Multiclass Routing and Medium Access Control for Heterogeneous Mobile *Ad Hoc* Networks

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Abstract—Efficient routing is very important for mobile *ad hoc* networks (MANETs). Most existing routing protocols consider homogeneous *ad hoc* networks, in which all nodes are identical, i.e., they have the same communication capabilities and characteristics. Although a homogeneous network model is simple and easy to analyze, it misses important characteristics of many realistic MANETs such as military battlefield networks. In addition, a homogeneous *ad hoc* network suffers from poor performance limits and scalability. In many *ad hoc* networks, multiple types of nodes do coexist; and some nodes have larger transmission power, higher transmission data rate, better processing capability, and are more robust against bit errors and congestion than other nodes. Hence, a heterogeneous network model is more realistic and provides many advantages (e.g., leading to more efficient routing protocol design). In this paper, we present a new routing protocol called multiclass (MC) routing, which is specifically designed for heterogeneous MANETs. Moreover, we also design a new medium access control (MAC) protocol for heterogeneous MANETs, which is more efficient than IEEE 802.11b. Extensive simulation results demonstrate that the MC routing has very good performance, and outperforms a popular routing protocol—zone routing protocol, in terms of reliability, scalability, route discovery latency, overhead, as well as packet delay and throughput.

Index Terms—Heterogeneous networks, medium access control, mobile *ad hoc* networks, routing.

I. Introduction

MOBILE *ad hoc* networks are dynamic multi-hop wireless networks that are established by a group of mobile nodes on shared wireless channels. It is characterized by no fixed infrastructure, dynamic topologies, variable capacity links, limited physical security, bandwidth-constrained and energy-constrained operation. Routing in *ad hoc* networks has been extensively studied over the past few years [1]–[8], and many *ad hoc* routing protocols have been proposed. Most existing routing protocols assume homogeneous mobile *ad hoc* networks (MANETs), that is, all nodes in the network have the same characteristics, e.g., having the same transmission power (range), transmission data rate, processing capability, reliability,

and security level. However, a homogeneous *ad hoc* network suffers from poor scalability, i.e., the network performance is degraded quickly as the number of nodes increases, which has been demonstrated by theoretical analyses, simulation experiments and testbed measurements [4]. Furthermore, in many realistic *ad hoc* networks, nodes are actually heterogeneous [12]–[14]. For example, in a battlefield network, portable wireless devices are carried by soldiers, and more powerful and reliable communication devices are carried by vehicles, tanks, aircraft, and satellites; these devices/nodes have different communication characteristics in terms of transmission power, data rate, processing capability, reliability, etc. So, it would be more realistic to model these network elements as different types of nodes. There are also many advantages that can be utilized to design more efficient routing protocols when nodes are modeled as different types.

In this paper, we propose a new routing protocol called multiclass (MC) routing, for heterogeneous MANETs. MC routing achieves good performance by exploiting node heterogeneity in many MANETs. Moreover, to further improve the performance of MC routing, we take a cross-layer approach and design a new medium access control (MAC) protocol called hybrid MAC (HMAC) to cooperate with MC routing. Extensive simulation results demonstrate that the MC routing achieves very good performance, and outperforms a popular routing protocol— zone routing protocol [1], in terms of reliability, scalability, route discovery latency, overhead, as well as packet delay and throughput. In addition, our results show that MC routing is more efficient with HMAC than with IEEE 802.11b.

The rest of the paper is organized as below. Section II discusses the related work. Section III presents our MC routing protocol. In Section IV, we compare the MC routing with zone routing protocol through extensive simulations. Section V concludes the paper.

II. Related Work

We classify the related work in four aspects. First, Xu *et al.* [4] propose MBN routing protocol based on backbone nodes. Although our MC protocol also utilizes backbone node, MC is different from MBN in selecting backbone nodes and routing packets through backbone nodes. Second, Ye *et al.* [7] consider heterogeneous MANETs, and they propose to place additional reliable nodes to assist routing. In contrast, MC routing does not consider placing additional reliable nodes in the network; instead, it utilizes existing nodes in heterogeneous MANETs. Some other papers [6] and [9] also address node heterogeneity. However, they mainly discuss how to solve the
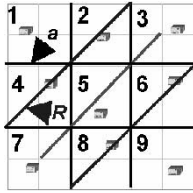
Fig. 1.   Routing cells.

asymmetric link problem in *ad hoc* networks. Third, zone routing protocol (ZRP) [1] is a hybrid routing protocol for MANETs that balances the tradeoff between proactive and reactive routing using a dynamically maintained zone topology. Differently, MC utilizes node location information to simplify routing strategy. Fourth, several routing algorithms based on location information have been proposed, such as LAR [3], DREAM [10], and GPSR [5]. However, these schemes do not utilize the heterogeneous capabilities of different nodes as we do.

