Adaptive Cell Relay Routing Protocol for Mobile *Ad Hoc* Networks

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***Abstract*—Most existing routing protocols for mobile *ad hoc* networks (MANETs) use a single routing strategy for different types of networks. Routing protocols suitable for small networks may not scale well in large networks. Routing protocols that perform well in sparse networks may not be suitable for dense networks. To achieve good performance, different routing strategies should be used for different types of networks. This philosophy motivates our design of a new routing protocol called the adaptive cell relay (ACR) routing protocol. Our ACR protocol can adapt the routing strategy for networks with different node density so high efficiency, low delay, and scalability can be achieved. Extensive simulation results demonstrate that the ACR has much better performance and scalability than a popular routing protocol—location-aid routing (LAR). In addition, both the analysis and the simulations show that the ACR routing protocol incurs only about 25% of the routing overhead of the LAR routing protocol.**

***Index Terms*—Adaptive algorithm, mobile *ad hoc* networks, routing.**

I. INTRODUCTION

A MOBILE *ad hoc* network (MANET) is a collection of wireless nodes that cooperatively form a network without using any fixed communication infrastructure. Many routing protocols for MANETs have been proposed in the literature (e.g., Fisheye State Routing (FSR) [9], Optimized Link State Routing (OLSR) [4], *Ad hoc* On-demand Distance Vector (AODV) [7], Dynamic Source Routing (DSR) [8], Zone Routing Protocol (ZRP), [6] and Hierarchical State Routing (HSR) [10]). However, most of the existing protocols use only one routing strategy for different types of networks. Routing protocols that have good performance in small networks may not scale well in large networks. Routing protocols suitable for sparse networks may not perform well in dense networks. An example of unsuitability of single routing strategy is the change of the node density in a military operation. In a military operation, soldiers move to a target area, remaining close and in compact formation during the moving phase. Assume soldiers communicate with each other via a mobile ad hoc network. During the moving phase, the network is a dense network because the units are close to each other. When the troop arrives at the target area, the attack phase begins; soldiers spread out to carry out the mission, such as attacking enemies and capturing their territory. In the attack phase, the average distance between two units is much larger than that in the moving phase; hence, the network becomes a loose network. To achieve good routing performance in such a scenario, different routing strategies should be used in different phases.

Many MANET applications call for different routing strategy for networks with different characteristics. In this paper, we design a new routing protocol called adaptive cell relay (ACR) routing protocol for MANETs with varying node densities. The ACR protocol consists of three components: 1) the cell relay (CR) routing scheme for dense networks; 2) the large cell (LC) routing scheme for sparse networks; and 3) an adaptive scheme that monitors node density changes and initiates a change of the routing strategy when node density changes sufficiently. With these three components, our ACR protocol is able to adapt the routing strategy for networks with varying node density so high efficiency, low delay, and good scalability can be achieved. Another nice property of our scheme is that the CR protocol for dense networks is an energy-aware routing protocol.

The rest of the paper is organized as follows. Section II discusses related work. In Section III, we describe the ACR routing protocol. Section IV presents the simulation results. Finally, we conclude the paper in Section V.

II. RELATED WORK

Research has shown that geographic location information can improve routing performance in ad hoc networks. Routing with assistance from geographic location information requires each node to be equipped with the global positioning system (GPS). This requirement is quite realistic today because such devices are inexpensive and can provide reasonable precision. The well-known location-based routing algorithms include location-aid routing (LAR) protocol [1], distance routing effect algorithm for mobility (DREAM) [3], and greedy perimeter stateless routing (GPSR) [5]. The LAR protocol uses location information to limit the area for flooding RR packets. To reduce the flooding area and hence the flooding overhead, LAR scheme 1 defines a request zone for flooding, which is a rectangular region covering the source location and the expected location of the destination. However, the request zone could still be very large and can cause large routing overhead. For example, if the source and destination nodes are in the opposite corner of the routing area, the flooding area will be the entire routing area. To mitigate this problem, we propose a new location-based routing protocol called ACR routing protocol. Under this protocol, the whole routing area is divided into multiple cells. An RR packet is flooded to only a serial of small cells rather than a rectangular region in LAR. Next, we present the ACR protocol.

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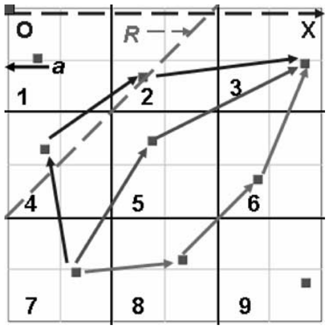

Fig. 1. Backup routes in CR routing.

