LAKER: Learning from Past Actions to Guide Future Behaviors in Ad Hoc Routing

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Abstract

In this paper we present a Location Aided Knowledge Extraction Routing (LAKER) protocol for mobile ad hoc networks (MANETs). **The novelty of LAKER is that it learns from past actions to guide future behaviors.** In particular, LAKER can *gradually discover* current topological characteristics of the network, such as population density distribution, residual battery map, and traffic load status. This knowledge can be organized in the form of a set of *guiding routes*, each of which consists of a chain of guiding positions between a pair of source and destination locations. The guiding route information is learned by individual nodes during route discovery phase, and it can be used to guide future route discovery processes in a more efficient manner. LAKER is especially suitable for mobility models where nodes are not uniformly distributed. LAKER can exploit topological characteristics in these models and limit the search space in route discovery processes in a more refined granularity than Location Aided Routing (LAR) protocol. Simulation results show that LAKER outperforms LAR and DSR in term of routing overhead, saving up to 30%~45% broadcast routing messages compared to LAR approach.

Key words: Guiding route and forwarding route, Knowledge discovery, Knowledge guided routing, LAKER, Mobile ad hoc networks

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1 Introduction

Mobile ad hoc network (MANET) is an infrastructureless network formed by a set of wireless nodes that are capable of moving around freely. There is no fixed infrastructure such as base stations. Each mobile node acts as an end-system as well as a router. Two mobile nodes within the transmission range of each other can communicate directly via the ad hoc wireless link. A multihop route is needed when the destination is beyond the coverage of the sender. Hence routing is a key component of MANET performance. A number of routing protocols have been proposed for MANETs during the recent years [1,2]. Most of these routing protocols can be classified into two categories: proactive protocols and reactive (on-demand) protocols. In proactive approaches, each node will maintain routing information to all possible destinations irrespective of its usage. In on-demand approaches, a node performs route discovery and maintenance only when needed. Due to the nodal mobility and fast changing topology, on demand protocols generally outperform purely proactive protocols.

In wireless network simulations, the mobility model has a significant impact on the performance of the protocol under evaluation. The mobility model dictates how the nodes move in the networks, which results in network dynamics such as link breakages, route failures, and changes in nodal density and topology. All these factors can affect the performance of the ad hoc routing protocol, in terms of routing overhead, packet delivery ratio, and end-to-end delay. A good summary and comparison of various mobility models can be found in [3].

Among the proposed models, the “Random Waypoint” [18] mobility model is most widely used in performance evaluation of ad hoc routing protocols. In this model, initially all the mobile nodes are uniformly distributed in the simulation area. When the simulation starts, each node stays at its initial position for a specific duration called *pausetime*, and then randomly selects a destination within the simulation area, and starts moving towards this destination with a stable speed, which is randomly chosen from a predefined range. When the mobile node arrives at the destination, it will stay there for *pausetime* seconds, then chooses another destination and new speed and continues to move, and so on.

The “Random Waypoint” mobility model does not capture the mobility and topological characteristics in the cases where nodes may cluster at some sub-regions of interest instead of randomly moving around. For example, there are several events occurring at different places on a large campus, mobile users roam from one event location to another, pausing for a certain period of time at each location. We believe this is more realistic than randomly choosing destination. Another example is that there is an obstacle region (like a lake) within the simulation area and the mobile users are restricted from entering these regions. In order to capture this kind of mobility patterns, a recent work [4] proposed the “Restricted Random Waypoint” model. In this modified mobility model, a mobile node will randomly choose a destination only from a set of sub-regions, which are separated as small parts of the whole simulation area. A similar mobility model was used in [5]. Some more recent work on ad hoc mobility modeling can be found in [6,7].

In this paper, we adopt the “Restricted Random Waypoint” mobility model, and propose a new routing approach: Location Aided Knowledge Extraction Routing (LAKER) protocol. The design of LAKER is aimed at taking advantage of topological characteristics (for example, distribution of population density) of the network. During a route discovery process, our approach attempts to extract knowledge of the node density distribution in the network, and memorizes the series of locations along the route where the nodal density is high. We call the series of “important” locations (not nodes) as a *guiding route*. The motivation behind the *guiding route* is that, in many situations, even though individual nodes may move fast, the population density distribution of the network does not change so rapidly. Take a look at the previous campus events example: while individual users may come and go from an event location to another, relatively fast, the topological distribution of these populated event spots will stay mostly unchanged over the time. This observation justifies the possibility of discovering topological characteristics of the network, which we term as guiding information. Using the guiding information, we can further narrow the search space in the route discovery process and, at the same time, overcome the problem of “void” area in the network. Simulation results show that LAKER can save up to 30%˜45% broadcast control messages compared to the LAR approach, while achieving higher delivery ratio and similar or better end-to-end delay.

The rest of this paper is organized as follows. In Section 2, we provide some preliminaries. The design of LAKER protocol is described in Section 3. Performance evaluation of LAKER based on simulation is presented in Section 4. Section 5 outlines the related efforts, followed by the concluding remarks in Section 6.

2 Preliminaries

In this section, we first introduce the operation of flooding based route discovery in ad hoc networks as well as techniques in reducing flooding overhead during the process. Our LAKER approach is related to this line of discussion. We then present some important assumptions made to facilitate the discussion for the rest of this paper. We will also discuss the notion of *guiding route*, which is the cornerstone of our work in this paper, and the difference between *guiding route* and *forwarding route*.

LAKER inherits the route caching strategy from DSR. In addition to caching *forwarding route* as DSR does, LAKER also attempts to cache a new kind of information about the network topology – *guiding route*. By caching the *guiding routes* in LAKER, the topological characteristics of the network are exploited, hence the mobility model used in study will have a greater impact on our algorithm.

2.1 Flooding Based Route Discovery

On-demand protocols, such as Dynamic Source Routing (DSR) [8] and Ad hoc On demand Distance Vector (AODV) routing [9], often use flooding techniques to search for a new route. Flooding based route discovery works as follows. When a node S has some data to send to node D but has no existing route to the destination, it will initiate a route discovery process by broadcasting a route-request packet. An intermediate node I, upon receiving the route-request packet for the first time, will rebroadcast the route-request again if it does not know a route to the destination node D. Finally, when the route-request packet arrives at a node (which may be the destination node D itself) that has a route to node D, a route-reply packet is sent back to the sender node S.

To reduce the flooding overhead, a variety of optimizations have been developed. For example, DSR aggressively utilizes route caching strategy to reduce the number of route-request messages. As the route-reply message propagates back to the requester, all neighboring nodes along the route can listen to the route information in a promiscuous way and store the route information in its cache. Later, when a new route-request message is propagating in the network, an intermediate node that has a cached route to the destination can reply to the requester without relaying the route-request message. So the total routing overhead can be reduced. The disadvantage of caching route is that these cached routes may be obsolete by the time it is used, especially under relatively high mobility. Our idea is that it will be more desirable to cache some long-lived properties of the network other than the to-be-broken routes. In real mobility patterns, nodal density may not be uniform across the network. Some parts of the network may have dense clusters of nodes, while some other parts may have sparsely distributed nodes. We believe it is helpful to discover and cache this kind of nodal distribution information and use it to guide future route discovery processes.