III. MULTICLASS ROUTING

Many *ad hoc* networks are heterogeneous MANETs, where physically different nodes present. Thus it would be more realistic to model nodes in such networks as different types of nodes [14]. For simplicity, we consider there are only two types of nodes in the network. One type of node has larger transmission range (power) and data rate, better processing capability, and is more reliable and robust than the other type. We refer to the more powerful nodes as backbone-capable (BC) nodes. In MC routing, BC-nodes can be elected as the backbone nodes (B-nodes). The less powerful nodes are referred to as general nodes (G-nodes). Usually, the transmission range of a B-node (denoted by R) is much larger than that of a general node, denoted by r.

The main idea of MC routing is to let most routing traffic go through B-nodes. This has the following advantages. 1) It provides better reliability and fault tolerance, since B-nodes are more reliable than general nodes. 2) It provides larger throughput since B-nodes have larger data rate than general nodes. 3) It reduces the number of hops in routing, and hence reduces the routing overhead and latency, since B-nodes have larger transmission range.

In order to utilize B-nodes in MC routing, we divide the entire routing area into multiple squares of equal size, called cells, and design a B-node selection mechanism to select a B-node in each cell if any BC nodes exists in one cell. Under this cell structure, we design routing protocols to discover the route between any two nodes on-demand. In addition, we design a location dissemination scheme to maintain node location information used by routing. Furthermore, we propose an efficient MAC protocol that leverages the difference between the B-nodes and G-nodes.

The rest of this section is organized as follows: Subsection III-A presents the cell structure used by MC routing. In Subsection III-B, we describe how to select a B-node in a cell. Subsection III-C presents the MC routing protocol. In Subsection III-D, we address dissemination of node location information. In Subsection III-E, we propose a new MAC protocol.

A. Cell Structure

The routing area is divided into cells as shown in Fig. 1. Denote a the side length of a cell and denote R the transmission range of a B-node. If $a = R/2\sqrt{2}$, where R is twice as much as the diagonal of a cell (see Fig. 1), then a B-node can communicate directly with the B-node in any nearby cell. In our cell structure, one (and only one) B-node is elected and maintained in each cell if there are BC-nodes available in the cell. In MC routing, we assume the routing area is fixed, i.e., the nodes move around in a fixed territory. This is true for many MANETs (e.g., military battlefield networks, disaster relief networks, networks in convention centers). Since the routing area is fixed, the position of each cell is also fixed. Given the location (coordinates) of a node, there is a predefined mapping between the node location and the cell, in which the node is located. To obtain this mapping, each node only needs to know the side length of a cell and the coordinates of a reference point, which serves as the origin of the entire routing area. In our architecture, a location server (to be described later) broadcasts the side length of a cell and the coordinates of a reference point to all the nodes.

B. B-Node Election

Given a cell structure as described above, a B-node needs to be selected in a cell before the MC routing takes place. Initially, one B-node is elected in a cell if there are BC-nodes available in the cell. Since a B-node may move out of its current cell, a re-election algorithm is needed to elect a new B-node to replace the leaving B-node. The re-election algorithm could be triggered by a leaving B-node or a G-node that notices there is no B-node in the cell due to failure of a B-node (as stated in step 6 of the MC routing protocol).

The re-election algorithm works as follows. The leaving B-node or the G-node floods an election message to all the nodes in the cell. When a BC-node receives the election message, it broadcasts a claim message that claims it will become the B-node of the cell. Due to propagation delay, multiple BC-nodes may broadcast within a time period of not more than the propagation delay. To reduce such concurrent broadcasts, we use a random timer; i.e., each BC-node defers broadcasting its claim by a random time set by the timer. If a BC-node hears a claim message during this random time, it gives up its broadcast. Then one of the BC-node T becomes the new B-node in the cell, and T will start using the second address, which is the same as the cell id. Since all nodes in the cell can hear the claim message, they know that T is the new B-node. This idea is similar to the random competition-based clustering (RCC) scheme in [4]. Note that those BC-nodes that do not act as B-node should act as G-nodes, e.g., using transmission range of r rather than R.

The initial election of a B-node is similar to part of the above re-election algorithm (i.e., initially, each BC-node broadcasts a claim message with a random delay, and one of the BC-node becomes the B-node). Once a B-node is elected in each cell, we can run the MC routing protocol, described next.