III. ADAPTIVE CELL RELAY ROUTING PROTOCOL

In this section, we present the ACR routing protocol for mobile *ad hoc* networks. The main idea of the protocol is to use cells (in the direction from the source to the destination) to relay route discovery packets. Under the ACR protocol, the entire routing area is divided into squares of the same size, called cells. Assume the node transmission range is R, and the side length of each cell, denoted by a, satisfies $a = R/(2\sqrt{2})$. The relationship between a and R is shown in Fig. 1, where a is the side length of a square and R is twice as long as the diagonal of a square. R is the longest distance between two nodes located in two nearby cells, respectively; hence, each node in a cell is within the transmission range of any node in any neighboring cell.

The network is installed with a grid, where the side length of each cell is $a = R/(2\sqrt{2})$. An example of the grid structure with nine cells is shown in Fig. 1. Each cell has a unique ID (e.g., the number in Fig. 1). We assume each node knows its location, either from GPS or through other means. Given the position of a reference point (e.g., point O in Fig. 1) in the grid and a direction (e.g., the X axis in Fig. 1), each node can determine the cell in which it locates, based on its own location and cell size. The reference point and the direction are broadcasted to all nodes in the network.

The ACR protocol takes two routing strategies: one for dense networks and one for sparse networks. Specifically, the ACR protocol consists of three components: 1) the CR routing for dense networks; 2) the LC routing for sparse networks; and 3) an adaptive scheme that detects node density changes and chooses either CR or LC routing, based on the node density. We present the three components in Sections III-A–C, respectively. Route maintenance is discussed in Section III-D. In Section III-E, we compute the probability of having at least one node in one cell, to justify the suitability of using CR and LC.

A. Cell Relay Routing Protocol for Dense Networks

CR routing is an on-demand routing protocol based on source routing. It is used for a network with high node density. In a dense network, there are a large number of nodes in the routing area; hence, there is a high probability that every cell has at least one node if the cell size is appropriately chosen. The CR routing protocol in dense networks is also an energy-aware protocol (i.e., only those nodes with more remaining energy in a cell participate in routing and packet forwarding), thereby increasing the lifetime of the whole network. Next, we describe the CR routing protocol.

Assume a source node S wants to send a packet to a destination node D. Assume S knows the current location of the destination D; also assume the source node S knows its own location. The CR routing protocol is given as follows:

1) Based on the location of source and destination, a line L is drawn between the geometric center of the cell of the source node S and the geometric center of the cell of the destination node D.
2) The line L intercepts with several cells, and these cells are denoted as $\mathrm{C}_0, \mathrm{C}_1, \mathrm{C}_2, \ldots, \mathrm{C}_k$, starting from the cell of source node S. S records the cells in a cell_list field. Based on the average speed of node D and an estimation of the routing latency, the possible cells where node D will be are also included in the cell_list.
3) Then, an RR packet is sent from source node S to nodes in cell C_1 by flooding. The RR packet contains the following fields: session_id, source, destination, cell_list, and path_list. session_id plus the ID of the source uniquely determines a flooding session. Only the nodes in cell C_1 will process this packet. Before the RR packet is forwarded to the next hop, the RR packet will record the current node ID in path_list. Then, nodes in cell C_1 will forward the RR packet to nodes in cell C_2 with a delay of $t_d = \alpha/E + t_r$, where E is the remaining energy of the node, α is a system parameter that can be adjusted, and t_r is a small (compared with α/E) random backoff time. If a node in cell C_1 hears the flooding to C_2 from some other node in C_1, it knows that the RR packet has already been forwarded to the next cell, and it will not flood the RR packet again. This avoids duplicated flooding of the same RR packet, leading to the reduction of routing overhead. Because of the delay α/E, only the nodes with more remaining energy would participate in the routing. This avoids draining out some nodes too early. The small random backoff time t_r is used to avoid simultaneous forwarding of the RR packet by several nodes having almost the same remaining energy E. The value of α is chosen to be large enough so t_d is different for different E, but α should not be too large; otherwise, it may cause a large routing delay.
4) Then, the nodes in cell C_2 will receive the RR packet; duplicated RR packets will be discarded by the nodes in C_2; and the same process as indicated in step 3 repeats until the RR packet reaches the destination node D. Note that the RR packet will record the route in path_list as it travels.
5) When node S hears the flooding of sending RR to cell C_2 by the nodes in C_1, node S knows there is at least one node in cell C_1 and the RR packet has been sent to the next cell. If node S does not hear any flooding for a certain period of time, it is very likely that there is no node in the next cell C_1. If there is no node in cell C_{i+1}, then node in C_i will send the packet via two backup routes. How to find backup routes is described later.

6) When the destination node D receives the RR packet, it sends a route reply (RP) packet back to node S along the incoming route.
7) When the source node S receives the RP packet, it knows the route to node D and can start sending data packets to D.