Another technique to reduce flooding overhead is using the geographical location to limit the flooding area. This approach is used in some protocols such as LAR [10] and DREAM [11]. According to both the sender and the receiver's locations, a reduced flooding sub-region can be defined instead of flooding the entire network. For example, in LAR the geographical location information is carried with the route-request messages. Upon receiving a route-request message, an intermediate node will determine if it is in the reduced flooding area. Only those nodes in the limited area rebroadcast the route-request message, hence the number of routing messages is reduced. In some cases, however, this method of defining the flooding area solely by the source and destination locations is too coarse in granularity. In some other cases, it may not be able to overcome the "void" area in the network and has to resort to flooding the entire network (discussed later in Section 3.1).

Our motivation behind LAKER is to exploit the topological characteristics in non-uniform network environments. With the assistance of guiding knowledge, LAKER naturally leads to even more limited search space and thus more reduced routing overhead, while being capable of bypassing some "void" area.

2.2 Assumptions

The assumptions we make for our discussion about LAKER are as follows.

- Each node knows its current location, for example, by means of Global Positioning System (GPS) [14]. In cases where the mobile nodes do not have

GPS capabilities, some form of localization technique can been used to obtain location information of individual nodes. A lot of GPS-free localization methods for mobile networks have been proposed in the literature (for example, see [15,16]), which is beyond the scope of this paper.

- Each node keeps track of the number of neighbors it has. This can be achieved, for example, by means of periodic beaconing messages on the network layer, or with assistance from the data link layer.
- Each node has an End-system Unique Identifier (EUI).
- There exists a geographical location service (for example, see [17]). When node S has data to send to node D, node S can obtain node D's approximate location by looking up the location service.

2.3 Guiding Route v.s. Forwarding Route

The basic idea of LAKER is to distinguish *guiding route* from *forwarding route*. A *forwarding route* is a series of node EUIs which connect a source node to a destination node hop by hop. A *guiding route* is a series of "important" locations which start from one location (source) and lead to another location (destination). In particular, we consider node population distribution in this paper, and the importance of a location is determined by the number of neighboring nodes at that place. In this context, a guiding route is a series of locations along a *forwarding route* where there seems to be many nodes clustering together. For example, S → B → L → M → A → C → W → D is a forwarding route between nodes S and D. Assume that nodes B, M, W are in locations where the node density is high, whereas nodes L, A, C are in lightly populated areas. Therefore, a guiding route between S's location and D's location is: $(X_s, Y_s) \rightarrow (X_b, Y_b) \rightarrow (X_m, Y_m) \rightarrow (X_w, Y_w) \rightarrow (X_d, Y_d)$.

The rationale behind this approach is that, although individual nodes may come and go fast, the structure of populated areas is not expected to change so rapidly. So it is possible to discover and cache this long-lasting guiding information during the route discovery process. In the next round of route discovery process, this information can be used to guide the route discovery direction and narrow the search space, even at a finer granularity than the LAR approach.

3 LAKER Protocol

In this section, we describe our proposal – a Location Aided Knowledge Extraction Routing (LAKER) protocol for MANETs. The *guiding routes* – which have the knowledge of the population density distribution of the network – play an important role in LAKER's route discovery process. Existing knowledge can be used to guide the flooding, and new knowledge may be discovered in the course of route discovery. We will discuss two important functionalities of LAKER: knowledge guided route discovery and location aided knowledge discovery.

3.1 Knowledge Guided Route Discovery

With self-discovered knowledge of current network status, LAKER can direct route discovery processes in a more efficient manner. In this subsection, we describe the new fields we add to LAKER's routing messages to accommodate guiding information. We also present LAKER's knowledge guided routing algorithm, and the advantages of using this approach.

3.1.1 Extensions to Routing Messages

In addition to the functionalities of DSR and LAR, LAKER needs extensions to the route-request and route-reply messages to facilitate knowledge discovery and smart routing behaviors. The important fields in LAKER's route-request message and their meanings are listed in Table 1.

field name	meaning
source_EUI	ID of source node
destination_EUI	ID of destination node
traversed_forwarding_route	place to store newly discovered forwarding route
source_location	location of source node
destination_location	location of destination
guiding_route	existing guiding information
traversed_guiding_route	place to store newly discovered guiding information

Table 1

Important fields in LAKER's route-request message

As shown in Table 1, the first three items are standard contents of a DSR route-request message. As the name indicates, *traversed_forwarding_route* stores a chain of node EUIs that have been traversed so far. The next two items, *source_location* and *destination_location,* are introduced in LAR to define the request zone, which may be chosen as a rectangular shape. The last two items are newly introduced in our proposal of LAKER. The field *guiding_route* stores the existing guiding information to direct current route discovery process. Initially this field may be empty if the source node does not have any guiding route to the destination location. As the route-request message propagates in the network, intermediate nodes may fill in some guiding information if they have. Even if the route-request message starts with a guiding route, intermediate nodes can still update the field *guiding_route* if they have newer information. The field *traversed_guiding_route* stores a chain of "important" positions, i.e., the newly discovered partial guiding information, as the route-request message propagates in the network.

The route-reply message contains these fields: *source_EUI*, *destination_EUI*, *discovered_forwarding_route*, and *discovered_guiding_route*. Their meanings are similar to those fields in the route-request message.

3.1.2 Route Discovery Algorithm

LAKER uses an on-demand request-reply mechanism in route discovery. When node S needs a route to node D but cannot find one in its cache, it will initiate a route discovery process by broadcasting route-request message into the network.

The LAKER route discovery algorithm is shown in Algorithm 1. RREQ stands for a route-request message, and RREP for a route-reply message. Upon receiving RREQ, intermediate node X first adds its guide position to the *traversed_guiding_route* field in RREQ if it thinks its location is important (this will be further discussed in Section 3.2). Node X then decides if it is within the request zone based on the guiding information carried in RREQ, and processes RREQ accordingly, that is, rebroadcasts or drops it. During this process, intermediate nodes can update the *guiding_route* field in RREQ if they have newer guiding information towards the destination location.

This algorithm is executed at intermediate nodes, hop by hop, until the route-request message reaches a node that has a forwarding route to the destination, or reaches the destination node itself. One or multiple route-reply messages will get back to the source node.

