# Location-Aided Routing (LAR) in mobile ad hoc networks [*]

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A mobile ad hoc network consists of wireless hosts that may move often. Movement of hosts results in a change in routes, requiring some mechanism for determining new routes. Several routing protocols have already been proposed for ad hoc networks. This paper suggests an approach to utilize *location information* (for instance, obtained using the global positioning system) to improve performance of routing protocols for ad hoc networks. By using location information, the proposed *Location-Aided Routing* (LAR) protocols limit the search for a new route to a smaller "request zone" of the ad hoc network. This results in a significant reduction in the number of routing messages. We present two algorithms to determine the *request zone*, and also suggest potential optimizations to our algorithms.

## 1. Introduction

Mobile ad hoc networks consist of wireless mobile hosts that communicate with each other, in the absence of a fixed infrastructure.[1] Routes between two hosts in a Mobile Ad hoc NETwork (MANET) may consist of hops through other hosts in the network [7]. Host mobility can cause frequent unpredictable topology changes. Therefore, the task of finding and maintaining routes in MANET is nontrivial. Many protocols have been proposed for mobile ad hoc networks, with the goal of achieving efficient routing [6,9,11,13,16,18–20,23,28,30,31,33,35]. These algorithms differ in the approach used for searching a new route and/or modifying a known route, when hosts move.

In this paper, we suggest an approach to decrease overhead of route discovery by utilizing location information for mobile hosts. Such location information may be obtained using the global positioning system (GPS) [10,29]. We demonstrate how location information may be used by means of two *Location-Aided Routing* (LAR) protocols [19,20,22] for route discovery. The LAR protocols use location information (which may be out of date, by the time it is used) to reduce the search space for a desired route. Limiting the search space results in fewer route discovery messages.

This paper is organized as follows. Section 2 discusses some related work. In section 3, we describe proposed approach for using location information for route discovery in MANET. Performance evaluation of our protocols is presented in section 4, and several optimizations to our basic approach are described in section 5. Finally, section 6 presents conclusions.

## 2. Related work

Design of routing protocols is a crucial problem in mobile ad hoc networks [5,32], and several routing algorithms have been developed (e.g., [6,9,11,13,16,18–20,23,28,30, 31,33,35]). One desirable qualitative property of a routing protocol is that it should adapt to the traffic patterns [7]. Johnson and Maltz [17,18] point out that conventional routing protocols are insufficient for ad hoc networks, since the amount of routing related traffic may waste a large portion of the wireless bandwidth, especially for protocols that use periodic updates of routing tables. They proposed using Dynamic Source Routing (DSR), which is based on *on-demand* route discovery. A number of protocol optimizations are also proposed to reduce the route discovery overhead. Perkins and Royer [31] present the AODV (Ad hoc On demand Distance Vector routing) protocol that also uses a demand-driven route establishment procedure. TORA (Temporally-Ordered Routing Algorithm) [27,28] is designed to minimize reaction to topological changes by localizing routing-related messages to a small set of nodes near the change. Hass and Pearlman [13] attempt to combine proactive and reactive approaches in the Zone Routing Protocol (ZRP), by initiating route discovery phase on-demand, but limiting the scope of the proactive procedure only to the initiator's local neighborhood. Recent papers present comparative performance evaluation of several routing protocols [4,8].

The previous MANET routing algorithms do not take into account the physical location of a destination node. In this paper, we propose two algorithms to reduce route discovery overhead using location information. Similar ideas have been applied to develop *selective paging* for cellular PCS (Personal Communication Service) networks [1]. In selective paging, the system pages a selected subset of *cells* close to the last reported location of a mobile host. This allows the location tracking cost to be decreased. We propose and evaluate an analogous approach for routing in MANET. In a survey of potential applications of GPS,

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[1] We will use the terms *host* and *node* interchangeably.

Dommety and Jain [10] briefly suggest use of location information in ad hoc networks, though they do not elaborate on how the information may be used. Other researchers have also suggested that location information should be used to improve (qualitatively or quantitatively) performance of a mobile computing system [34,36]. Metricom's Ricochet is a packet radio system using location information for the routing purpose [24]. The Metricom network infrastructure consists of fixed base stations whose precise location is determined using a GPS receiver at the time of installation. Metricom uses a geographically based routing scheme to deliver packets between base stations. Thus, a packet is forwarded one hop closer to its final destination by comparing the location of packet's destination with the location of the node currently holding the packet. A routing and addressing method to integrate the concept of physical location (geographic coordinates), into the current design of the Internet, has been investigated in [14,25]. Recently, another routing protocol using location information has been proposed [3]. This protocol, named DREAM, maintains location information of each node in routing tables and sends data messages in a direction computed based on these routing (location) tables. To maintain the location table accurately, each node periodically broadcasts a control packet containing its own coordinates, with the frequency of dissemination computed as a function of the node's mobility and the distance separating two nodes (called the distance effect). Unlike [3], we suggest using location information for route discovery, not for data delivery.

