Node-Disjoint Multipath Routing with Group Mobility in MANETs

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Abstract

Group mobility is quite usual in many realistic mobile and wireless environments, but it is rarely adopted in multipath routing. We propose a Group mobility-based Multipath Routing protocol (GMR) for large and dense mobile ad-hoc networks (MANETs). The GMR protocol adapts intra-group routing and inter-group routing to handle group mobility. The routing table maintained by a group leader is used to discover routes in intra-group routing, while the reactive routing, with the zoning method, is used to discover multiple node-disjoint paths in inter-group routing. The purpose of the zoning method is to ensure that a path is mapped to a separate zone, so that nodes are disjointed in multiple paths. Performance analysis and simulation results show that the proposed protocol provides satisfactory routing performance in large and dense networks with group mobility patterns.

Keywords: mobile ad-hoc networks, multipath routing, zoning method, node-disjoint paths, group mobility

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1. Introduction

A mobile ad-hoc network (MANET) consists of a set of mobile nodes that do not depend on any fixed infrastructure. *Entity mobility* and *group mobility* are well-known models that mimic the movements of mobile nodes [1]. Existing routing protocols include single path routing [2, 3] and multipath routing [4, 5, 13]; most of them are proposed based on entity mobility, where nodes move independently of each other. Compared with single path routing, multipath routing can improve robustness, load balancing, and throughput. Ad-hoc on-demand distance vector multipath (AODVM) [4] routing is a typical protocol, which guarantees finding multiple node-disjoint routes in a reactive way. Multiple zone-based (M-Zone) [5,13] protocol is a node-disjoint multipath routing based on geographic information.

Group mobility is very common in many applications, such as in battlefields, conference seminar sessions, and tourism scenarios. Nodes within a group have the same pattern so that it is efficient to select a group leader, or a cluster head, to represent the mobility of a group. The clustering algorithm for group mobility has been proposed in [6]. Landmark ad hoc routing (LANMAR) [7] and hierarchical state routing (HSR) [8] are single path routing protocols with group mobility. To the best of our knowledge, there does not exist any multipath routing with special consideration for group mobility in MANETs. In a large and dense network, the average length of a path increases, and it becomes easy for the path to break. If there is just one path between a source and a destination, it is very easy to result in frequent route rediscovery. Therefore, we propose a Group mobility-based Multipath Routing (GMR) protocol, where the network region between a source and a destination is divided into multiple zones based on geographic information. We call this method the *zoning method*, which ensures that each path is mapped to a separate zone, and thus, routing paths are node disjointed, except for the source and the destination. It is effective to use proactive routing when the network topology does not change quickly, so we adapt a proactive way within a group. As for routing among groups, we use reactive routing with the zoning method to discover multiple node-disjoint paths, because the network topology among different groups is dynamic.

The remainder of this paper is organized as follows: Section II introduces the network model. The design of the proposed GMR protocol is presented in Section III. Performance analysis is presented in Section IV. Simulation studies are conducted in Section V. We conclude this paper in Section VI.

2. Network Model

We consider that groups have been preset. This is very common in realistic applications, for example, in a battlefield, there are a great number of brigades, and different brigades have been arranged for different tasks in advance, thus different brigades are regarded as different groups with different movement trajectories. In this way, it is not necessary to partition or reorganize a group, and a group leader needs not to be selected frequently.

We assume that there are two types of nodes in the network: *super* nodes and *normal* nodes. Super nodes have more power, and stronger computational capability than normal nodes. This assumption is widely used in MANETs, such as in references [4, 9, 10]. Now, many modern hardware devices have multi-level radios, thus, super nodes are equipped with two-level radios: the long radio with long transmission range, and the short radio with short transmission range; while normal nodes only have short radio. We argue that this assumption is reasonable in practice [9, 10], e.g., on a battlefield, a mobile device equipped on a tank has a stronger capability than the one equipped on a foot soldier. Each node knows its geographic location by equipping it with a global positioning system (GPS) device.