3.1.3 Further Reduced Search Area

Using *guiding route* to direct the route discovery process has advantages over LAR approach. First, it can guide the route discovery direction more precisely and further narrow the search space even compared to the LAR approach. An

Algorithm 1 Knowledge guided route discovery in LAKER

```
when intermediate node X gets RREQ from node S to node D :
if node X is located in an important position
    add X's guiding position to traversed_guiding_route in RREQ
endif
if node X has forwarding_route to the destination D
    send RREP back to the source S
else
    if node X has newer guiding_route to the destination D
        update guiding_route in RREQ
    endif
    if guiding_route exists in RREQ
        if node X in the LAKER request zone
            rebroadcast RREQ
        else
            drop RREQ silently
        endif
    else
        rebroadcast RREQ
    endif
endif
```

example is illustrated in Figure 1. P1 and P2 are two guiding positions along the guiding route. The request zone of LAKER is defined by the location of the source node S, the guiding positions, and the "expected zone", which is the estimated region where the destination node is currently located. As discussed earlier, the population density is not uniformly distributed in the network area. There are some sub-regions with higher population density. In route discovery phase, it is very likely to find a feasible route by limiting the search space along this chain of "populated spots". Only nodes in this narrow band will participate in the route discovery process. Since the search area is further reduced, LAKER is expected to incur less routing overhead than LAR approach.

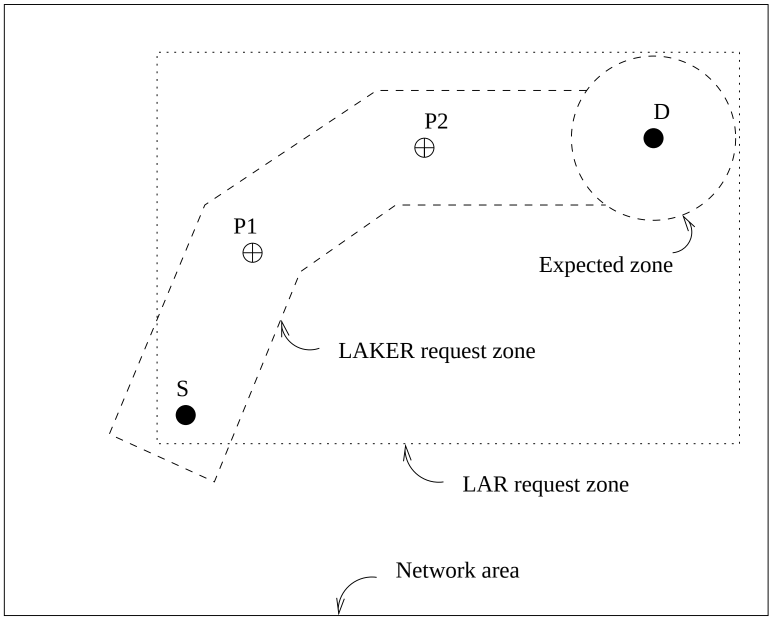

Fig. 1. Request zone: LAKER v.s. LAR

3.1.4 Dealing Smartly with Void Area

The second advantage of using guiding routes is that a route-request message can smartly pass around the "void" areas that exist in the network, as illustrated by an example shown in Figure 2. Note that there is a void area (which may be a lake) in the network area. If using LAR's rectangular request zone, it will fail in searching a feasible route to the destination and will have to repeat with an expanded request zone up to the whole network. If the source node S has related guiding information in cache, say, S → P1 → P2 → P3 → D is the guiding route, it can use this information to direct the route discovery process to pass around the void area instead of expanding request zone up to the entire network.

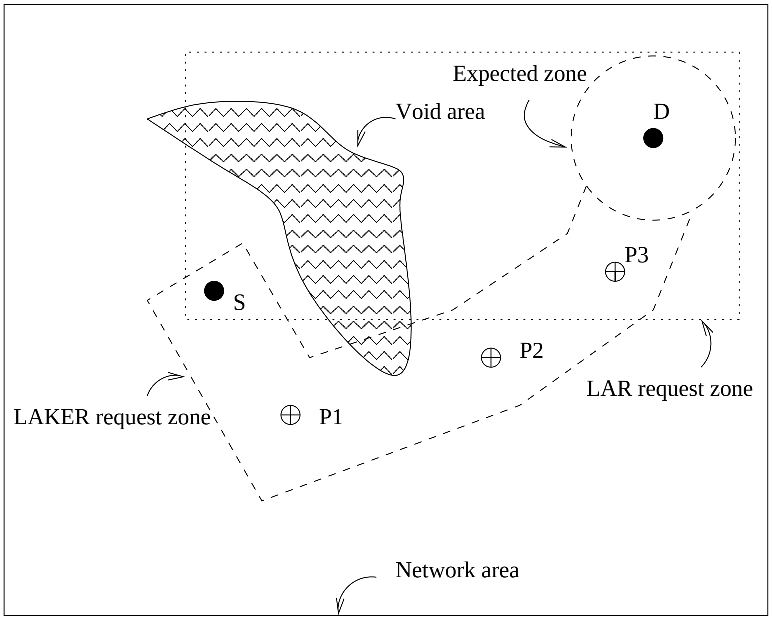

Fig. 2. Route discovery with void area in the network

3.2 Location Aided Knowledge Discovery

In the route discovery phase of LAKER, our design allows mobile nodes to extract partial knowledge of the topological characteristics in the network. So, in the route discovery phase, not only a forwarding route is searched to a *node* with the requested EUI, but also a guiding route is searched towards a geographical *location* in the network. In this section, we discuss how LAKER can collect information about "important" positions as the route-request message propagates in the network, how this kind of guiding information is extracted to form a guiding route, and how to make necessary adaptation on existing guiding routes as time goes by and nodes move around.

3.2.1 Information Collection

In order to discover potential knowledge of current network status, a route-request message needs to collect necessary information as it is being broadcasted hop by hop. In particular, it attempts to identify and remember those important locations in terms of metrics of interest. Examples of such metrics of interest are population density, residual energy capacity, traffic load, etc. In our discussion on the design of LAKER, we mainly consider population density, i.e., try to remember those places with dense distribution of mobile nodes.

As described in Algorithm 1, when relaying a route-request packet, if an intermediate node believes that its location is of importance, it will calculate its *guiding position*, and append this information to the *traversed_guiding_route* field in the route-request packet. Note that a node's *guiding position* is different from its own geographical location. Instead, it is a *calculated* position which indicates a spot where there are many mobile nodes.

Algorithm 2 Determination of a node's guiding position

```
At intermediate node I, upon relaying a RREQ message:
ctr = 0; G={} /* G is initially an empty set*/
for each neighboring node $N_i$ of node I
  if speed($N_i$) $< S_1$
    put $N_i$ into G set
    ctr ++
  endif
if ctr $> K_1$
  mark this position as "important" in RREQ message
  calculate node I's guiding position:
    $Guide\_Pos(I).X = \frac{\sum_{i=1}^{|G|} X_i}{|G|}$ /* $|G|$ is the number of nodes in G set */
    $Guide\_Pos(I).Y = \frac{\sum_{i=1}^{|G|} Y_i}{|G|}$
endif
```

How can a node determine its guiding position? The procedure is shown in Algorithm 2. First, each node keeps track of the number of its direct neighbors. If the number of *slow* neighbors (i.e., with speed under S_1) exceeds a certain threshold, K_1, the node will consider itself located in an important position in term of population density. We only consider relatively slow neighbors because we are interested in stabler clusters. Second, the node calculates its guiding position by obtaining the average of coordinates of all its slow neighbor nodes. This use of average coordinates can overcome inaccuracy when an intermediate node is located at the edge of a populated spot, because its guiding position is the center of its neighbors instead of its own position. An example for such cases is illustrated in Figure 3.