## 3. Location-Aided Routing (LAR) protocols

### 3.1. Route discovery using flooding

In this paper, we explore the possibility of using location information to improve performance of routing protocols for MANET. As an illustration, we show how a route discovery protocol based on *flooding* can be improved. The route discovery algorithm using flooding is described next (this algorithm is similar to DSR [17,18] and AODV [31]). When a node S needs to find a route to node D, node S broadcasts a *route request* message to all its neighbors[2] – hereafter, node S will be referred to as the *sender* and node D as the *destination*. A node, say X, on receiving a route request message, compares the desired destination with its own identifier. If there is a match, it means that the request is for a route to itself (i.e., node X). Otherwise, node X broadcasts the request to its neighbors – to avoid redundant transmissions of route requests, a node X only broadcasts a particular route request once (repeated reception of a route request is detected using sequence numbers). Figure 1 illustrates this algorithm. In this figure, node S needs to determine a route to node D. Therefore, node S broadcasts a route request to its neighbors. When nodes B
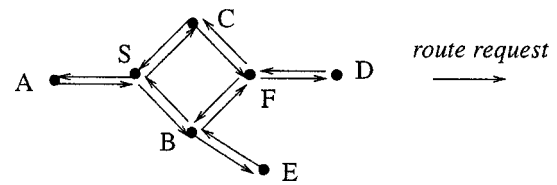
Figure 1. Illustration of flooding.

and C receive the route request, they forward it to all their neighbors. When node F receives the route request from B, it forwards the request to its neighbors. However, when node F receives the same route request from C, node F simply discards the route request.

As the route request is propagated to various nodes, the path followed by the request is included in the route request packet. Using the above flooding algorithm, provided that the intended destination is reachable from the sender, the destination should eventually receive a route request message. On receiving the route request, the destination responds by sending a *route reply* message to the sender – the route reply message follows a path that is obtained by reversing the path followed by the route request received by D (the route request message includes the path traversed by the request).

It is possible that the destination will not receive a route request message (for instance, when it is unreachable from the sender, or route requests are lost due to transmission errors). In such cases, the sender needs to be able to re-initiate route discovery. Therefore, when a sender initiates route discovery, it sets a timeout. If during the timeout interval, a route reply is not received, then a *new* route discovery is initiated (the route request messages for this route discovery will use a different sequence number than the previous route discovery – recall that sequence numbers are useful to detect multiple receptions of the same route request). Timeout may occur if the destination does not receive a route request, or if the route reply message from the destination is lost.

Route discovery is initiated either when the sender S detects that a previously determined route to node D is broken, or if S does not know a route to the destination. In our implementation, we assume that node S can know that the route is broken only if it attempts to use the route. When node S sends a data packet along a particular route, a node along that path returns a *route error* message, if the next hop on the route is broken. When node S receives the route error message, it initiates route discovery for destination D.

When using the above algorithm, observe that the route request would reach every node that is reachable from node S (potentially, all nodes in the ad hoc network). Using location information, we attempt to reduce the number of nodes to whom route request is propagated.

Dynamic source routing (DSR) [17,18] and ad hoc on-demand distance vector routing (AODV) [31] protocols proposed previously are both based on variations of flooding. DSR and AODV also use some optimizations – several of these optimizations as well as other optimizations sug-

gested in this paper can be used in conjunction with the proposed algorithms. However, for simplicity, we limit our discussion to the basic flooding algorithm, and location-aided route discovery based on "limited" flooding.

### 3.2. Preliminaries

*Location information*

The proposed approach is termed Location-Aided Routing (LAR), as it makes use of location information to reduce routing overhead. Location information used in the LAR protocol may be provided by the Global Positioning System (GPS) [10,15,26,29]. With the availability of GPS, it is possible for a mobile host to know its physical location.[3] In reality, position information provided by GPS includes some amount of *error*, which is the difference between GPS-calculated coordinates and the real coordinates. For instance, NAVSTAR Global Positioning System has positional accuracy of about 50–100 m and Differential GPS offers accuracies of a few meters [15,26]. In our initial discussion, we assume that each host knows its current location *precisely* (i.e., no error). However, the ideas suggested here can also be applied when the location is known only approximately – section 4 considers this possibility.

In this paper, we assume that the mobile nodes are moving in a two-dimensional plane.

