A novel distributed routing protocol to support ad hoc mobile computing, 1996 IEEE 15th Annu. Int. Phonex Conf. Comp. Commun. (1996) 480–486.

[12] R. Dubr, C.D. Rais, S.K. Tripathi, Signal stability-based adaptive routing (SSA) for ad hoc mobile networks, IEEE Personal Commun. (1997) 36–45.

[13] Z.J. Hass, A new routing protocol for the reconfigurable wireless networks, IEEE Universal Personal Communications Record, Conference Record, 1997, pp. 562–566.

[14] V.D. Park, M.S. Corson, A highly adaptive distributed routing algorithm for mobile wireless networks, IEEE INFOCOM'97 (1997) 1405–1413.

[15] A. Alwan, R. Bagrodia, N. Bambos, M. Gerla, L. Kleinrock, J. Short, J. Villasenor, Adaptive mobile multimedia networks, IEEE Personal Commun. (1996) 34–51.

[16] R.L. Baggrodia, W. Liao, Maisie: a language for the design of efficient discrete-event simulations, IEEE Trans. Software Engng (1994) 191–198.

[17] Z.J. Hass, On the performance of a medium access control scheme for the reconfigurable wireless networks, MILCOM'97 (1997) 1558–1564.