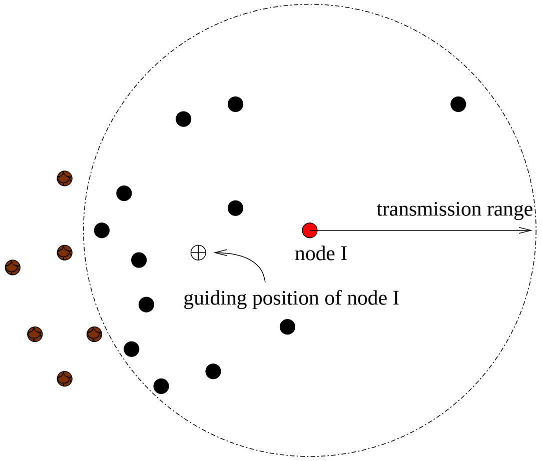

Fig. 3. An example: how node X gets its "accurate" guiding position

3.2.2 Knowledge Extraction

When a route-request message finally reaches the destination node, it contains both forwarding route and guiding positions information. Based on our assertion, a guiding route is a chain of locations that indicates a "good" search direction for route discovery process. To achieve this design goal, we need to extract *appropriate* guiding positions from all those potential candidates to form a "good" guiding route. By *appropriate*, we mean that we do not want two adjacent guiding positions to be too close or too far away. If they are too close or too far, the resultant guiding route will lose its function as an indicator of search direction. In our simulations, we find that this parameter is quite application-specific and depends on factors such as wireless transmission range and network density.

After the destination node extracts forwarding route and guiding route information from the received route-request message, it will send a route-reply message back to the route requester (i.e., the source). As the route-reply packet propagates back to the source node, it contains both forwarding route and guiding route between the source and destination pair. We assume that each mobile node operates in a promiscuous mode, so it can *snoop* [1] guiding route as well as forwarding route information from all pass-by routing packets it eavesdrops.

When the route-reply message gets back to the source node, it will cache both the *guiding route* as well as the *forwarding route* information. Note that, before adding newly learned guiding route to its cache, a node will first decide whether this guiding route adds *new* knowledge by comparing it with prior guiding routes in cache. If it is determined that this new guiding route is fairly close to one of the existing guiding routes in cache, the new guiding route will be discarded. Since cache size is limited, if the cache if full, a victim entry will chosen to be deleted based on their freshness in order to spare space for the new guiding route. After caching useful knowledge, the node starts sending data packet using the newly obtained forwarding route. After some time, the *forwarding route* may be broken. The source node will then pick a *guiding route* from its cache, and initiate a new route discovery process.

3.2.3 Knowledge Adaptation

The motivation of caching guiding routes is to learn from the past and better direct future behaviors. As time goes by and a node moves around significantly, some guiding routes in the cache may become obsolete. So a node needs to adapt its knowledge in the cache from time to time as it moves around. There are two possibilities: the node has moved closer to, or farther away from the first position of a guiding route. If the node has moved too far away from the

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[1] The technique of snooping has been used in Dynamic Source Routing (DSR) protocol.

first guiding position, it will just delete the guiding route from its cache. If the node has moved towards the first guiding position and it is now close enough to the second guiding position, it will update the guiding route by deleting the first guiding position.

4 Performance Evaluation

In this section, we evaluate the performance of LAKER protocol through simulations using the *ns-2* simulator [20]. The Monarch Group's mobility extension [21] to the *ns-2* simulator provides detailed implementation of IEEE 802.11 radio and MAC specifications. In order to compare the results of the LAKER approach and the LAR approach, we utilize the code-base of DSR in the *ns-2* simulator and integrate LAR and LAKER algorithms into DSR.

To evaluate the performance of LAKER, we mainly consider three metrics: the number of routing messages, the packet delivery ratio, and the end-to-end delay. For each *pausetime* (i.e., each point of the curves), we run multiple rounds of simulations using different moving patterns. We then obtain the average results and compare the performance of DSR, LAR, and LAKER protocols.

4.1 Non-Uniform Network

As discussed in Section 1, mobility modeling will have great impact on the performance of routing protocols. To show LAKER's ability in exploiting the topological characteristics of the network, we use a more or less artificial model in simulation as shown in Figure 4. Note that population density is not uniform in different parts of the network. Connections take place between mobile nodes located in the diagonal "corner" parts of the network.

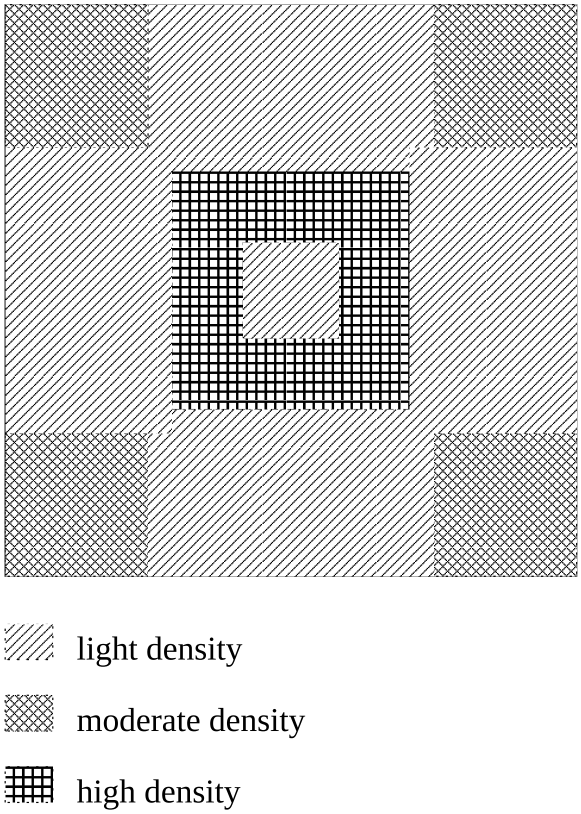

Fig. 4. Simulation mobility model I: A non-uniform network

The simulation area is 1200×1200 square meters. A node's speed is uniformly distributed in the range of (0, 10) meters per second, and the wireless transmission range is 250 meters. We use a 150 node network in simulation. There are 12 constant-bit-rate (CBR) connections, each of which randomly starts during the first 100 seconds and has a bit rate of 2 packets per second. We intendedly choose a relatively light to medium traffic load to evaluate the routing performance while avoiding unacceptable packet drop due to traffic queue overflow for all three protocols. Each simulation runs for 300 seconds of simulation time. Mobile nodes move within the simulation area according to the "Restricted Random Waypoint" mobility model. The parameter *pausetime* reflects the degree of mobility. For different mobility degree, we use different *pausetimes* of 0, 30, 60, 120, 180, 240 and 300 seconds. When *pausetime* is 0 seconds, it means that all nodes are moving all the time and the MANET has a high degree of mobility. When *pausetime* is 300 seconds, it means that all nodes are stationary during the simulation.