*Expected zone and request zone*

*Expected zone.* Consider a node S that needs to find a route to node D. Assume that node S knows that node D was at location L at time $t_0$, and that the current time is $t_1$. Then, the "*expected zone*" of node D, from the viewpoint of node S at time $t_1$, is the region that node S expects to contain node D at time $t_1$. Node S can determine the expected zone based on the knowledge that node D was at location L at time $t_0$. For instance, if node S knows that node D travels with average speed $v$, then S may assume that the expected zone is the circular region of radius $v(t_1 - t_0)$, centered at location L (see figure 2(a)). If actual speed happens to be larger than the average, then the destination may actually be outside the expected zone at time $t_1$. Thus, expected zone is only an estimate made by node S to determine a region that potentially contains D at time $t_1$. In general, it is also possible to define $v$ to be the maximum speed (instead of the average) or some other measure of the speed distribution.

If node S does not know a previous location of node D, then node S cannot reasonably determine the expected zone – in this case, the entire region that may potentially be occupied by the ad hoc network is assumed to be the expected zone. In this case, our algorithm reduces to the basic flooding algorithm. In general, having more information regarding mobility of a destination node, can result in a smaller expected zone. For instance, if S knows that

[3] Current GPS provides accurate three-dimensional position (latitude, longitude and altitude), velocity and precise time traceable to Coordinated Universal Time (UTC) [12].
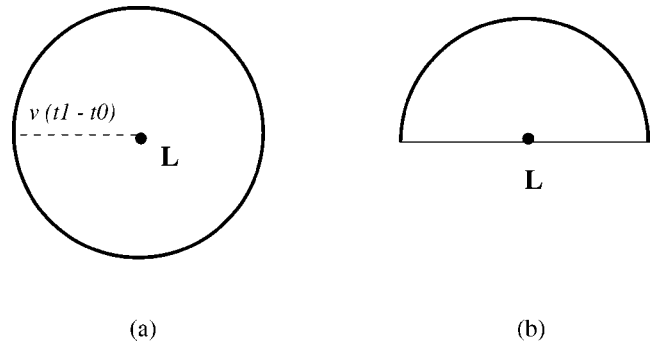


Figure 2. Examples of expected zone.

destination D is moving north, then the circular expected zone in figure 2(a) can be reduced to a semi-circle, as in figure 2(b).

*Request zone.* Again, consider node S that needs to determine a route to node D. The proposed LAR algorithms use flooding with one modification. Node S defines (implicitly or explicitly) a *request zone* for the route request. A node forwards a route request *only if* it belongs to the request zone (unlike the flooding algorithm in section 3.1). To increase the probability that the route request will reach node D, the request zone should include the *expected zone* (described above). Additionally, the request zone may also include other regions around the request zone. There are two reasons for this:

- When the expected zone does not include host S, a path from host S to host D must include hosts outside the expected zone. Therefore, additional region must be included in the request zone, so that S and D both belong to the request zone (for instance, as shown in figure 3(a)).

- The request zone in figure 3(a) includes the expected zone from figure 2(a). Is this an adequate request zone? In the example in figure 3(b), all paths from S to D include hosts that are outside the request zone. Thus, there is no guarantee that a path can be found consisting only of the hosts in a chosen request zone. Therefore, if a route is not discovered within a suitable timeout period, our protocol allows S to initiate a new route discovery with an expanded request zone – in our simulations, the expanded zone includes the entire network space. In this event, however, the latency in determining the route to D will be longer (as more than one round of route request propagation will be needed).

Note that the probability of finding a path (in the first attempt) can be increased by increasing the size of the initial request zone (for instance, see figure 3(c)). However, route discovery overhead also increases with the size of the request zone. Thus, there exists a trade-off between latency of route determination and the message overhead.
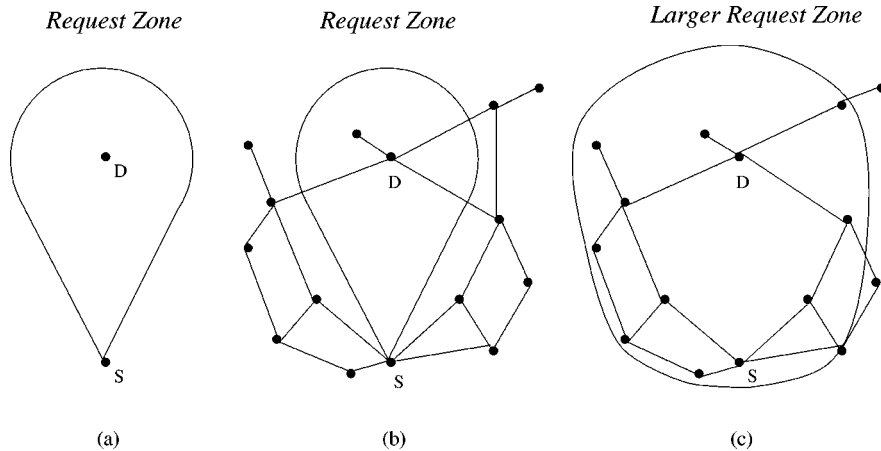
Figure 3. Request zone. An edge between two nodes means that they are neighbors.
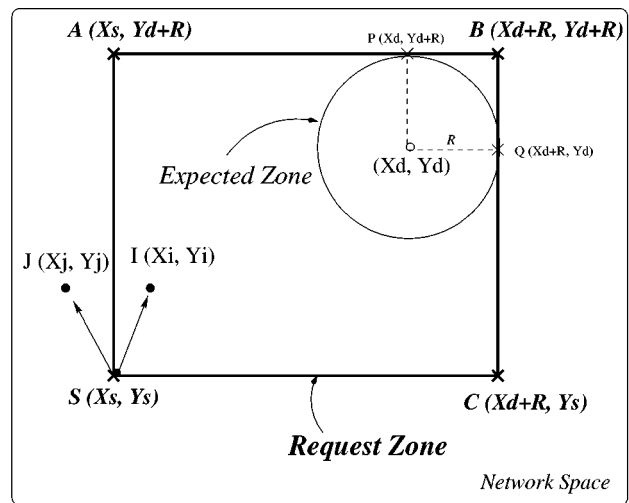
## 3.3. Determining membership of request zones