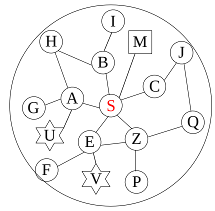


Figure 1. A group maintained by S

We adopt the reference point group mobility (RPGM) model [1], which is widely used and represents the random motion of a group of nodes, as well as the random motion of each individual node within the group. In the RPGM model, each group has a logical center. The motion of the logical center is calculated by a group motion vector, and it completely characterizes the movement of its corresponding group of nodes, including their direction, speed, and so on. Each individual node in a group has a reference point, whose movement depends on the group movement. Each node distributes and moves around this reference point.

Let the super node, which is the closest to the logical center, be a group leader, and other super nodes in the group be backup group leaders. Normal nodes and backup group leaders are called group members. The long radio is used for communication between group leaders, and the short radio is used for communication between a group leader and its group members, or among group members within the group.

3. The GMR Protocol

3.1. Intra-Group Routing

Intra-group routing means that a source and a destination are in the same group. Each group leader maintains a routing table of its group members, which is called the *intra-group routing table*. Each node has an identifier *group ID* to sign which group it belongs to, so that a group leader can identify its group members. Fig. 1 describes a group, where the group leader is *S*, and other nodes are group members, except for *M*, *U*, and *V*. Although *M*, *U*, and *V* lie in the geography of the group maintained by *S*, they belong to other groups, and it is easy for them to break away from this group. Therefore, *S* just needs to maintain the routing information of its group members. Since the topology of a group changes slowly, it will not cause large overhead for a group leader to maintain an intra-group routing table.

Table I shows the intra-group routing table maintained by the group leader *S*. There are two paths, *S-A-H* and *S-B-H* from *S* to *H* in Fig. 1, thus, *A* and *B* are put into the next-hop list in Table I. *S* can choose multiple paths or a path to its group members. The communication between a group leader and its group members can be carried according to the intra-group routing table, which is in a proactive way.

Within a group, each group member periodically broadcasts a message to its group leader with its *node ID* and current time stamp. *Node ID* is the global identifier of a node, which is given at the system start-up time. Other group members that have forwarded the message encapsulate their own node IDs into this message. Thus, when the group leader receives all those messages, it calculates the routes amongst all members, and then broadcasts the intra-group routing table to its group members. If the group leader does not receive messages from a group member for a certain period of time, it assumes that the group member has broken down, and then deletes the information of this group member from the routing table. If group members have not received messages from the group leader for a given time, they believe the group leader has failed. Then, backup group leaders communicate with each other by comparing their distance to the logical center in order to select a new group leader.

Table 1. Intra-group routing table

Destination	Next-Hop List	Others
A	A	TTL, Locations,...
B	B	TTL, Locations,...
H	A, B	TTL, Locations,...

The communication between two group members can be built by the aid of an intra-group routing table. Here, we do not consider intra-group routing in detail. In a large and dense network, we mainly focus on communication among groups, that is, the inter-group routing.

3.2. Inter-Group Routing

Inter-group routing means that a source and a destination are in different groups. Reactive routing is adaptive to a dynamic topology since a route is only built when needed, but it will cause large overhead in a large network with high node density. Then, we use reactive routing with the zoning method, which limits its routing overhead effectively, based on geographic information, to find multiple paths among groups.

A source knows the geographic location of a destination via some location service, which is assumed in most location-based routing protocols [3, 12]. If the source or the destination is a group member, it records the location of its group leader according to intra-group routing. There are eleven groups in Fig. 2, where the nodes with capital letters, such as *A*, *B*, and *C*, are group leaders, and others are group members, such as *a* and *b*. When a group member *a* intends to communicate with another group member *b*, *a* forwards packets, which contains geographic information of *b* and *D*, to *S* by using proactive routing at first, and then *S* forwards packets to *D* using long radio, according to reactive routing with the zoning method. At last, *D* communicates with *b* according to proactive routing.

The region between two group leaders is divided into *N* strip-shaped zones to discover *N* node-disjoint paths, where *N* is the number of node-disjoint paths. Each path is mapped to a distinct zone.