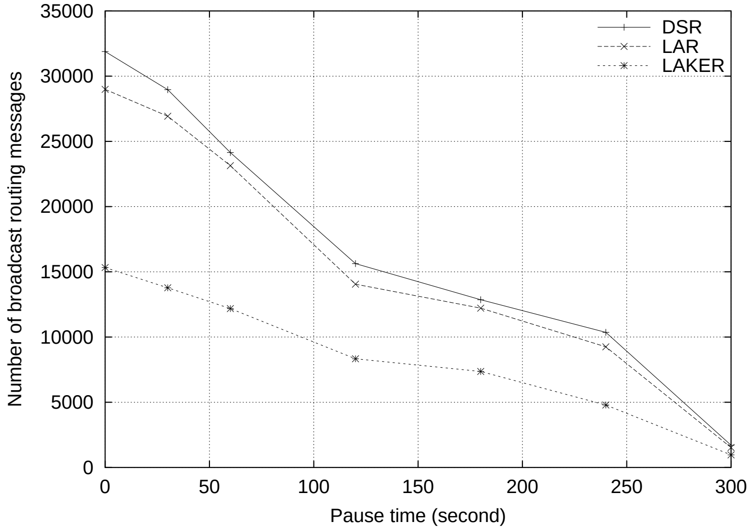

Fig. 5. Non-uniform network: Number of broadcast routing messages

First, the routing overhead is shown in Figure 5. We can observe that LAKER can greatly reduce the number of broadcast routing messages, compared to both DSR and LAR. LAKER protocol can discover topological characteristics of the network and use this information to guide its route discovery in a more efficient manner. On an average, LAKER can save up to 30% broadcast control message compared to LAR. As the *pausetime* increases, the difference between routing overhead in LAKER, LAR and DSR reduces. This is because the mobility of the network reduces as *pausetime* increases, and routing activities become less and less. Note that the number of broadcast routing messages in LAR is just a little less than that of DSR in our simulation, which is natural because communicating nodes are in the four corners and connections take place between nodes in the diagonal corners, and thus the LAR request zone is often comparable to the entire network area.

Second, the path optimality ratio is shown in Figure 6. The path optimality ratio is defined as:

$$Path\,optimality\,ratio = \frac{Hop\,count\,of\,actual\,route}{Hop\,count\,of\,ideal\,route} \tag{1}$$

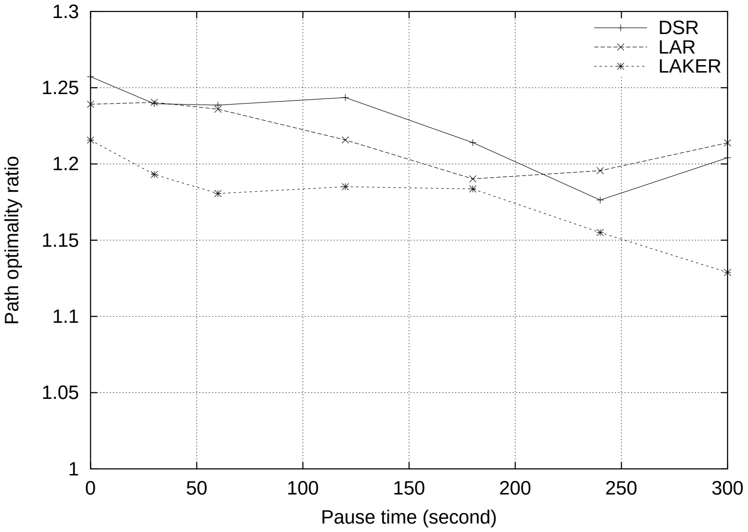

Fig. 6. Non-uniform network: Path optimality ratio

The path optimality ratio is an important metric for considering the quality of routes that are discovered. Because routes discovered will be used to transfer many data packets, the smaller is the path optimality ratio, the better are the discovered routes. We observe that, on an average, all the three protocols can achieve almost the same path optimality ratios. Considering that LAKER uses a further reduced search space in route discovery processes, it is very desirable that it does not sacrifice path optimality while reducing routing overhead.

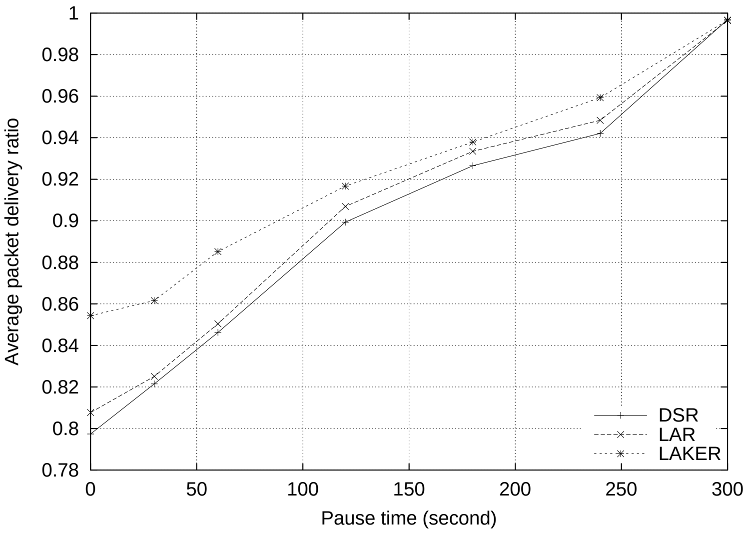

Fig. 7. Non-uniform network: Delivery ratio

Third, Figure 7 shows the end-to-end delivery ratio. As *pausetime* increases, the packet delivery ratios in all three protocols increase because the network mobility is reduced. We observe that LAKER can achieve a higher delivery ratio than LAR and DSR. We believe this is because of the fact that LAKER can reduce the number of broadcasting messages, which leads to fewer packet collisions.

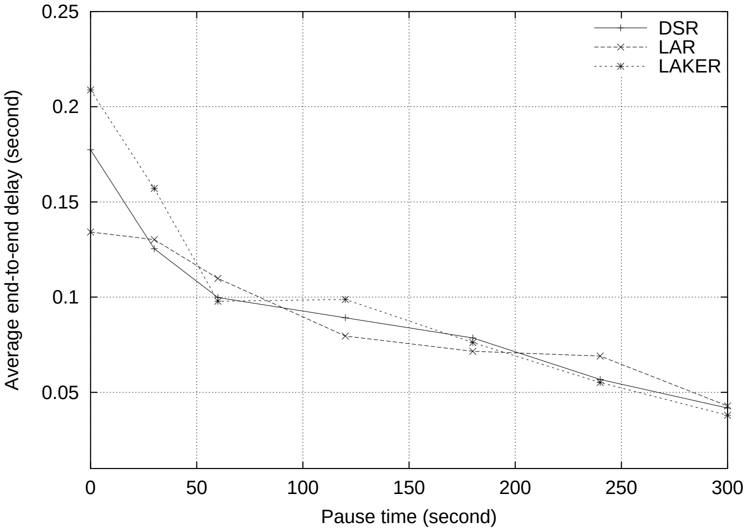

Fig. 8. Non-uniform network: End to end delay

Now let us observe the end-to-end delay shown in Figure 8. Except for some cases at small *pausetime*s (such as 0 and 30 seconds), LAKER can achieve almost the same delay as LAR and DSR. The reason that LAKER has a little higher end-to-end delay at low *pausetime*s is because LAKER attempts to search for new routes in a very limited space, which may lead to the discovery of some fragile routes, which in turn will incur more delay for packet delivery.