As noted above, our LAR algorithms are essentially identical to flooding, with the modification that a node that is *not* in the request zone does not forward a route request to its neighbors.[4] Thus, implementing LAR algorithm requires that a node be able to determine if it is in the request zone for a particular route request – the two LAR algorithms presented here differ in the manner in which this determination is made.
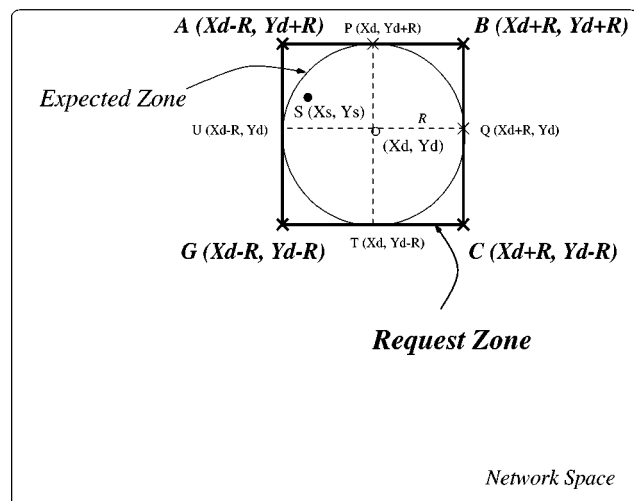
### 3.3.1. LAR scheme 1

Our first scheme uses a request zone that is rectangular in shape (refer to figure 4). Assume that node S knows that node D was at location $(X_d, Y_d)$ at time $t_0$. At time $t_1$, node S initiates a new route discovery for destination D. We assume that node S also knows the average speed $v$ with which D can move. Using this, node S defines the expected zone at time $t_1$ to be the circle of radius $R = v(t_1 - t_0)$ centered at location $(X_d, Y_d)$. (As stated before, instead of the average speed, $v$ may be chosen to be the maximum speed or some other function of the speed distribution.)

In our first LAR algorithm, we define the request zone to be the smallest rectangle that includes current location of S and the expected zone (the circular region defined above), such that the sides of the rectangle are parallel to the $X$ and $Y$ axes. In figure 4(a), the request zone is the rectangle whose corners are S, A, B and C, whereas in figure 4(b), the rectangle has corners at point A, B, C and G – note that, in this figure, current location of node S is denoted as $(X_s, Y_s)$.

The source node S can, thus, determine the four corners of the request zone. S includes their coordinates with the route request message transmitted when initiating route discovery. When a node receives a route request, it discards the request if the node is not within the rectangle specified by the four corners included in the route request. For instance, in figure 4(a), if node I receives the route request from another node, node I forwards the request to its neigh-

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[4] Recall that, in the flooding algorithm, a node forwards a route request if it has not received the request before and it is not the intended destination.



(a) Source node outside the Expected Zone



(b) Source node within the Expected Zone

Figure 4. LAR scheme 1.

bors, because I determines that it is within the rectangular request zone. However, when node J receives the route request, node J discards the request, as node J is not within the request zone (see figure 4(a)).

When node D receives the route request message, it replies by sending a route reply message (as in the flooding algorithm). However, in case of LAR, node D includes its current location and current time in the route reply message. When node S receives this route reply message (ending its route discovery), it records the location of node D. Node S can use this information to determine the request zone for a future route discovery. (It is also possible for D to include its current speed, or average speed over a recent time interval, with the route reply message. This information could be used in a future route discovery. In our simulations, we assume that all nodes know each other's average speed.)