Let the coordinates of the source leader and the destination leader be (x_1, y_1) and (x_2, y_2), respectively, and the straight line *L* between two leaders is given by the equation $Ax + By + C = 0$, $A = y_2 - y_1$,

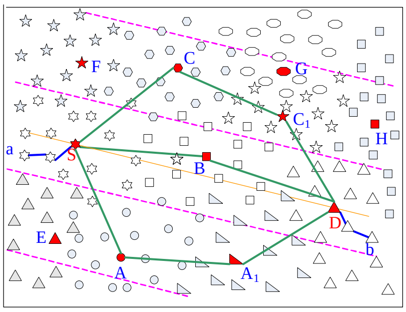


Figure 2. The routing process

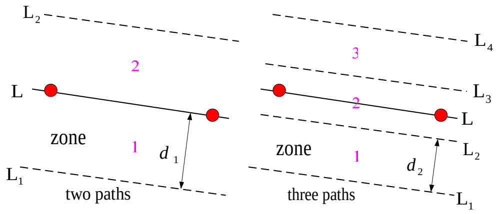


Figure 3. The division of zones

$B = x_1 - x_2$, and $C = x_2 y_1 - y_2 x_1$. A node obtains its distance to L using the following Eq. (1):

$$D_i = (Ax + By + C) \Big/ \sqrt{A^2 + B^2}, \tag{1}$$

where (x_i, y_i) denotes the geographic location of the node. The distance can be negative from Eq. (1) in order to confirm which zone the node belongs to. A zone is a strip-shaped region bounded by two lines based on their distance to L.

As shown in Fig. 3, for two paths, the ranges of the two zones are as follows: 1 $(-d_1, 0)$; 2 $(0, d_1)$.

For three paths, the ranges of the three zones are as follows: 1 $(-3d_2/2, -d_2/2)$; 2 $(-d_2/2, d_2/2)$; 3 $(d_2/2, 3d_2/2)$.

We take the three paths case as an example to describe the method of zone division more clearly: Zone 1 is within the range $(-3d_2/2, -d_2/2)$, where $-3d_2/2$ is the distance from the boundary L_1 to L, and $-d_2/2$ is the distance from the boundary L_2 to L. Zone 2 is within the range $(-d_2/2, d_2/2)$, where $-d_2/2$ is the distance from the boundary L_2 to L, and $d_2/2$ is the distance from the boundary L_3 to L. Zone 3 is within the range $(d_2/2, 3d_2/2)$, where $d_2/2$ is the distance from the boundary L_3 to L, and $3d_2/2$ is the distance from the boundary L_4 to L. Any node whose distance to L is within the range of a certain zone belongs to the corresponding zone.

Since nodes can be mobile, multiple zones need to be updated according to new locations of two leaders. It looks like multiple zones move periodically along with the movement of leaders, thus, it is called the *zoning method*. In the interest of simplification, we use Fig. 4, where only group leaders are shown to describe the inter-group routing with the zoning method in detail.

Fig. 4 shows that S forwards packets to D through three paths. S computes three zones according to the geographic locations of S and D. Then, S puts the information of the three zones into route request (RREQ) packets, and broadcasts RREQ packets in three zones via long radios. Sequence numbers are used to distinguish the freshness of a packet and prevent loops. When a neighbor group leader receives the RREQ packet, it checks whether or not it is closer to the destination than its previous node. If it is, it must increase the hop count, and record its previous node before broadcasting the RREQ packet in its zone. Otherwise, it discards this packet. When a group leader receives a duplicate RREQ packet, If the hop count in the new RREQ packet is smaller than that in the older one, the leader will forward this new RREQ packet again, otherwise, the packet will be discarded. In Fig. 4, C and F, which are neighbor leaders of S, receive the RREQ packet. F just discards the packet because F is farther from the destination than S. C is closer to D than S so that it broadcasts the RREQ packet in zone 3. G and C_1 receive the packet from C, and both of them are closer to D than C, so they continue to broadcast packets. When C_1 receives the RREQ packet from G, C_1 finds that it is a duplicate packet, and the hop count of this packet is larger than the older one, thus, C_1 just discards this packet.