4.2 Network with Void Area

To verify LAKER's capability of dealing smartly with "void" area, we have run simulations with a non-uniform network with a lake of rectangular shape, as shown in Figure 9. The network area is 1200×1200 square meters, and a lake of 300×500 square meters is located in the center region. Here we assume that no mobile node can enter the lake area. For the purpose of guide route discovery, we place two flag nodes near the two ends of the rectangular lake.

When a mobile node finds itself close enough (say, 150 meters) to a flag node, it will think it is located in an important position. In our simulations, two CBR connections take place between the shadowed parts on the right and the left sides. All other simulation parameters are the same as those in Section 4.1 unless it is stated otherwise.

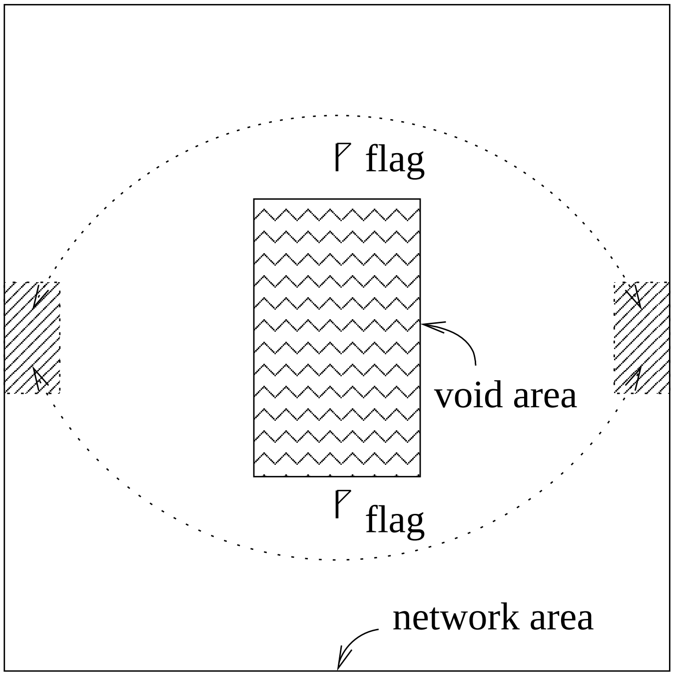

Fig. 9. Simulation mobility model II: A network with void area

First, the number of broadcast routing messages is shown in Figure 10. As the pausetime increases, all three protocols incur less and less routing overhead because the network becomes more stable. In general, LAKER has reduced routing overhead compared to both DSR and LAR. On an average, LAKER can save up to 30% broadcast control message compared to LAR. In cases of low pausetimes (0 and 30 seconds), LAR has even higher overhead than DSR. This is because LAR does realize the existence of void area, and it fails a couple of times in search of new routes using its rectangular request zone. LAR has to enlarge its request zone when the outstanding route-request is expired without any reply message. In the worst case, it has to resort to network wide flooding for route discovery. This trial process of LAR results in unnecessary routing overhead when there exists obstacles in the network area. On the contrary, LAKER can discover helpful guiding route information and bypass the lake area and go through only the top or the bottom region, which naturally leads to reduced routing overhead.

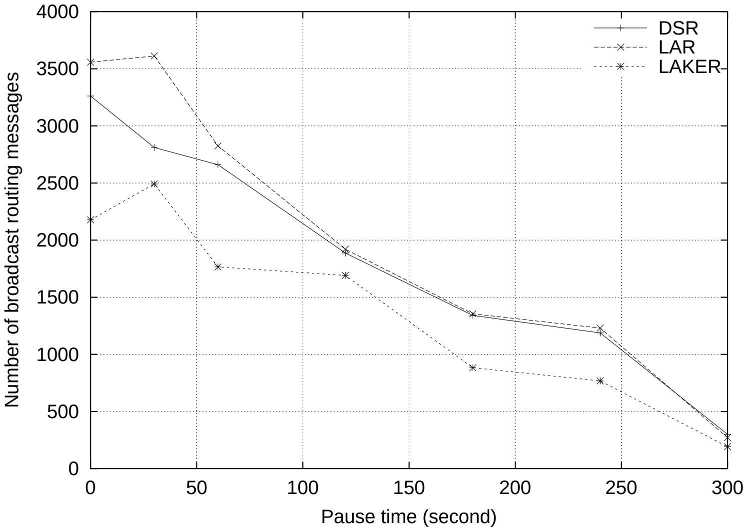

Fig. 10. Network with void area: Number of broadcast routing messages

Second, Figure 11 shows the packet delivery ratio. We observe that LAKER outperforms both DSR and LAR. LAR achieves worse delivery ratio than DSR in all pausetimes. We believe that LAKER performs better because it successfully reduces the broadcasting overhead, which translates to fewer collisions and higher delivery ratio. The reason that LAR delivers much less traffic is two fold. On one hand, its higher routing overhead (at low pausetime cases) can result in more transmission collisions. On the other hand, more importantly, LAR's process of expanding ring search incurs too much delay in route discovery, which may lead to many data packets' drop-off due to lifetime expiration.

Third, as shown in Figure 12, LAKER achieves almost the same end-to-end delay as DSR. However, LAR shows much higher end-to-end delay than both DSR and LAKER. Since transmission time should be basically the same in all three protocols, the end-to-end delay is mainly due to the waiting time for new routes to be discovered. This again demonstrate s that LAR's route discovery process incurs too much delay in presence of void areas in the network.