*Size of the request zone.* Note that the size of the rectangular request zone above is proportional to (i) average speed of movement $v$, and (ii) time elapsed since the last known location of the destination was recorded. In our implementation, the sender comes to know location of the destination only at the end of a route discovery (as noted in the previous paragraph). At low speeds, route discoveries occur after long intervals, because routes break less often (thus, $t_1 - t_0$ is large). So, although factor (i) above is small, factor (ii) becomes large at low speeds, potentially resulting in a larger request zone. At high speeds as well, for similar reasons, a large request zone may be observed. So, in general, a smaller request zone may occur at speeds that are neither too small, nor too large. For low speeds, it is possible to reduce the size of the request zone by piggybacking the location information on other packets, in addition to route replies (this optimization is not evaluated here).

### 3.3.2. LAR scheme 2

In LAR scheme 1, source S explicitly specifies the request zone in its route request message. In scheme 2, node S includes two pieces of information with its route request:

- Assume that node S knows the location $(X_d, Y_d)$ of node D at some time $t_0$ – the time at which route discovery is initiated by node S is $t_1$, where $t_1 \geqslant t_0$. Node S calculates its distance from location $(X_d, Y_d)$, denoted as $\text{DIST}_s$, and includes this distance with the route request message.

- The coordinates $(X_d, Y_d)$ are also included with the route request.

When a node I receives the route request from sender node S, node I calculates its distance from location $(X_d, Y_d)$, denoted as $\text{DIST}_i$, and:

- For some parameters $\alpha$ and $\beta$, if $\alpha(\text{DIST}_s) + \beta \geqslant \text{DIST}_i$, then node I forwards the request to its neighbors. When node I forwards the route request, it now includes $\text{DIST}_i$ and $(X_d, Y_d)$ in the route request (i.e., it replaces the $\text{DIST}_s$ value received in the route request by $\text{DIST}_i$, before forwarding the route request).

- Else $\alpha(\text{DIST}_s) + \beta < \text{DIST}_i$. In this case, node I discards the route request.

When some node J receives the route request (originated by node S) from node I, it applies a criteria similar to above: if node J has received this request previously, it discards the request. Otherwise, node J calculates its distance from $(X_d, Y_d)$, denoted as $\text{DIST}_j$. Now,

- The route request received from node I includes $\text{DIST}_i$. If $\alpha(\text{DIST}_i) + \beta \geqslant \text{DIST}_j$, then node J forwards the request to its neighbors (unless node J is the destination for the route request). Before forwarding the request, J replaces the $\text{DIST}_i$ value in the route request by $\text{DIST}_j$.

- Else $\alpha(\text{DIST}_i) + \beta < \text{DIST}_j$. In this case, node J discards the request.

Thus, a node J forwards a route request forwarded by I (originated by node S), if J is "closer" to or "not much farther" from $(X_d, Y_d)$ than node I. For the purpose of performance evaluation, initially we use $\alpha = 1$ and $\beta = 0$ in the next section. Nonzero $\alpha$ and $\beta$ may be used to trade-off the probability of finding a route on the first attempt with the cost of finding the route. Nonzero $\alpha$ and $\beta$ may also be appropriate when *location error* is nonzero, or when the hosts are likely to move significant distances during the time required to perform route discovery. To see how the parameters of $\alpha$ and $\beta$ affect the routing overhead, we do more simulations with the change of those parameters in section 4.2.

Figure 5 illustrates the difference between the two LAR schemes. Consider figure 5(a) for LAR scheme 1. When nodes I and K receive the route request for node D (originated by node S), they forward the route request, as both I and K are within the rectangular request zone. On the other hand, when node N receives the route request, it discards the request, as N is outside the rectangular request zone. Now consider figure 5(b) for LAR scheme 2 (assume $\alpha = 1$ and $\beta = 0$). When nodes N and I receive the route request from node S, both forward the route request to their neighbors, because N and I are both closer to $(X_d, Y_d)$ than node S. When node K receives the route request from node I, node K discards the route request, as K is farther from $(X_d, Y_d)$ than node I. Observe that nodes N and K take different actions when using the two LAR schemes.

*Error in location estimate.* In the above, we assume that each node knows *its own* location accurately. However, in reality there may be some error in the estimated location. Let $e$ denote the maximum error in the coordinates estimated by a node. Thus, if a node N believes that it is at location $(X_n, Y_n)$, then the actual location of node N may be anywhere in the circle of radius $e$ centered at $(X_n, Y_n)$.