Finally, when the destination D receives an RREQ packet in a zone, it does not reply to the RREQ packet at once, but waits a given time because the destination may receive more than one RREQ packet in a zone. D replies to the RREQ packet with the least hop count in each zone. Here, in zone 3, D receives two RREQ packets, and it selects the packet with the smaller hop count from C_1 to reply. When C_1 receives the route reply (RREP) packet from D, C_1 builds a reverse route

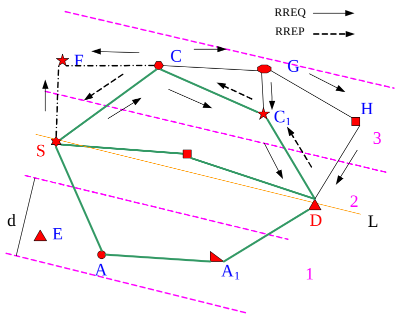


Figure 4. Three paths among groups

to *D*, and forwards this RREP packet to *C*. This route reply process continues until the source *S* receives the RREP packet; these intermediate nodes in the path of zone 3 can get a route to *D* for free. RREP packets in other zones are replied to *S* via the same procedure.

In this way, *S* obtains a shortest route in a zone to *D*, so that *S* forwards data packets to *D* through these three routes. Each route is mapped to a zone such that the three routes are node-disjoint. Each intermediate node in multiple paths records its next node and next-to-next node. If the path between a node and its next node breaks, the node will try to broadcast RREQ packets in the local region to find another node that can communicate with its next-to-next node. By using such local routing maintenance, the route can be repaired quickly, so that the lifetime of the routing can be lengthened.

4. Performance Analysis

The following properties are analyzed according to the following values: Let the distance between a source and a destination be *D*. *d* denotes the zone width and *N* denotes the number of paths. Network width is *W*, and network length is *L*. The average number of nodes in a group is *m*, the number of groups is *n*, and the number of the communication pairs is *e*.

The group density *p* is defined as the average number of groups residing in a unit area of one square meter. It can be computed via Eq. (2):

$$p = \frac{n}{WL} \tag{2}$$

Property 1: In multiple paths between a source and a destination, which are group leaders, the nodes are disjointed, except for the source and the destination.

Proof: For multiple paths between a source and a destination, each path is mapped to a distinct zone that is divided based on geographic information. Nodes in multiple paths belong to multiple zones, respectively, and there is a small probability that a node will lie at the boundary of two zones. If this does happen, the node will not be selected as a forwarder. Thus, nodes in different paths do not locate in the same zone, and they are disjointed, except for the source and the destination.

Property 2: For the given transmission of super nodes and group density, the zone width has to be bigger than the minimum value.

Proof: The minimum hops between a source and a destination is $\frac{D}{R}$, where *R* denotes the long transmission range of group leaders. For a zone, the number of group leaders is the group leader density *p* multiplied by the zone area. Thus, there are dDp groups in a zone region. To ensure finding a path in a zone, the number of group leaders of a zone must be bigger than the minimum number of leaders in the zone. Hence, we have $dDp > \frac{D}{R} - 1$, so $d > (\frac{1}{pR} - \frac{1}{Dp})$.

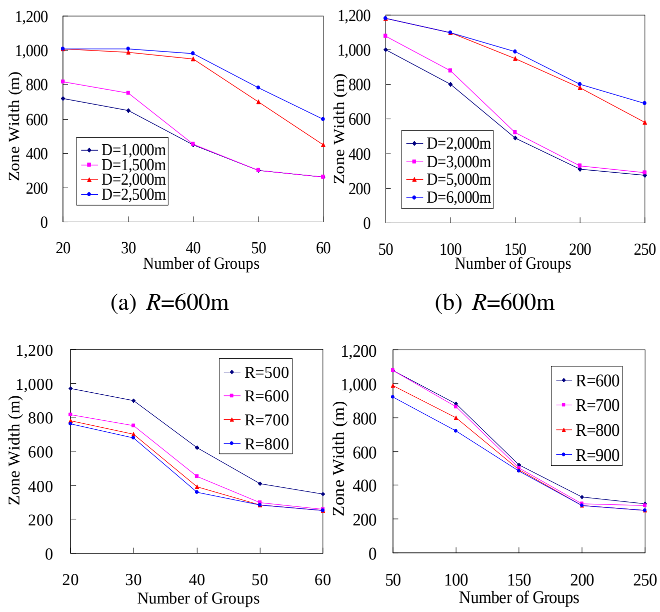
Property 3: For a given total zone width *Z* of a source and a destination, and a given group density *p*, the value of *N* has a great influence on the data packet delivery ratio.