C. Multiclass Routing Protocol

1) Each node has its own unique id; moreover, there is a unique id for each cell. In Fig. 1, the number is the id for each cell. One (and only one) B-node is elected and maintained in each cell, and each B-node has a second address, which is the same as the id of the cell in which it stays. Thus a B-node can send packet to a B-node in a nearby cell by using the second address, even though the identity of that B-node may change.

2) When a B-node moves out of a cell, it initiates a B-node election process in the cell before it leaves the current cell, and a BC-node will be elected as the new B-node using the aforementioned B-node selection scheme.

3) **Routing among B-nodes.** First, we discuss how B-nodes find routes to other B-nodes. B-nodes use their second addresses to communicate with each other. Assume B-node B_S (in cell C_S) wants to send a packet to B-node B_d (in cell). Although nodes move around, the cells are fixed. B_S knows the cell in which B_d stays based on B_d's second address, which is the same as the cell id. A straight line L is drawn between the centers of cell C_S and. An example is given in Fig. 1. Assume B-node 7 wants to send a packet to B-node 3. The center line is line L. Two border lines which are parallel to line L with distance of W from L are drawn from C_S to C_d. All the cells that are within the two border lines are defined as *routing cells*. The value of W depends on the density of BC-nodes in the network. If there are enough BC-nodes in the network, i.e., with high probability there is at least one BC-node in each cell, then W can be set as zero, i.e., *routing cells* are only the cells that intercept with line L—cell 7, 5, 3 in the example. Then the B-nodes from the *routing cells* form a route for B_S to B_d. In Fig. 1, the route is $B_7 \rightarrow B_5 \rightarrow B_3$ when W is zero. For the simulations presented in Section IV, W is zero. If the number of BC-nodes is small, large W can be used. For the example in Fig. 1, if W is set as $a\sqrt{2}/2$, where a is the side length of a cell, then the *routing cells* are cell 7, 5, 3; 4, 2; and 8, 6. When W is larger than zero, routing among B-nodes is described in the next step.

4) **Route Discovery.** Consider a node S wants to send a data packet to a destination node D. We first discuss the case where S is a B-node. And we will discuss the routing scheme when S is a general node in step 8. S is the starting B-node in routing. In MC routing, the starting B-node S needs to know the current location of the destination node D. The scheme by which S obtains D's location is described in steps 6 and 7. With D's location information, S knows the cell in which D stays, and S knows the B-node in cell is B_d. Then S determines the *routing cells* between S and B_d, and sends route request (RR) packets to B-nodes in *routing cells*. If W is zero, then the RR packet is just forwarded by a serial of B-node in the *routing cells*, e.g., $B_7 \rightarrow B_5 \rightarrow B_3$ as in the example. If W is larger than zero, the route is discovered as follows. The RR packet includes the following fields: Starting_B-node, Next_cells,

Routing_cells, Path and Destination_cell. Starting_B-node is the B-node initiates the route discovery. Next_cells are the cells to which current B-node needs to multicast the RR packet (e.g., if $W = a\sqrt{2}/2$, the Next_cells for node B7 is cell 4, 5, and 8), and one multicast can be realized by a single transmission. Routing_cells are the *routing cells*. Path is the route via which the RR packet traveled, and Destination_ cell is the cell including the destination node. When a B-node in *routing cells* receives a RR packet, it adds itself to the Path, and determines Next_ cells based on the location of itself, the location of Destination _cell, and Routing_cells. The neighbor *routing cells* in the direction towards the destination are Next_cells. Then the B-node multicasts the RR packet to B-nodes in Next_cells. When B_d receives the first RR packet, a route reply (RP) packet (with the discovered path) is sent back via the coming path, and a route based on B-nodes is discovered. All other RR packets are discarded by B_d. Then S can start sending data packet to B_d. If S does not receive a RP from B_d for a certain time, S assumes the route discovery failed, and S will flood the RR packet to all B-nodes in the network, and finds a B-node-based route to B_d. B-node flooding is needed only when the number of B-nodes in the network is small. And flooding among a small number of B-nodes does not cause large routing overhead. Assume nodes in *ad hoc* networks do not move very fast. (If nodes move too fast, then besides flooding data packet, no routing protocols can successfully deliver data. Since a previously discovered route will become broken because some nodes in the route move away when data packet comes.) So most of the time, destination node D is still in cell, or in nearby cells of. And since B-node B_d can reach all nodes in nearby cells, B_d can send the data packet to D directly. When D receives the packet, D will send an Ack (acknowledge) packet back to node B_d. If D is a general node, there is a unidirectional link problem here. D cannot send the Ack packet to B_d in one hop. Instead, the Ack packet is sent to B_d via flooding in cell (or plus a nearby cell). If B_d does not receive the Ack for a certain time, it means D is no long in the nearby cells of. Node B_d will hold the data packet (before receiving Ack) and request the updated location information of node D (described in steps 6 and 7). Then B_d can send the data packet to the B-node closest to the new location of D, and that B-node can send the packet to D directly. After receiving the Ack packet from destination node D, B_d will send an Ack packet to source node S via the incoming path.