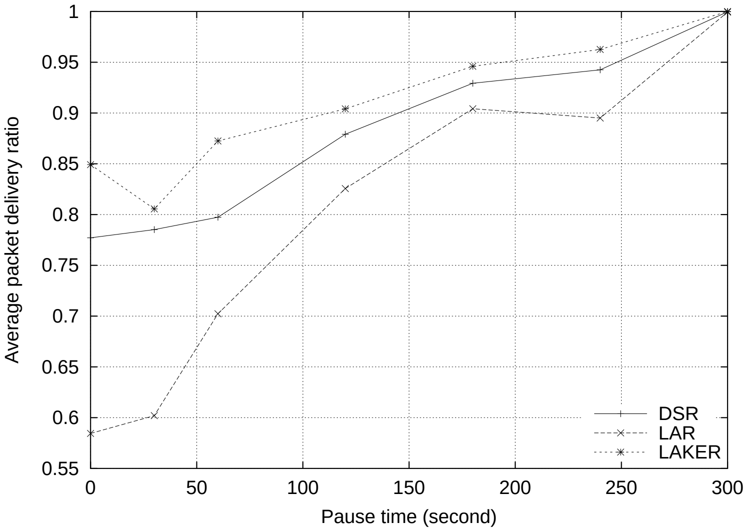

Fig. 11. Network with void area: Delivery ratio

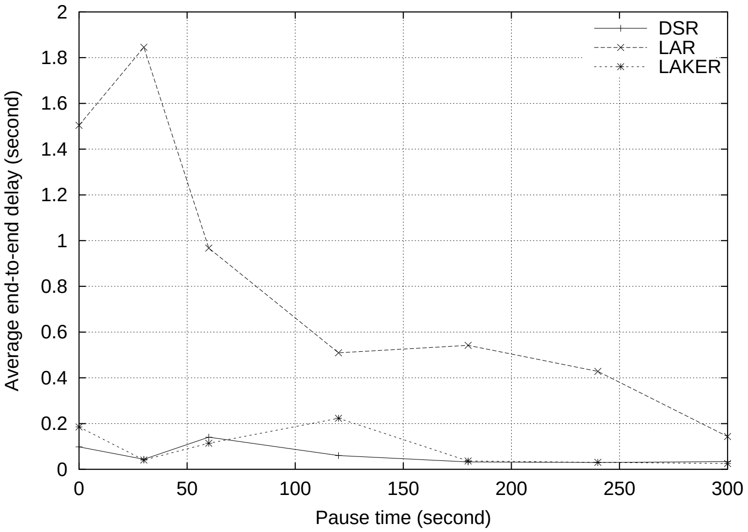

Fig. 12. Network with void area: End to end delay

As a summary for this sub-section, in presence of void areas in the network, LAR may end up with poor performance without any knowledge of the topology. On the contrary, LAKER can bypass the void areas using discovered guiding information, and achieve better routing performance than LAR and DSR.

We also run simulations in networks with uniform node distributions. The network area is 1200×1200 square meters. All the simulation parameters are the same as in Section 4.1 except that mobile nodes are uniformly distributed and move according to the Random Waypoint Model. As in previous simulations, we consider routing overhead, delivery ratio, and end-to-end delay.

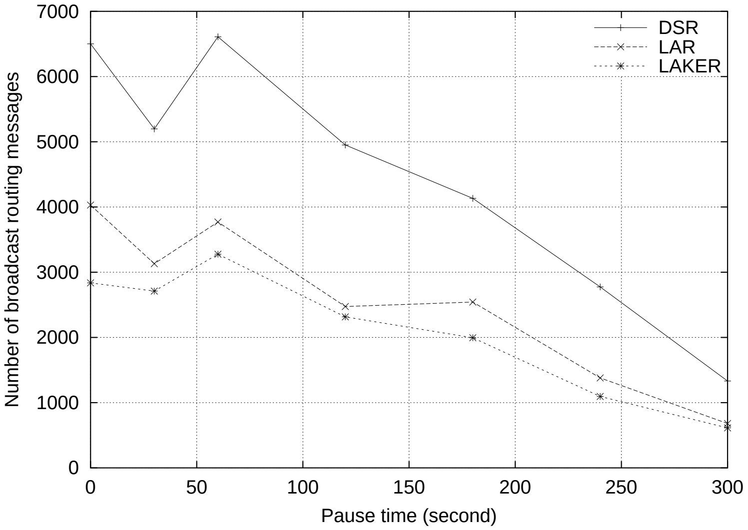

Fig. 13. Uniform network: Number of broadcast routing messages

As shown in Figure 13, the number of broadcast routing messages in LAKER is almost the same as LAR, while both LAKER and LAR incur much less routing overhead than DSR. That is to say, when there is no significant topological structures in a uniform network, LAKER can still act as good as LAR approach.

The results for the delivery ratio is presented in Figure 14. We can observe that in a uniform network, both LAKER and LAR achieve almost the same performance as DSR. As the *pausetime* increases, network mobility decreases and all the three protocols achieve a higher delivery ratio. Figure 15 shows the end-to-end delay. On an average, all the three protocols achieve almost the same end-to-end delay.

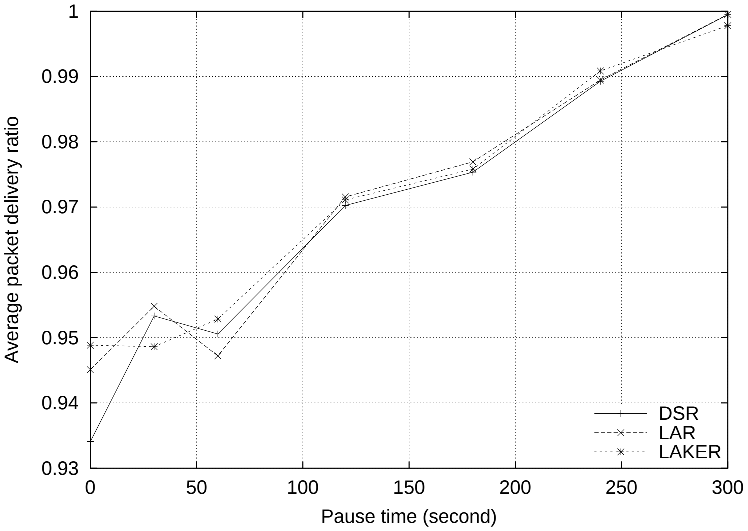

Fig. 14. Uniform network: Delivery ratio

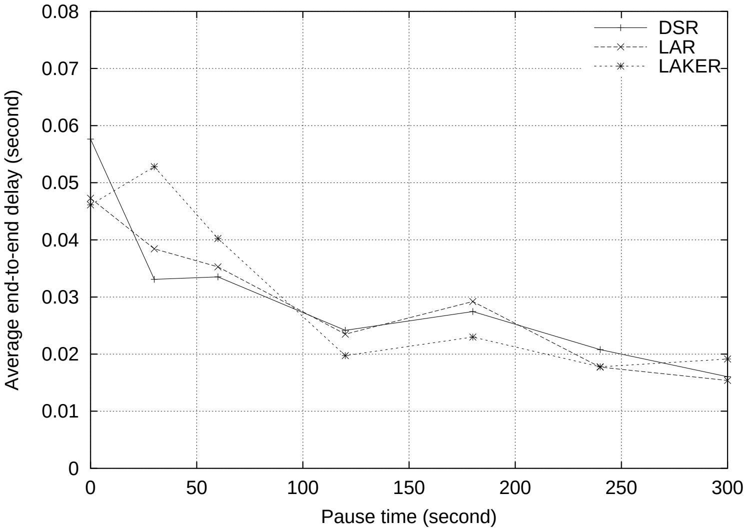

Fig. 15. Uniform network: End to end delay

In summary, we observe that LAKER performs almost the same as LAR in a uniform network. This is because, by design, LAKER will degrade to LAR when there is no topological structure in the network. However, in the presence of any topological non-uniformity, LAKER outperforms both DSR and LAR.