Proof: The source forwards packets through multiple node-disjoint paths, simultaneously. If the destination receives data packets from one of these paths, then data packets are delivered successfully. Let the probability of a path to fail in a certain time be *f*, then the probability of *N* paths to fail is f^N. Thus, the data delivery ratio increases as *f* decreases.

For the given *Z* and *p*, the number of group leaders in a zone decreases as *N* increases. In other words, it becomes harder to find a path in a small zone width, where there are few group leaders. Even the source finds such a path, but it is easy for this path to break since nodes can move to other zones easily. Therefore, *f* decreases as *N* increases. To guarantee a certain data delivery ratio, *N* must to be selected very carefully considering the total zone width, and the number of groups.

Property 4: The control complexity of GMR is $O(mn + Npd\sqrt{W^2 + L^2})$.

Proof: The control complexity is caused by con-



(a) R=600m (b) R=600m

(c) D=1,500m (d) D=3,000m

Figure 5. Relationship between the zone width and the number of groups

trol packets. For the GMR, the control overhead is caused mostly by RREQ packets, and maintaining an intra-group routing table. RREP packets are ignored here because the number of RREP packets is much less than other control packets. Each group leader needs to broadcast m packets to maintain the routing table, then the total broadcast packets for maintaining the routing table in the network is nm.

The RREQ packets that are forwarded by GMR have a relationship with zone width d, group density p, and the number of paths N. In the worst case, it has to forward $Npd\sqrt{W^2+L^2}$ RREQ packets. Hence, the control overhead of GMR is $O(mn + Npd\sqrt{W^2+L^2})$.

Property 5: The communication complexity of GMR is $O(\sqrt{n})$.

Proof: The average path length increases as the network size increases. If the node density is constant, the average path length is expected to increase with the spatial diameter of the network. Since routing is mainly at the group leaders in GMR, and the maximum number of the group leaders is equal to the total number of groups n, the communication complexity in GMR is $O(\sqrt{n})$.

Property 6: The storage complexity of GMR is $O(m+e)$.

Proof: The storage complexity measures the order of the table size used by the protocols [11]. Each group leader maintains an intra-group routing table, and the average number of routing entries is m. A group leader also needs to record the number of communication pairs e. Thus, the storage complexity of GMR is $O(m+e)$.

5. Simulation Studies

OMNeT++ has become a popular simulation platform in the scientific community, with strong GUI support, and an embeddable simulation kernel. We simulate GMR, M-Zone, and AODVM in the Mobility Framework model of OMNeT++.

In the simulations, the speed of a group is uniformly distributed over [0, 2m/s], and the intra-group movement has been fixed to 2m/s. 2m/s is neither too slow, nor too fast, and this simulation speed is adapted widely, such as in reference [2]. The transmission range of normal nodes is 250m, and the transmission range of super nodes is 600m. We consider two network sizes, $2,000m \times 2,000m$ and $5,000m \times 5,000m$, and the simulation time is 400s. The average number of nodes in a group is 15. The following performance metrics are used in the simulations:

The Relationship between the zone width and the number of groups: Given the number of groups, this metric shows the minimum value of the zone width that make the average path length shortest.

Data packet delivery ratio: The number of data packets received by destinations divided by the number of data packets transmitted by sources.

Average path length: The average number of hops from all sources to destinations.

Routing overhead: The total number of control packets generated by all nodes during simulations.

Average path length and routing overhead are very important metrics, and they reflect throughput and delay in some way. Throughput increases, and delay decreases, as the path length and routing overhead decrease.