In the next section, we will refer to $e$ as *location error*. In the above LAR schemes, we assume that node S obtained the location $(X_d, Y_d)$ of node D at time $t_0$, from
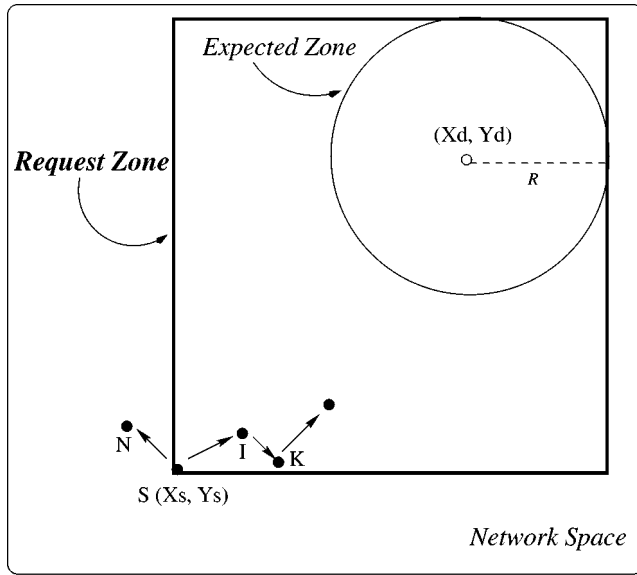
(a) LAR scheme 1
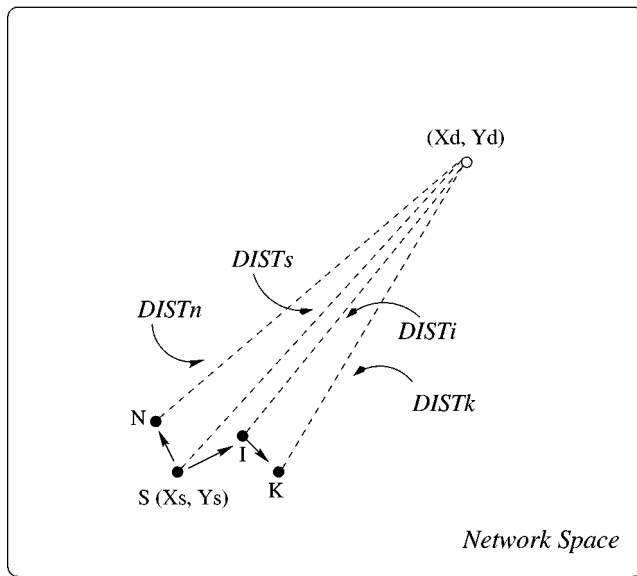


(b) LAR scheme 2

Figure 5. Comparison of the two LAR schemes.

node D (perhaps in the route reply message during the previous route discovery). Thus, node S does not know the actual location of node D at time $t_0$ – the actual location is somewhere in the circle of radius $e$ centered at $(X_d, Y_d)$.

To take the location error $e$ into account, we modify LAR scheme 1 so that the expected zone is now a circle of radius $e + v(t_1 - t_0)$. The request zone may now be bigger, as it must include the larger request zone. Apart from this, no other change is needed in the algorithm. As the request zone size increases with $e$, the routing overhead may be larger for large $e$. We make no modifications to LAR scheme 2, even when location error $e$ is nonzero.

However, the performance of scheme 2 may degrade with large location error, because with larger $e$, there is a higher chance that the request zone used by the scheme will not include a path to the destination (resulting in a timeout and another route discovery). This degradation could be offset by using appropriate $\alpha$ and $\beta$ values. We briefly evaluate the case of $e > 0$ at the end of the next section.

## 4. Performance evaluation

To evaluate our schemes, we performed simulations using modified version of a network simulator, MaRS (Maryland Routing Simulator) [2]. MaRS is a discrete-event simulator built to provide a flexible platform for the evaluation and comparison of network routing algorithms. Three routing protocols were simulated – flooding, LAR scheme 1 and LAR scheme 2. We studied several cases by varying the number of nodes, transmission range of each node, and moving speed.

### 4.1. Simulation model

Number of nodes in the network was chosen to be 15, 30 and 50 for different simulation runs. The nodes in the ad hoc network are confined to a 1000 unit $\times$ 1000 unit square region. Initial locations ($X$ and $Y$ coordinates) of the nodes are obtained using a uniform distribution.

We assume that each node moves continuously, without pausing at any location. Each node moves with an *average* speed $v$. (In simulations presented here and in [21], average speed of mobile nodes is used to define the expected zone for LAR scheme 1. Results reported in [22] used maximum speed instead.) The actual speed is uniformly distributed in the range between $v - \delta$ and $v + \delta$ units/s, where we use $\delta = 1.5$ when $v < 10$ and $\delta = 2.5$ when $v \geqslant 10$. We consider average speeds ($v$) in the range 1.5–32.5 units/s.

Each node makes several "moves" during the simulation. A node does *not* pause between moves. During a given move, a node travels distance $d$, where $d$ is exponentially distributed with mean 20 units. The direction of movement for a given move is chosen randomly. For each such move, for a given average speed $v$, the actual speed of movement is chosen uniformly distributed between $[v - \delta, v + \delta]$. If during a move (over chosen distance $d$), a node "hits" a wall of the $1000 \times 1000$ region, the node bounces and continues to move after reflection for the remaining portion of distance $d$.

Two mobile hosts are considered disconnected if they are outside each other's transmission range. All nodes have the same transmission range. For the simulations, transmission range values of 200, 300, 400, and 500 units were used. All wireless links have the same bandwidth, 100 Kbytes per second.