5) **Route Repair.** We will use the example in Fig. 1 to discuss the route repair in MC routing. Assume the discovered route is $B_7 \rightarrow B_5 \rightarrow B_3$, when a B-node (e.g., B_5) in the route moves out of its cell (or fails) and no new B-node is elected, an established route becomes broken. The upstream B-node B_7 (closer to source) can detect there is no B-node in next *routing cell* if it does not overhear transmission from a B-node in the cell for a certain time after it sends the packet to the cell. Then B_7 first

broadcasts route repair (RE) packets to nearby B-nodes and tries to find a repaired route via B-nodes. The RE packet includes the next B-node B_3 and a time-to-live (TTL) in hops. When a B-node receives an RE packet, the TTL is decreased by 1. And if the TTL is 0, the B-node will not forward the RE packet. When the next B-node B_3 receives the RE packet, a Repaired packet is sent back to the B-node starting the repair via the reverse path, and an alternative path is found. If no Repaired packet is received within a timeout, the upstream B-node B_7 assumes route repair via B-nodes failed, and it will try to find a repaired route via general nodes. B_7 floods route repair (RE) packets to general nodes in the next two cells (cells 5 and 3 in the example), to find out a path via general nodes to next B-node (B_3 in the example). The RE packet includes the following fields: Repairing_B-node, Next_cell, Routing_cells, Destination_cell, Destination_node and Path. Repairing_B-node is the B-node starting the route repair process. Next_cell is (cell 3 in the example) the next downstream routing cell after the cell without B-node (different from Next_cells in step 4). Routing_cells are the *routing cells* from Repairing_B-node to destination node. Path is the route via which the RE packet traveled, which includes both B-nodes and general nodes. An algorithm similar to AODV can be used to find a repaired route via general nodes to next B-node B_3. However, the flooding of RE packet is only in the next two routing cells (cells 5 and 3 in the example). When the next B-node receives the first RE packet, a route reply (RP) packet is sent back to the Repairing_B-node B_7 via the coming path, and a repaired route is discovered. All other RE packets are discarded by the next B-node B_3. Then the data packet is sent to the next B-node B_3. If general nodes in Next_cell (cell 3 in the example) do not overhead an RP packet from a B-node for a certain time, it means there is also no B-node in Next_cell, then general nodes in Next_cell will forward the RE packet to the next downstream routing cell (downstream cell of cell 3 in the example) according to Routing_cells field, until a B-node responses with RP packet or the destination node responses with RP packet when it receives a RE packet. In the worst case, i.e., if none of the routing cells have B-nodes, MC routing is similar to AODV, but the flooding area is limited to the routing cells. So even in the worst case, MC still has less routing overhead than AODV.

6) **Routing from General Node.** If S is not a B-node, then S first needs to find out a path to a nearby B-node. S floods an RR packet in its cell to find the nearest B-node. S includes its location information in the RR packet. Only nodes in the same cell as S will process and forward the RR packet to other nodes. This reduces the overhead from flooding. A node can determine if it is in the same cell as S based on the location of S and itself. The intermediate node records its identity in the *path* field of the RR packet. When the B-node B_S in the cell receives the RR packet, because B_S has large transmission range, it can send the RP packet directly to node S with the *path* included. Then

S can send the data packet to B_S following the *path*. And the rest is the same as in step 4. A node can discover there is no B-node in the cell if it does not receive the RP packet for a certain time after it sends out RR packet, and it will initiate a B-node election process. The B-node election process is discussed in the following.