Now, we describe how to find backup routes. Let's look at an example. In Fig. 1, originally source node 7 wants to send a packet to node 3 via node 5. If there is no node in cell 5 (in which node 5 is located), then the packet can not be sent along the route $(7 \rightarrow 5 \rightarrow 3)$. However, there are two alternative paths that can be used to send the packet to node 3. One is the path from $7 \rightarrow 4 \rightarrow 2 \rightarrow 3$, and the other one is the one $7 \rightarrow 8 \rightarrow 6 \rightarrow 3$. In the CR routing protocol, when there is no node available for routing in cell 5, node 7 will send the packet along both the backup paths to node 3. This will increase the probability of successful transmission. If node 3 receives both copies of the packet, it will only keep one. For a dense network, we assume either the main path or a backup path should be available. In case none of them is available, the packet is sent via flooding to the destination node D.

In summary, the CR routing uses node location information and localized flooding (within a selected cell) to reduce routing overhead, compared with unrestricted flooding.

B. Large Cell Routing Protocol for Sparse Networks

In a sparse network, the number of nodes in the routing area is small. If we set the side length of a cell to be $a = R/(2\sqrt{2})$, some cells may not include any node. For routing in a sparse network, we first need to consider how to guarantee the delivery of data packets, and then we can consider how to reduce the routing overhead to achieve efficiency. To avoid confusion with the CR routing protocol for dense networks, we call the routing protocol for sparse networks as LC routing protocol. The main idea of LC routing protocol is given as follows.

Based on the number of nodes in the routing area, an LC can be defined. An LC is a square, and it is large enough so there is a high probability for each LC to contain at least one node. The way to determine the size of LC is discussed in Section III-E. When a source node S needs to send data packets to a destination node D, a line L is drawn between the geometric centers of the two LCs that contain S and D. An RR packet is forwarded by the LCs on the line L until it reaches the destination. When a node in an intermediate LC receives the RR packet, it floods the RR packet to nodes in the same cell and the next cell (listed in cell_list). The RR packet is then forwarded to the nodes in the same cell because some nodes in an LC may not be directly reachable by any node in nearby cells. Backup paths are also used in LC routing in case the main path is not available. If both the main path and backup paths are not available, then flooding will be used.

LC routing is very similar to CR routing; in particular, CR routing can be regarded as a special case of LC routing when an LC [where $a > R/(2\sqrt{2})$] reduces to a small cell [where $a \leq R/(2\sqrt{2})$], but there are some important differences between CR routing and LC routing. CR routing is suitable for dense networks. With high probability, each cell has at least one node, and only the nodes with more remaining energy would participate in routing and forwarding packets. In CR routing, any node in a cell can reach all nodes in neighboring cells. The RR packet is flooded to nodes in the next cell. While in LC routing, all nodes in the cell participate in flooding, and they flood the RR packet to nodes in both the same cell and the next cell.

Next, we present an adaptive scheme that decides which routing protocol (among LC routing and CR routing) should be used.

C. Scheme of Measuring Node Density and Changing Routing Strategy

Local node density is not a good measure for changing the routing strategy between CR routing and LC routing because in MANETs nodes can move around, and usually, there is no fixed mobility pattern. At a certain time, some cells may have many nodes whereas other cells may have very few nodes. Thus, a global node density should be used as the criterion for changing the routing strategy. The global node density is defined as the total number of nodes in the network divided by the routing area. We say the node density changes when at least one of the following events occurs: 1) the number of active nodes in the routing area changes; and 2) the size of the routing area changes.

For the entire routing area, a node is selected as the adaptive head (AH) that detects a global node density change and determines if the routing strategy should be changed. An AH could be a usual node in a homogeneous MANET, or it could be a powerful backbone node in a heterogeneous MANET. An AH is preferable to be a node with less mobility (static is better). If there is no way to find a relatively static node as AH, then the current AH will broadcast its location to all other nodes when the AH moves into a new cell. Thus, each node knows the current location of the AH, and it can easily send a message to the AH.

Initially, the AH knows how many nodes and their IDs are in the network. The AH and all other nodes know the boundary of the routing area. When any of the aforementioned events happens, a density change (DC) message is sent to the AH. For example, when a new node joins the network, the new node will send a DC message to the AH. The AH will increase the node number counter by one. If a node detects that its neighbor dies out due to running out of battery, the node will also send a DC message to the AH, and the AH will decrease the node number counter by one. When a node moves out of the boundary of the current routing area, it estimates the approximate area in which it will move and sends the new boundary to the AH. For example, it could be a new cell added to the current routing area.