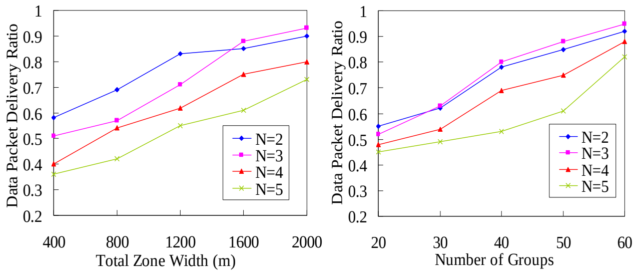


Figure 6. Left: data packet delivery ratio vs. total zone width; Right: data packet delivery ratio vs. the number of groups

Fig. 5(a) and Fig. 5(b) show the relationship between zone width and the number of groups in the $2,000m \times 2,000m$ and $5,000m \times 5,000m$ network sizes when transmission range is 600m. *D* denotes the distance between a source and a destination. Ten pairs of nodes, whose distances are equal to the given value *D*, are randomly selected to perform this simulation. The number of paths between a source and a destination is three. The zone width decreases as the number of groups increases in these two figures. This is due to the fact that when the number of groups is small, the group density is small too. It needs a larger width for GMR to find multiple paths. When the group density increases as the number of groups increases, it becomes easy for a source to find multiple paths to a destination in a comparatively small zone width, thus, the zone width decreases. When the distance between a source and a destination decreases, the zone width decreases too. When the group density is small, the decreasing trend of the zone width for short distance, such as $1,000m$ in the $2,000m \times 2,000m$ network size, and $2,000m$ in the $5,000m \times 5,000m$ network size, is faster than that for long distances, such as, $2,500m$ in the $2,000m \times 2,000m$ network size, and $5,000m$ in the $5,000m \times 5,000m$ network size. When the group density becomes very high, the decreasing trend of the zone width becomes slow. The zone width of long distances decreases quickly when the group density increases at a high value. We can deduce that the longer the distance between a source and a destination, the wider the zone width will be for them to find adequate routes.

When the distance between pairs of sources and destinations is $1,500m$ in the $2,000m \times 2,000m$ network size, and $3,000m$ in the $2,000m \times 2,000m$ network size, Fig. 5(c) and Fig. 5(d) show the relationship between the zone width and the number of groups for different long transmission range *R* of group leaders. The zone width is comparatively large when *R* is at a small value. This is because the number of neighbors of a group leader decreases as the transmission range of group leaders decreases for a given number of groups. It needs a large zone width to find multiple paths when *R* is small. When *R* becomes large, the number of neighbors for a group becomes large too. Then, for a comparatively small zone region, the group leader can find more neighbors to forward packets. Therefore, the long transmission range makes a great impact on the zone width.

Fig. 6 shows the results of the data packet delivery ratio for a different number of paths in network size $2,000m \times 2,000m$. In the left graph, the number of groups is 50, *N* denotes the number of paths. The data packet delivery ratio increases as the total zone width increases. When the total zone width is small, the data packet delivery ratio decreases as the value of *N* increases. When the total zone width becomes larger, the data packet delivery ratio of different *N* becomes close to each other. The results of the data packet delivery ratio are in accordance with the *Property* 3. Therefore, it is not a bigger value of N that causes a better data packet ratio. The given total zone width is $1600m$ in the right figure. As the number of groups increases, the data packet delivery ratio increases. The data packet delivery ratio of *N*=2 and *N*=3 is better than that of *N*=4 and *N*=5. Therefore, it is important to select a suitable value of *N*. Generally speaking, multipath routing protocols adapt 2 or 3 paths to forward packets. When *N* equals 2 or 3, the packet delivery ratio achieves impressive performance in our simulation. So, the zoning method used in the GMR protocol is a useful and effective way to find multiple node-disjoint paths.