D. Dissemination of Node Location Information

As mentioned in step 4, in MC routing, a start-B-node S needs to know the current location of destination node D. Since nodes move around, an algorithm is needed to disseminate updated node location information. In this paper, we propose an efficient dissemination scheme, and it is described in the following. If a node moves within the same cell, there is no need to update its location information. When a node moves out of its previous cell, it sends a location update packet (with its new location) to the B-node in the new cell (or the nearest B-node). The location update packet can be sent out via broadcast within a small hop count. In addition, all B-nodes periodically send aggregated node location information to a special B-node B_0. For example, B_0 can be the commands headquarter in a battlefield. The period of updating location information should not be too large, because this will cause the location information to be not accurate. The period should also not be too small, because updating the location information too often will cause large overhead. The special B-node B_0 is preferred to be a fixed B-node, or a B-node only moves within one cell. If B_0 is fixed or within one cell, the dissemination algorithm is very simple. When a starting B-node S needs to know the location of a node D, S sends a location request packet to B_0, then B_0 sends the location of D to S. Since both S and B_0 are B-nodes, they know how to communicate with each other (step 2). If B_0 also moves around, then B_0 needs to multicast its current location to all B-nodes when it moves from one cell to another. Then all B-nodes know the current location of B_0, and they can request location information from B_0. In many MANETs, it is possible to choose a static or slowly-moving B-node to be B_0. And in many MANETs (like military ones), it is possible (and advantageous) to deploy a static B-node as B_0. For MANETs where it is not easy to find a good candidate like B_0, the node location information dissemination can be achieved via several existing location service schemes such as [11].

E. New Media Access Control Protocol

IEEE 802.11b is not an efficient MAC protocol. For MC routing with backbone nodes, we designed a new MAC layer protocol that is more efficient than IEEE 802.11b for heterogeneous MANETs. The key idea is to combine a time-slotted mechanism with a contention-based mechanism. We call this new MAC protocol the HMAC. In the following example, we use B and G to represent the B-node and the general node, respectively. A large time frame is divided into three subframes, which include G-to-G, B-to-B, and B-to-G. G-to-G is a time slot assigned for the traffic between two general nodes. B-to-B and B-to-G time slots have similar meaning. The G-to-B traffic is included in G-to-G subframe, so there is no G-to-B

subframe. Inside each subframe, the corresponding nodes use contention-based mechanism—IEEE 802.11b to decide which node should transmit packets. In B-to-B subframe, a B-node may piggyback another B-node the scheduling information in B-to-G subframe. An important parameter is the length of each subframe. The subframe length depends on the amount of traffic of each subtype (e.g., G-to-G, B-to-B), which depends on many factors, including the number of B-nodes in the network, the number of general nodes in the network, the average distance between a general node and a B-node, and so on.

One can first use the estimated length of each subframe, and then use a scheme to adaptively adjust the subframe length of each type of traffic such that both fairness and good throughput are achieved. The HMAC protocol is designed to minimize contention (i.e., maximize energy efficiency) and trade off fairness with throughput Details on HMAC can be found in [12] and [13].

IV. PERFORMANCE EVALUATION

MC routing protocol is implemented in QualNet [8], a scalable packet-level simulator with an accurate radio model. HMAC was used as the MAC protocol. For the simulations presented in this section, there are a total of 20 time-slots, in which G-to-G subframe takes eight time-slots, B-to-B subframe takes eight time-slots, and B-to-G subframe takes four time-slots. In the following simulations, the slot allocation was fixed. We did not use any adaptive scheme to adjust the subframe length in the current experiments. We performed simulations with several topologies. Here, we present simulations performed by distributing 100 nodes uniformly at random in an area of 1000×1000 m. Among the 100 nodes, 25 are BC nodes. The transmission range of B-node and general node are 400 and 100 m, respectively. The interference range and sensing range of a general node and a BC-node are twice the corresponding transmission range. The side length of a cell is set as $a = R/1.6$. There are 16 cells in the routing area, so there will be at most 16 B-nodes. The number of B-nodes is small. The width of the *routing cells—W* is set to zero, i.e., *routing cells* are the cells which intercept with line L. Each simulation was run for 600 simulated seconds. The mobility in the environment was simulated using the random-waypoint mobility model. In our simulations, the pause time was set to 0 s, which corresponds to constant motion. We control the node mobility by varying the node velocities range. The maximum velocities vary from 0 to 50 m/s. In all simulations, B-nodes have the same set of parameters in random-waypoint mobility model as general nodes.

We set the application in the following scenario. There are several source-destination pairs. The constant bit rate (CBR) generators generate data traffic and it is sent to the destination nodes. The source sent packet of 512 bytes at a rate of four packets per second. We ran each simulation ten times to get an average result for each simulation configuration. We compared our MC routing with ZRP [1], an efficient hybrid routing protocol for MANETs. IEEE 802.11 is used as the MAC protocol for ZRP. The following metrics are used to compare the routing performance.
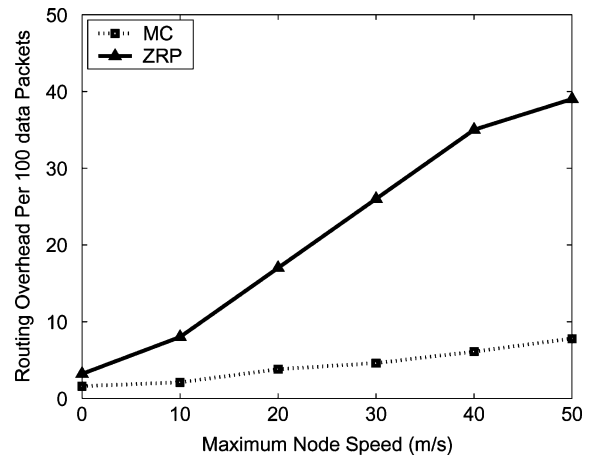

Fig. 2. Overhead under different mobility.