The previous scheme can detect most of the node density changes, except when the routing area shrinks. We propose the following scheme to handle the case where the routing area shrinks. Periodically, say every T seconds, one node in each boundary cell (a cell that is on the boundary of the routing area) sends an update message with its ID and the cell number to the AH. (Note: Time synchronization is not a problem because each node has a GPS receiver, and GPS provides synchronized time.) Each node in a boundary cell sends the update message with a random backoff time after every T seconds. When other nodes overhear the update message from a node in the same cell, they will not send it again. If the AH finds that there is no node reports from a certain cell C for N consecutive times, the AH will not include cell C in the routing area anymore. (T and N are system parameters and can be tuned via simulations.)

When any of the aforementioned events happens, the AH updates the global node density, and it uses the following algorithm to decide whether the routing strategy should be changed. A two-threshold algorithm is used to provide routing stability (i.e., there are two thresholds for node density, D1 and D2, where D1 $>$ D2). When the global node density is larger than D1, the routing strategy is changed from LC to CR; when the global node density is less than D2, the routing strategy is switched from CR to LC. Also, there is a minimum running time T_r. Each routing strategy should run for at least T_r before switching the routing strategy. This further ensures the routing stability and reduces possible oscillation.

When the AH decides to change the routing strategy, it will flood a strategy change (SC) message to all nodes in the network. The ongoing route discovery processes will still use the current routing strategy. However, any new route discovery will use the new routing strategy.

Another adaptive scheme is to use human intervention. In many realistic MANETs, the detection of node density change becomes easier when there is certain side-band channel (e.g., node density changes can be detected from certain events, such as the spreading of troops in the example in Section I). In a military battlefield or disaster relief field, a commander can serve as the detector and initiate the change of routing strategy. For example, when the commander issues an order to let the solider spread out in the battlefield, or when he notices that another unit of soldiers joins his group, the commander will flood the message of changing the routing strategy in the network. Of course, this human-assisted approach works only for some special MANETs. However, the (non-human-assisted) adaptive scheme discussed previously can handle all general MANETs.

D. Routing Maintenance

In CR and LC routing, established route may become broken when a node in the route moves away or fails. The routing maintenance in CR and LC is presented in the following. Consider part of an established route $A \rightarrow B \rightarrow C$. After node A, send a packet to the downstream node B (closer to the destination); if A does not overhead any transmission from node B within a timeout, A will assume that B is not available anymore, and A will try to use two backup paths to send the packet to node C. The backup paths are the same as in Fig. 1. If both backup paths are not available, node A will send a Route Failure message to the source node S, and S will try to find another path to the destination.

E. Probability of Having Nodes in One Cell

To ensure CR routing and LC routing work well, it is important to have at least one node in each (small or large) cell. We compute the probability of having nodes in one cell in the following. To simplify the analysis, we assume nodes move toward all directions with equal probability. Assume there are totally M cells and N nodes in the network. For each cell, the probability of having a certain node in the cell is $1/M$, and the probability that this node is not in the cell is $1-(1/M)$. The probability of having zero node in the cell is $[1-(1/M)]^N$. So, the probability of having at least one node in the cell is

$$P_h = 1 - [1-(1/M)]^N. \quad (1)$$

TABLE I
PROBABILITY OF HAVING NODES IN ONE CELL

	Small Dense	Small Sparse	Large Dense	Large Sparse
M	36	9	144	36
N	100	30	400	120
P_h	0.940	0.971	0.938	0.966

Based on (1), we compute the probability P_h for the four networks used in our simulations. The results are listed in Table I, where "Small Dense" refers to the small dense network, and others refer to the corresponding networks. As we can see, the probabilities are very high for all cases. The high probability of having nodes in each cell guarantees the good performance of CR and LC.

In addition, given confidence level P_h and the number of nodes N, we can determine the number of cells M by solving (1). From M and the size of the routing area, we can further determine the side length of a cell (a). If $a > R/(2\sqrt{2})$, then the cells are regarded as LCs; otherwise, they are regarded as small cells. For LCs, we use LC routing; for small cells, we use CR routing.

IV. SIMULATION RESULTS

The ACR, CR, LC, and LAR routing protocols have been implemented in QualNet [2]. To evaluate the performance of these protocols, we conduct simulations under several topologies. For the dense network case, we distribute 100 nodes uniformly at random in an area of 500×500 m. We test CR routing protocol under this setting. The routing area is divided into 36 cells, so there is a high probability for each cell to have at least one node. For the sparse network case, we simulate the scenario with 30 nodes distributed in the 500×500 m area; we test LC routing protocol under this setting. The routing area is divided into 9 LCs. Each LC consists of four small cells.

We also test the performance of ACR when the global node density changes and compared its performance with that under CR or LC only. Each simulation is run for 600 simulated seconds. The mobility in the environment is simulated using a 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 velocity range. The maximum velocity ranges from 0 to 50 m/s.