5 Related Work

Mobility modeling and location guided routing have gained much attention from researchers recently. A survey on mobility models in ad hoc networks can be found in [3], and a number of position based routing protocols are summarized in [2]. Here we only discuss a few efforts that are closely related to our work.

LANMAR routing protocol [19] attempts to exploit the network characteristics aiming at addressing the scalability problem. The protocol adopts a "Reference Point Group Mobility" model and attempts to keep track of logical subnets in which the members have a commonality of interests and are likely to move as a "group". LAKER is different from LANMAR in that it attempts to keep track of the population density distribution of the network, aiming at reducing routing overhead by means of better guidance in route discovery.

The restricted random waypoint mobility model we adopt in this paper was proposed in [4]. The authors of [4] also proposed an "Anchored Geodesic Packet Forwarding" approach to solve the problem of "void" area in the network. As proposed in [4], the knowledge of "anchored path" is generated with assistance from a set of friend nodes in the network, or based on a predefined map of population density. When forwarding data packet,"anchored path" is used as loose source routing information, which is similar to our notion of "guiding_route". Our work is different from [4] in the sense that we use a different way to generate and utilize this guiding information. In particular, LAKER can gradually *discover* partial knowledge of the network characteristics in route discovery phase, and smartly use this information to guide future route discovery processes.

GFG routing protocol proposed in [12] can achieve guaranteed delivery in unicasting, broadcasting, and geocasting in ad hoc networks. A major feature of

GFG is that it does not require duplicate message or persistent use of memory of any node during message delivery. Based on a static and connected topology, the authors showed the correctness of the protocol, even in face of a “void” area where all neighbors are further away towards the destination. Another protocol proposed in [13], named GPSR routing protocol, also aggressively uses geographical location information in making routing decision. When an intermediate node receives a packet, it will greedily forward this packet to one of its neighbors, which can mostly reduce the distance towards the destination node. When a packet is stuck at some intermediate node due to the existence of “void” area in the network, a perimeter routing technique is applied to find a bypassing route towards the destination.

6 Conclusion

In this paper we present a Location Aided Knowledge Extraction Routing (LAKER) protocol for MANETs. In mobility models where nodes are not uniformly distributed, LAKER can gradually discover topological characteristics of the network, such as population density distribution, during the route discovery process. This kind of knowledge can be organized in the form of a set of guiding routes, and can be used to guide future route discovery processes more precisely and more efficiently. Simulation results show that, in networks with non-uniform node population distributions, LAKER can save up to 30%˜45% broadcast control messages compared to LAR approach, while achieving higher delivery ratio and similar or better end-to-end delay. In the presence of void areas in the network, LAKER can smartly direct its route discovery process to bypass the void area and thus achieve much better performance than DSR and LAR approach.

The key feature of LAKER is that it learns from past actions to improve future performance. In our simulations, we only use population density distribution and a lake as void area for demonstration. It is also possible for LAKER to discover other topological characteristics such as residual energy map and current traffic load. LAKER can be considered as a generic approach for knowledge discovery and knowledge guided routing in wireless ad hoc networks.

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References

[1] E.M. Royer and C.-K. Toh. A Review of Current Routing Protocols for Ad-hoc Mobile Wireless Networks. IEEE Personal Communications, Apr.1999, pp.46-55.

[2] M. Mauve, J. Widmer, and H. Hartenstein. A Survey on Position-based Routing in Mobile Ad hoc Networks. IEEE Network Magazine, 15(6):30-39, November 2001.

[3] T. Camp, J. Boleng, and V. Davies. Mobility Models for Ad Hoc Network Simulations. Wireless Communication & Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications, 2002.

[4] L. Blazevic, S. Giordano, and J. L. Boudec. Self Organized Routing in Wide Area Mobile Ad-Hoc Networks. Proc. IEEE GLOBECOM 2001.

[5] E. Elmallah, H. Hassanein, and H. AboElFotoh. Supporting QoS Routing in Mobile Ad Hoc Networks using Probabilistic Locality and Load Balancing. Proc. IEEE GLOBECOM 2001.

[6] J. Yoon, M. Liu, and B. Nobel. Random Waypoint Considered Harmful. In Proc. of IEEE INFOCOM 2003.

[7] A. Jardosh, E.M. Belding-Royer, K. C. Almeroth, and S. Suri. Towards Realistic Mobility Models for Mobile Ad hoc Networks. In Proc. of ACM MOBICOM 2003.

[8] D.B. Johnson, D.A. Maltz, and J. Broch. DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks. Ad Hoc Networking, edited by C. E. Perkins, Addison-Wesley, 2001.

[9] C.E. Perkins and E. M. Royer. Ad hoc On-Demand Distance Vector Routing. Ad Hoc Networking, edited by C. E. Perkins, Addison-Wesley, 2001.

[10] Y-B Ko and N. H. Vaidya. Location-Aided Routing (LAR) in Mobile Ad Hoc Networks. ACM/Baltzer Wireless Networks (WINET) journal, Vol.6-4, 2000.

[11] S. Basagni, I. Chlamtac, V.R. Syrotiuk, and B.A. Woodward. A Distance Routing Effect Algorithm for Mobility (DREAM). Proc. of ACM MOBICOM'98, pp. 76-84.

[12] P. Bose, P. Morin, I. Stojmenovic and J. Urrutia. Routing with Guaranteed Delivery in Ad Hoc Wireless Networks. ACM Wireless Networks, 7, 6, November 2001, pp.609-616; Proc. of 3rd ACM Int. Workshop DIAL-M '99, Seattle, August 20, 1999, pp.48-55.

[13] B. Karp and H. T. Kung. GPSR: Greedy Perimeter Stateless Routing for Wireless Networks. Proc. of ACM MOBICOM 2000, pp.243-254.

[14] J. G. McNeff. The Global Positioning System. IEEE Trans. on Microwave Theory and Techniques, vol. 50, no. 3, pp. 645-652.

[15] N. Bulusu, J. Heideimann, and D. Estrin. GPS-less Low Cost Outdoor Localization For Very Small Devices. IEEE Personal Communications Magazine, 7(5), pp.28-34, Oct. 2000.

[16] S. Capkun, M. Hamdi, and J. Hubaux. GPS-Free Positioning in Mobile Ad Hoc Networks. Proc. of the 34th HICSS, Vol.9, 2001.

[17] J. Li, J. Jannotti, D. Decouto, D. Karger, and R. Morris. A Scalable Location Service for Geographic Ad-hoc Routing. Proc. ACM MOBICOM 2000.

[18] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva. A Performance Comparison of Multi-hop Wireless Ad-hoc Network Routing Protocols. Proc. ACM MOBICOM '98, pp. 85-97, October 1998.

[19] M. Gerla, X. Hong, and G. Pei. Landmark Routing for Large Ad Hoc Wireless Networks. Proc. IEEE GLOBECOM 2000.

[20] The Network Simulator *ns-2*, available online at http://www.isi.edu/nsnam/ns/.

[21] The Monarch Group at Rice University, project website http://www.monarch.cs.rice.edu/.