1) Routing overhead and energy consumption. Subsections IV-A and IV-B present the results of routing overhead comparison. The result of energy consumption comparison is similar to that of routing overhead, and it is not reported in this paper because of the page limit. In Subsection IV-G, we also compare the routing overhead of MC and ZRP for different densities of BC-nodes.
2) Throughput and delay. Subsections IV-C and IV-D present the results of throughput and delay comparison.
3) Scalability. The results of scalability test are reported in Subsection IV-E.

In the following tests, the routing overhead of MC includes the overhead of disseminating node location information.

A. Routing Overhead Under Different Mobility

First, we compared the routing performance of MC with ZRP for different node mobility. The traffic load in the experiments is 150 kbits/s. Fig. 2 shows that the routing overhead of both MC and ZRP increases as the node speed increases. Higher mobility causes more broken links, and thus increases routing overhead. However, the overhead of MC is much smaller than ZRP. Since B-nodes have a large transmission range, the number of hops in MC is small, and the routing latency in MC is low. Low routing latency means the time between route discovery and sending data packet is small, and the intermediate nodes are not far away from their previous locations when the data packet comes, which means less broken links. Under high node mobility, MC has much less broken links than ZRP, thus much less routing overhead than ZRP.

B. Routing Overhead versus Transmission Range

We then compared the routing overhead of MC and ZRP for different node transmission range. The result is presented in Fig. 3. Here, we only change the transmission range of the general nodes. In the experiments, the maximum node speed is 20 m/s, and the traffic load is 150 kbits/s. Fig. 3 shows that the overhead of MC routing is much smaller than that of ZRP. This is because when the transmission range of general nodes is large enough, source node and destination node can
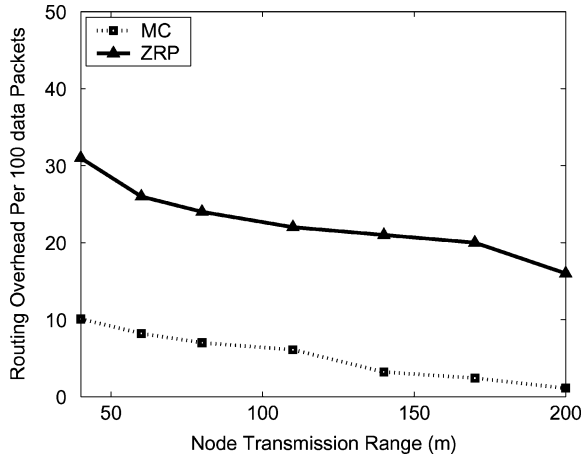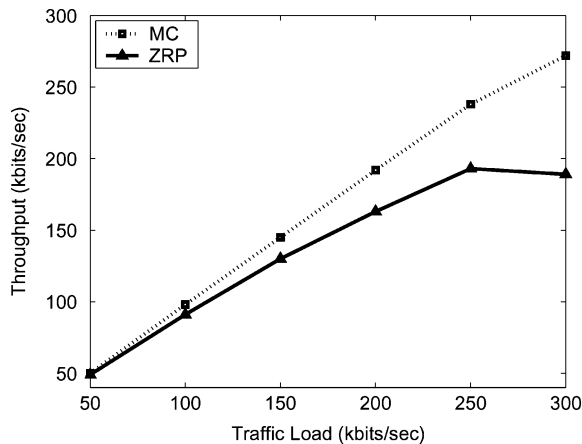
Fig. 3. Overhead versus transmission range.

Fig. 4. Throughput comparison.

communicate with nearby B-node directly. So, there is no need to flood the route request packet or the Ack packet to the nearby B-node, which substantially reduces the routing overhead.

C. Throughput Under Different Traffic Load

We present the result of the throughput comparison in Fig. 4. In the simulation, the maximum node speed is set to 20 m/s. Fig. 4 shows that under ZRP, the network starts saturation when the traffic load is heavy. The throughput actually decreases when the traffic load is larger than 250 kbits/s. This is because ZRP incurs large routing overhead from inter-zone routing and maintaining routes within zones. When the network traffic is heavy, congestion occurs and packets are dropped in the network, and cause the throughput decreases.