The application layer is set as shown here. There are several source destination pairs. The sources generate constant bit rate (CBR) traffic; the CBR is five packets per second and the packet size is 512 bytes. We run each simulation 20 times to get an average result for each simulation configuration. We compare

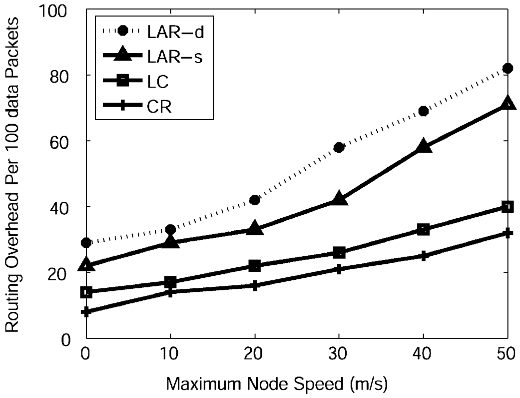

Fig. 2. Routing overhead under different mobility.

CR routing and LC routing with LAR. Five issues are considered. The first is to compare the routing overhead when the node mobility varies. The second is to measure how the node transmission range affects the routing overhead. The third is to compare the throughput under different routing protocols for different traffic load. The fourth is the delay under different traffic load. The fifth is to study the scalability of CR routing and LC routing. In Section IV-F, we evaluate the performance of the ACR routing protocol.

A. Routing Overhead Under Different Mobility

In this experiment, we measure the routing overhead of CR routing and LC routing under different mobility and compare their overheads with that of LAR. In the simulation, we use scheme 1 of LAR [1]. In this paper, by "routing overhead," we mean the routing-related packets (i.e., RR and RP) received by various nodes. Fig. 2 shows the routing overheads of different routing protocols versus different maximum node speed; the y axis is the routing overhead (number of routing-related packets) per 100 data packets received; LAR-d refers to LAR in the dense network, and LAR-s refers to LAR in the sparse network.

Fig. 2 shows that the routing overheads of all protocols increase as mobility increases because higher mobility causes more existing links broken. Fig. 2 also shows that CR (in the dense network) has much smaller overhead than LAR-d. The reason is stated as follows. In a dense network, each cell contains several nodes with a high probability. For LAR routing, all nodes in the request zone participate in the flooding, and this causes large routing overhead. In contrast, CR routing significantly reduces the flooding area, which only consists of a serial of small cells from source to destination. Furthermore, in each cell on the route, only one node forwards the RR packet. Also, CR routing has high probability of success because the network is dense. Backup paths further increase the success chance of CR routing. For these reasons, CR routing has very small routing overhead. In addition, Fig. 2 shows that LC has much less routing overhead than LAR-s in the sparse network. This is because LC routing reduces the flooding area for route discovery, which only consists of a serial of LCs from source to destination.

Besides simulations, we also estimate the routing overhead by analytic model. The estimation of the routing overhead of CR and LAR in a dense network is given as follows. Without loss of generality, we make the following assumptions: Nodes are distributed uniformly in the routing area; the routing area is divided into $m \times m$ cells, where m is an even number; there are N nodes in the routing area. For a source node S and a destination node D, we consider the following two extreme cases. First, if S is located on the border of the routing area, the longest distance between S and D is m—1 hops (or cells), with m cells involved in CR routing. For LAR routing, the largest request zone is the entire routing area with m^2 cells. Second, if S is located in the center of the routing area, the longest distance between S and D is $m/2$ hops, with $1 + m/2$ cells involved in CR routing. For LAR routing, the largest request zone is a quarter of the entire routing area with $m^2/4$ cells.

Other location of S is between the previous two cases. We will use the average of these cases to approximate the routing overhead. In any of the previous cases, the closest distance between node S and D is one hop, with one cell (S and D in the same cell) involved in CR routing. Similarly, the smallest request zone in LAR routing is one cell, when S and D are in the same cell. So, in CR routing, the average number of involved cells is $(m + 1)/2$ for case 1 and $(1 + m/2 + 1)/2$ for case 2. The average of the two cases is

$$\frac{(m+1)/2 + (1+m/2+1)/2}{2} = \frac{3}{8}m + \frac{3}{4}.$$

For LAR routing, the average number of involved cells of the two cases is

$$\frac{(m^2+1)/2 + (m^2/4+1)/2}{2} = \frac{5}{16}m^2 + \frac{1}{2}.$$

In the dense network simulations, we use $m = 6$; hence, from the previous formulas, the numbers of involved cells for CR and LAR are 3 and 12, respectively. That is, the routing overhead in LAR is four times as much as that in CR routing. Although the previous estimation is not very accurate, it gives a rough idea of how much saving can be achieved by CR routing; besides, the simulation results shown in Fig. 2 confirm such overhead saving due to CR routing. What is more important from the simple analysis is that the routing overhead of CR is linear in the network size m, whereas the routing overhead of LAR is quadratic in the network size m. Therefore, the traffic saving by CR routing increases as the network size becomes larger.