In our simulation, simulation time is inversely proportional to the average speed. For instance, simulations for average speed 1.5 units/s run 4000 s of execution, whereas

about 1333 s for average speed 4.5 units/s. As the average speed is increased, for a given simulation time, the number of moves simulated increases. If simulation time is kept constant, as speed is increased, a particular configuration (for instance, partition) that may not have occurred at a lower speed can occur at the higher speed. Therefore, we chose to vary simulation time inversely with average speed. (On a related note, observe that a configuration that did occur at a lower speed unavoidably lasts a shorter time when the speed is higher.)

For the simulation, a sender and a destination are chosen randomly. Any data packets that cannot be delivered to the destination due to a broken route are simply dropped. The source generates 10 data packets per second (on average), with the time between two packets being exponentially distributed. The data rate was chosen low to speed up the simulation. However, this has the impact of sending small number of packets between two route discoveries (as compared to when the source continuously sends packets). This, in turn, results in higher *number of routing packets per data packet* (defined below).

When using the LAR schemes for route discovery, the sender first uses our algorithm to determine a route – if a route reply is not received within a timeout interval, the sender uses the flooding algorithm to find the route. The timeout interval is 2 s on average (specifically, the timeout interval is equal to the time required to generate 5 data packets).

In our simulations, we do not model the delays that may be introduced when multiple nodes attempt to transmit simultaneously. Transmission errors and congestion are also not considered.

### 4.2. Simulation results

Initially, we assume that a node knows its current location accurately, without any error. At the end of this section, we briefly consider the impact of *location error* on performance of our algorithms.

In the following, the term "data packets" (or DP) is used to refer to the data packets *received* by the destination – the number of data packets received by the destination is different from number of data packets sent by the sender, because some data packets are lost when a route is broken. In the following, the term "routing packets" (or RP) is used to refer to the routing related packets (i.e., route request, route reply and route error) *received* by various nodes – number of such packets received is different from number of packets *sent*, because a single broadcast of a *route request* packet by some node is received by *all* its neighbors.

We compare the results from LAR scheme 1 and LAR scheme 2 with those from the flooding algorithm. In each run, one input parameter (e.g., average speed, number of nodes, or transmission range) was varied while the other parameters were kept constant. Our simulation results are averaged over 30 runs, each with a different
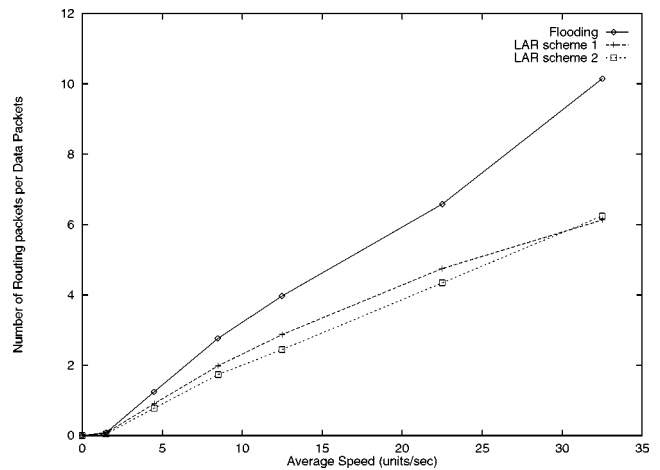


(a) Number of RPs per DP
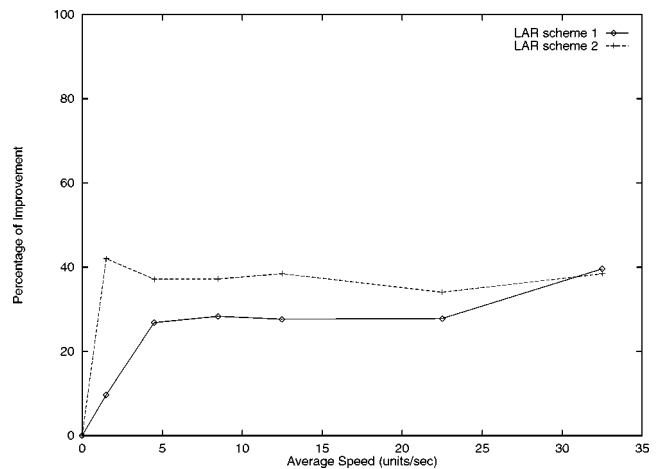


(b) Percentage improvement

Figure 6. For 30 nodes, and transmission range 300 units: (a) the number of RPs per DP versus average speed, (b) percentage of improvement versus average speed.

mobility pattern (different mobility patterns were obtained by choosing different seeds for a random number generator).