Fig. 7 shows the results of the average path length in two network sizes: $2,000m \times 2,000m$ with 750 nodes and 50 groups, and $5,000m \times 5,000m$ with 2,250 nodes and 150 groups. We can see that the average path length of GMR is close to that of AODVM, and the average path length of M-Zone is the longest. The multiple paths of GMR are selected from the given

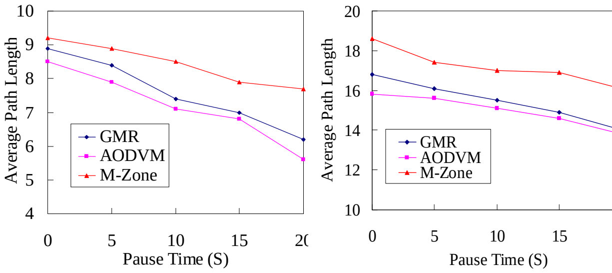


Figure 7. Average path length in two network sizes. Left: $2,000m \times 2,000m$ **with 750 nodes, 50 groups; Right:** $5,000m \times 5,000m$ **with 2,250 nodes, 150 groups**

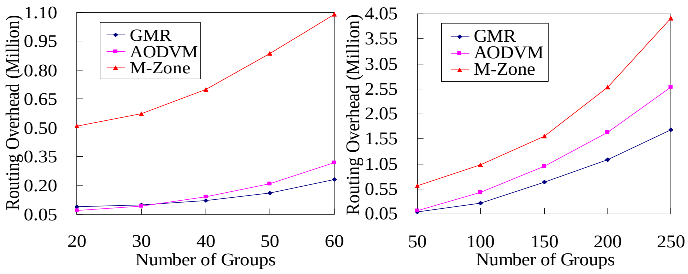


Figure 8. Routing overhead in two network sizes. Left: $2,000m \times 2,000m$**; Right:** $5,000m \times 5,000m$

zones, and each path is the shortest in a zone. For the M-Zone protocol, the segment of a path is the shortest in a local region, but for a whole path, it may not be the shortest in a zone. The multiple paths of AODVM are selected from the whole network; they are shorter than those of GMR. Since the network is very dense, the shortest paths are close to the region of the source and the destination, thus, the average path length of GMR is close to that of AODVM.

Fig. 8 shows the results of the routing overhead. When the number of groups is small, the overhead of GMR is low. The overhead of GMR increases according to the increase of the number of groups. The overhead of M-Zone is larger than that of AODVM and GMR, due to the fact that each node has to maintain a routing table of vicinity. For AODVM, when the number of groups is small, the overhead of AODVM is low too. But, when the number of groups becomes large, the overhead of AODVM increases faster than that of GMR, because the RREQ packets of AODVM are forwarded in the whole network, while the RREQ packets of GMR are forwarded in some given multiple zones. The relative velocity of nodes in a group is very slow, such that it will not cause large overhead to maintain an intra-group routing table of GMR.

The simulation studies show that GMR has advantages in the $5,000m \times 5,000m$ network size. Hence, GMR can be scaled to large and dense MANETs with group mobility by using intra-group routing and inter-group routing.

6. Conclusion

We have proposed a node-disjoint multipath routing protocol GMR with the group mobility model. The GMR protocol adopts intra-group routing and inter-group routing to adapt two situations: within a group and among groups. Intra-group routing uses a proactive method, which is suitable for the intra-group where nodes have the same mobile pattern. Inter-group routing uses a reactive method with the zoning method, which is adaptive to the dynamic topology, and limits the region of broadcasting RREQ packets. Thus, the GMR protocol has good scalability in large and dense MANETs.

The performance analysis and simulation studies show that the zoning method is effective in discovering multiple node-disjoint paths, especially when finding two or three paths. The average path length of the GMR protocol is close to that of AODVM, and the routing overhead of this protocol is lowest compared with AODVM and M-Zone. So, we can conclude that the proposed protocol has impressive performance in large and dense networks. Although we bring to attention some assumptions, they are reasonable and included in other papers. If there are holes (voids) in the network, avoiding holes becomes an important issue. As our future work, we are trying to find more effective solutions to tackle this problem, and we will consider the discovery of multiple paths in other group mobility models.

Acknowledgments

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