B. Routing Overhead for Different Transmission Range

In this experiment, we study the routing overhead when node transmission range changes. Fig. 3 shows the effect of varying the transmission range on the routing overhead for different protocols. In the simulation, the maximum node speed is 25 m/s. We first compare the routing overhead of CR and LAR in the dense network. We observe that the routing overhead decreases for both protocols when the node transmission range becomes large. This is because with a larger transmission range, existing links break less frequently under the same mobility.

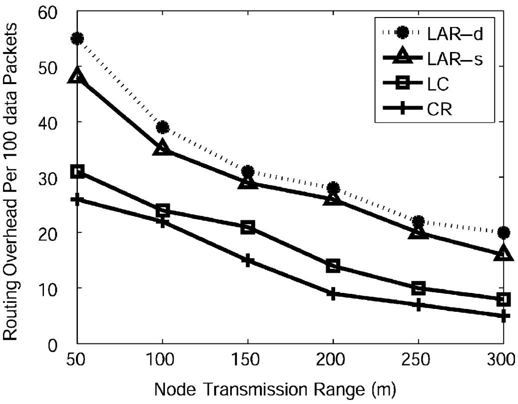

Fig. 3. Routing overhead versus transmission range.

Fig. 3 shows that the overhead of CR is much smaller than the overhead of LAR-d. This is because the CR routing significantly reduces the flooding area and hence reduces the routing overhead. Another reason for the small overhead of CR routing is that, as the transmission range R increases, the cell size becomes larger due to $a = R/(2\sqrt{2})$; hence, the number of cells on the path between the same source destination pair decreases, which results in fewer intermediate nodes participating in the routing and hence less routing overhead, but for LAR routing, when the transmission range becomes large, the request zone in LAR is still the same, and the same number of nodes needs to participate in flooding; hence, the routing overhead is not reduced. Just like CR versus LAR-d, we observe similar results for LC versus LAR-s in the sparse network. Also, we observe that LAR has less routing overhead in the sparse network than in the dense network. This is because in the sparse network there are fewer nodes in the same request zone than in the dense network.

C. Throughput Under Different Traffic Load

In this experiment, we compare the throughput of the routing protocols under different traffic load. The results are shown in Fig. 4. In the simulation, the maximum node speed is 25 m/s. The traffic load varies from 20 to 200 kb/s. Fig. 4 shows that both LAR-s and LAR-d cause network saturation when the traffic load is heavy (i.e., when the traffic load is more than 180 kb/s). The reason is listed as follows. Because LAR uses large area flooding, when the network traffic is heavy, congestion occurs and packets are dropped in the network, which decreases the throughput.

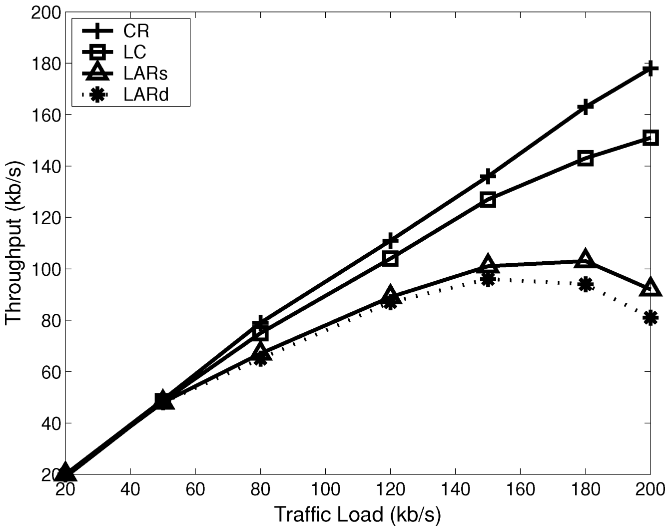

Fig. 4. Throughput versus traffic load.