D. Delay Comparison

The end-to-end delays for MC and ZRP under different traffic load are plotted in Fig. 5. As we can see, the delay of ZRP is close to MC when the traffic load is light. However, when the traffic load becomes heavy, the delay of ZRP increases rapidly, which means that lots of congestion and packet drops are caused in the network. On the other hand, MC has much smaller routing
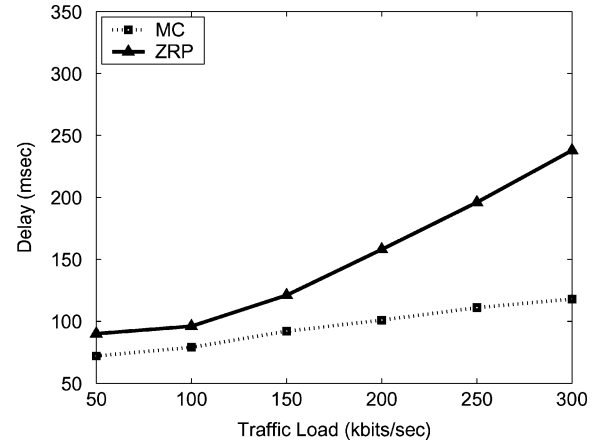

Fig. 5. Delay comparison.

overheads. There are little congestions and packet drops, even under a heavy traffic load. This is why the delay under MC routing increases slowly as the network traffic becomes heavy.

E. Scalability

Scalability is a very important aspect of MANET routing protocol design. A good routing protocol should scale well in large networks. In order to test the scalability of MC, we implemented a large testbed with 400 nodes distributed uniformly at random in an area of 2000×2000 m, where 100 nodes are backbone-capable nodes. The large testbed is four times the size of the small testbed (in terms of the node number and routing area) used in previous tests. We compare the performance of MC and ZRP in the large testbed. Fig. 6 reports the routing overheads of MC and ZRP for different mobility in large testbed, which are labeled as MC-L, ZRP-L. For comparison, in Fig. 6 we also plot the routing overheads of MC and ZRP in the small testbed, which are labeled as MC-S, ZRP-S. Fig. 6 shows that the routing overhead of MC-L (in the large testbed) is about twice the overhead of MC-S, but MC-L is still small even under high mobility. However, the routing overhead of ZRP-L is much larger than ZRP-S, especially under high mobility. For the same source-destination pair, MC needs much less intermediate nodes than ZRP because MC uses B-nodes to route packets, which have a long transmission range. So, the chance of repairing or re-routing is much smaller in MC than in ZRP. Also, MC has low routing latency as discussed in Subsection IV-A. Thus the routing overhead of MC in large network is still small.

We also measured the throughputs of MC and ZRP in a large testbed and these results are reported in Fig. 7. For comparison, the throughputs of MC and ZRP in the small testbed are also plotted in Fig. 7. The labels have the same meaning as in Fig. 6. As we can see, the throughput for MC-L is almost the same as MC-S, however, the performance of ZRP becomes worse in large networks than in small networks. For the larger network, the throughput of ZRP-L drops when traffic load is larger than 200 kbits/s.
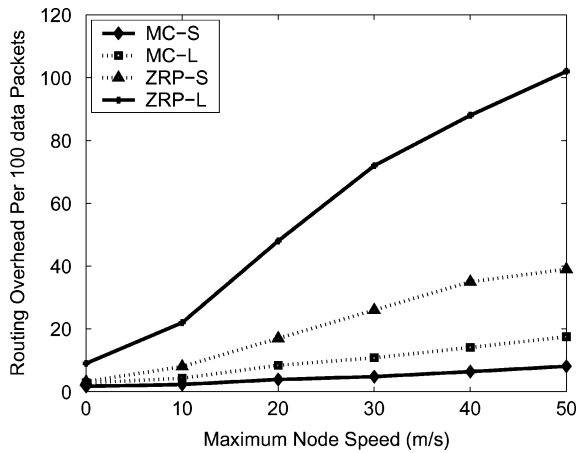
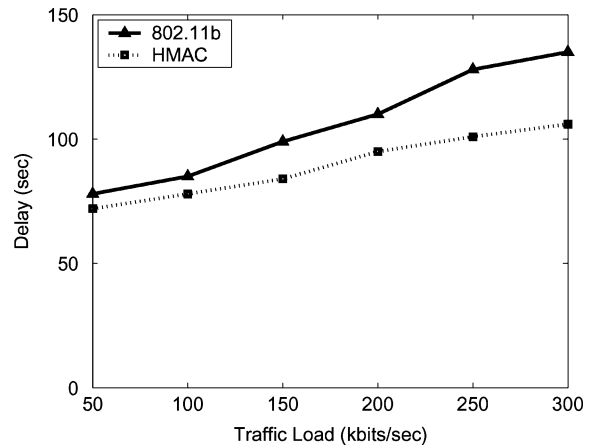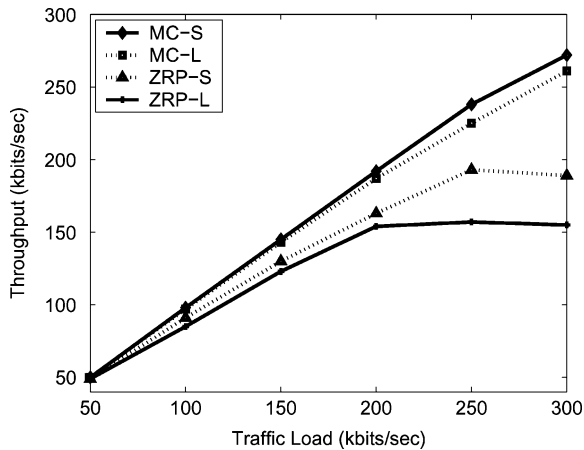Fig. 6.   Scalability–routing overhead.