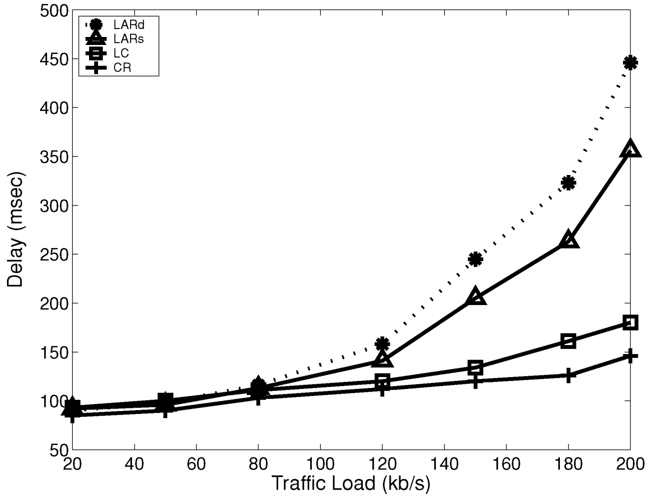

Fig. 5. Delay versus traffic load.

D. Delay

This experiment is to show the delay performance of different routing protocols. Note that the delay is the end-to-end for data packets, not for routing packets such as RR or RP packets. As shown in Fig. 5, when the traffic load is light (less than 80 kb/s), the delay under LAR is very close to that under CR and LC. This is because under light traffic, the network does not have congestion or packet loss. However, when the traffic load becomes heavy, the delay under LAR increases very quickly due to congestion and packet loss. CR routing and LC routing have much smaller routing overhead, so the delay under CR and LC increases slowly as the traffic becomes heavier. Fig. 5 also shows that the delay under LC is a little bit larger than that under CR; this is because LC incurs more routing overhead than CR.

E. Scalability of CR and LC Routing

In this experiment, we study the scalability of CR and LC and compare them with LAR. We implement large networks with both high and low node density, representing a dense network and a sparse network, respectively. For the large dense network, 400 nodes are distributed uniformly at random in a 1000×1000 m area; for the large sparse network, 120 nodes are uniformly distributed in a 1000×1000 m area. The experiment shows that CR and LC scale well (i.e., the routing overhead only increases a little bit) in the large network, whereas LAR has poor scalability (i.e., the routing overhead of LAR becomes very large in the large network).

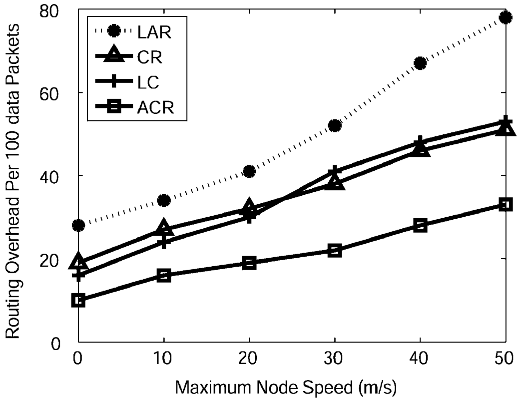

Fig. 6. Routing overhead versus maximum node speed.

F. Performance of Adaptive Cell Relay Routing Protocol

In the experiments, we compare the performance of ACR routing protocol to that of CR routing only, LC routing only, and LAR. In the simulations, 100 nodes are distributed over a 500×500 m area. We use two scenarios to test ACR. The first scenario is the following: At the beginning, all 100 nodes are activated; at the epoch of 500 s, 70 nodes are disabled; the remaining 30 nodes continue to run for another 500 s. This simulates the case where a dense network becomes a sparse network. In the second scenario, only 30 nodes are activated at the beginning; at the epoch of 500 s, the other 70 nodes are activated; then, all 100 nodes run for another 500 s. The second scenario simulates the case where the network node density increases.

The simulations are run for four different routing protocols—ACR, CR, LC, and LAR—and for the two aforementioned scenarios. We run the simulations ten times for each scenario and obtain the average of the ten tests. The test results are similar for the two scenarios, and the average of the two are reported as follows:

1) Routing Overhead: In this experiment, we study the routing overhead of the four protocols under different mobility. For ACR, the routing overhead includes all control packets that are used to detect the node density change and switch the routing strategy. Fig. 6 shows the routing overhead versus the maximum node speed. From Fig. 6, it can be observed that ACR incurs the least routing overhead, as compared with CR, LC, and LAR. This is due to the adaptability of ACR.

2) Throughput: The throughput comparison is presented in Fig. 7. In the simulation, the maximum node speed is 25 m/s. From Fig. 7, it can be seen that the throughput under LAR decreases when the traffic load is very high. The reason is the same as in Section IV-C. We also observe that ACR has higher throughput than CR, LC, and LAR. This is because when the node density changes, ACR can adaptively choose a routing strategy, which best matches the current node density so routing overhead is reduced and throughput is increased.

3) Delay: Fig. 8 plots the delay versus the traffic load for the four routing protocols. It can be observed that when the traffic load becomes heavy, the delay under LAR increases very fast due to congestion and packet loss. ACR, CR, and LC have much smaller routing overhead; hence, the delay under ACR, CR, and LC increases slowly as the traffic becomes heavier. Furthermore, we observe that ACR has a smaller delay than CR and LC; this is because ACR can adaptively switch the routing strategy to the one that performs better.

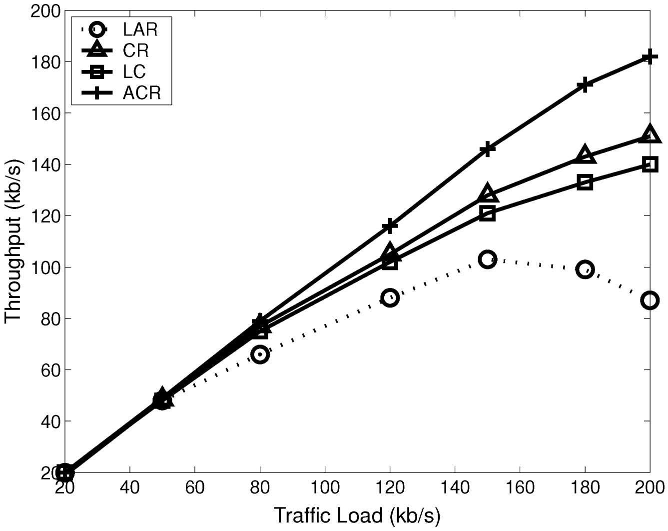

Fig. 7. Throughput versus traffic load.

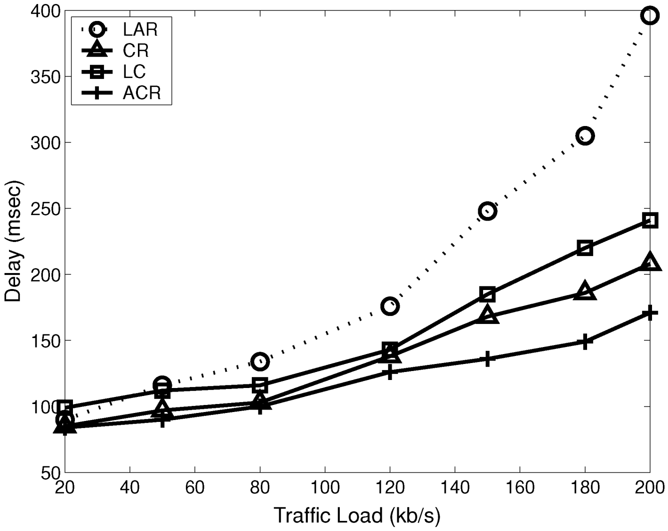

Fig. 8. Delay versus traffic load.

4) Scalability of ACR Routing: In this experiment, we study the scalability of ACR routing and compare it with LAR. We implement a large network with an area of 1000×1000 m. We change the number of nodes in the network from 120 to 400 (or vice versa) to simulate the case where the node density increases (or decreases). Fig. 9 depicts the routing overhead of ACR and LAR versus maximum node speed. In Fig. 9, the routing overhead of ACR and LAR in the large network are labeled as ACR1 and LAR1. For comparison, the routing overhead of ACR and LAR in the small network (500×500 m) are also plotted in Fig. 9, and they are labeled as ACR2 and LAR2. From Fig. 9, it can be seen that the routing overhead of LAR becomes very

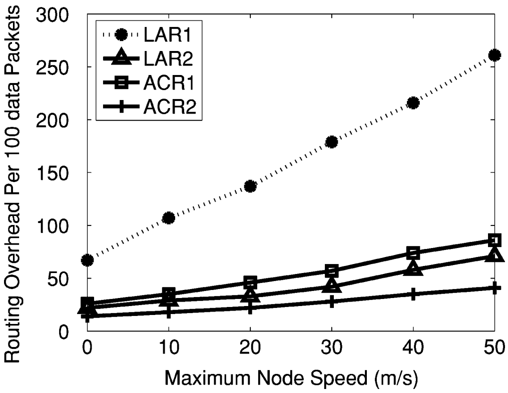

Fig. 9. Scalability of ACR and LAR.

large when the network size increases (illustrated by LAR1), whereas the routing overhead of ACR does not increase much.

V. CONCLUSION

In this paper, we proposed a novel routing protocol for mobile *ad hoc* networks—ACR routing protocol. The key idea is that ACR adaptively changes the routing strategy when the network node density changes. ACR consists of three components: 1) CR routing for dense networks; 2) LC routing for sparse networks; and 3) an adaptive scheme that detects node density changes and initiates the routing strategy change. Extensive simulation results show that ACR performs much better than LAR and performs better than the two single routing strategies—CR and LC. Specifically, ACR has less routing overhead, smaller delay, and larger throughput than LAR, CR, and LC. Our simulation results also demonstrate that ACR scales well in large *ad hoc* networks.

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