Fig. 7.   Scalability–throughput.

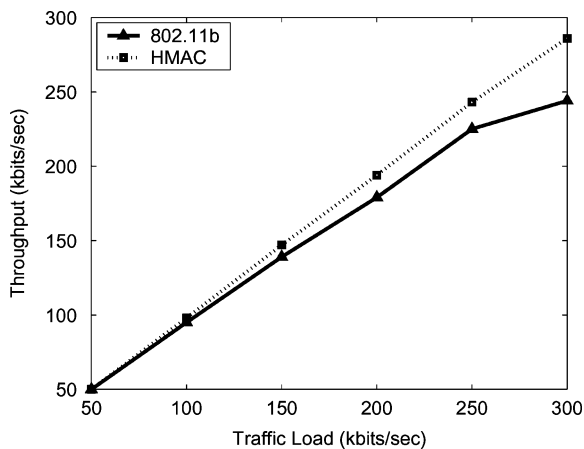Fig. 8.   Throughput performance.

F. Performance of HMAC

We studied the performance of the hybrid MAC protocol and compared the throughput and delay of MC routing using HMAC and IEEE 802.11b. The results are reported in Figs. 8 and 9, which show that HMAC provides higher throughput and incurs smaller delay than IEEE 802.11b.

Fig. 9.   Delay comparison.

G. Performance for Different BC-Node Densities

To ensure good performance of the MC routing protocol, it is important to have a B-node in most cells. If there is no B-node in a cell, then B-node flooding (during route discovery) or small-area flooding (during route repair) may be used, which increases routing overhead. In [2], Du proved that there is a high probability that each cell has at lease one B-node with a reasonable number of BC-nodes (about 1.5 times the cell number) uniformly and randomly distributed in the network.

We also use simulation to evaluate the performance of MC for different BC-node densities. In the simulation, the number of BC-nodes in MC varies from five to 35, with an increase of five. We compare the routing overhead of MC and ZRP for the different densities of BC-nodes. The experiment results show that MC has a larger routing overhead than ZRP when the density of the BC-nodes is low (for less than ten BC-nodes), but the routing overhead of MC decreases quickly as the number of BC-nodes increases.

V. CONCLUSION

In this paper, we presented multiclass routing, a novel routing protocol that takes advantage of different communication capabilities of heterogeneous nodes in many realistic mobile *ad hoc* networks. An efficient MAC layer protocol—HMAC for heterogeneous MANETs is also presented. Different types of nodes have different transmission power (range), bandwidth, processing capability, reliability and security. MC routing utilizes the more powerful nodes as backbone nodes (B-nodes). The routing area is divided into several small, equal-sized cells. One B-node is maintained in each cell, and the routing among B-node is very efficient and simply based on location information and cell structure. A source discovers a route to destination in an on-demand way, and most of the routing activities (packet forwarding) are among B-nodes. This reduces the number of routing hops and makes the routing more efficient and reliable, since B-nodes have large bandwidth, transmission range, and are more reliable. Extensive simulation tests demonstrate that MC has very good performance, and performs much better than

ZRP in terms of reliability, scalability, routing overhead as well as packet delay and throughput.

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