The number of routing packets (RP) per data packet (DP) is depicted in figure 6(a) as a function of average speed. This is calculated as the ratio of the number of routing packets, and the number of data packets received by the destination. Figure 6(b) shows the same data, but plotted as the percentage improvement using LAR, relative to flooding algorithm.

Figures 6(a) and (b) show that the number of routing packets per data packet is consistently lower for both LAR schemes as compared to flooding. As the speed of mobile hosts is increased, the number of routing packets begins to increase for all routing protocols. With higher speed, the frequency of route breaking increases, so routing overhead to discover new routes also increases. However, LAR schemes 1 and 2 provide a lower rate of increase than flooding. This is because, with LAR, number of route requests is significantly reduced by limiting route discovery to a smaller request zone.
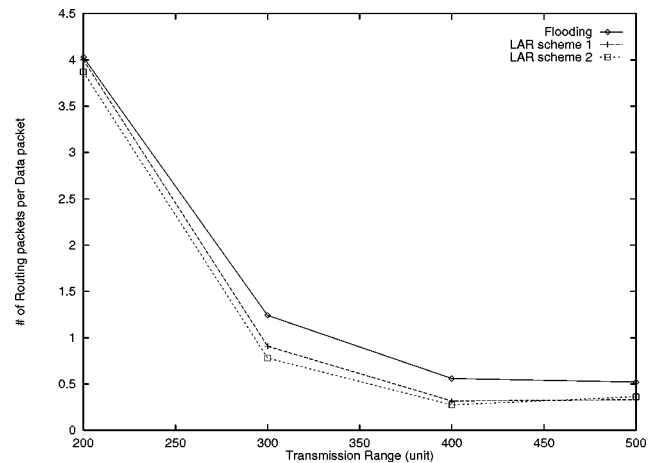
Table 1
95% confidence intervals (C.I.) for mean.

| Average speed (units/s) | C.I. for mean | Flooding | LAR 1 | LAR 2 |
|---|---|---|---|---|
| | mean | 0.0828 | 0.0748 | 0.0408 |
| 1.5 | lower limit | 0.0805 | 0.0727 | 0.0401 |
| | upper limit | 0.0851 | 0.0769 | 0.0414 |
| | mean | 1.2413 | 0.9079 | 0.7800 |
| 4.5 | lower limit | 1.2270 | 0.8926 | 0.7697 |
| | upper limit | 1.2556 | 0.9233 | 0.7904 |
| | mean | 2.7660 | 1.9819 | 1.7365 |
| 8.5 | lower limit | 2.6630 | 1.8971 | 1.6442 |
| | upper limit | 2.8689 | 2.0667 | 1.8288 |
| | mean | 3.9711 | 2.8729 | 2.4442 |
| 12.5 | lower limit | 3.9232 | 2.8151 | 2.4093 |
| | upper limit | 4.0189 | 2.9308 | 2.4791 |
| | mean | 6.5810 | 4.7497 | 4.3413 |
| 22.5 | lower limit | 6.4606 | 4.5998 | 4.2237 |
| | upper limit | 6.7014 | 4.8996 | 4.4588 |
| | mean | 10.1498 | 6.1296 | 6.2471 |
| 32.5 | lower limit | 9.7481 | 5.8235 | 6.0650 |
| | upper limit | 10.5515 | 6.4357 | 6.4292 |



(a) Average speed 4.5 units/sec



(b) Average speed 22.5 units/sec

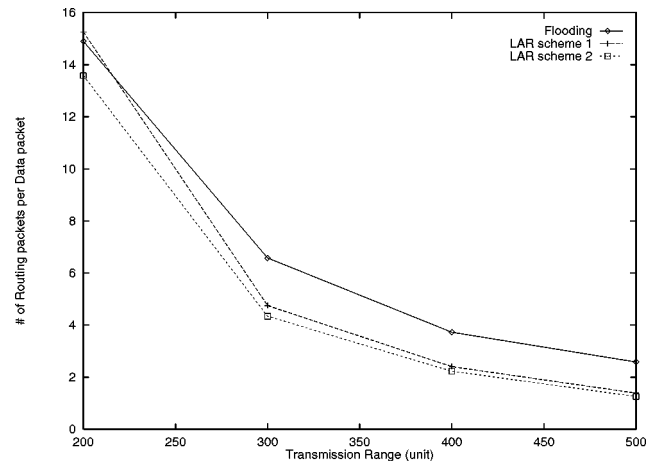Figure 7. The number of RPs per DP versus transmission range (with 30 nodes).

To clarify the results of figure 6, table 1 shows 95% confidence intervals – the table lists average overhead, and the upper and lower limits of the confidence intervals. For most speeds (except for average speed 32.5 units/s), LAR scheme 2 clearly performs best in terms of the number of routing packets per data packet. For the average speed 32.5 units/s, the confidence intervals for LAR schemes 1 and 2 significantly overlap.

Figure 7 shows the effect of varying the transmission range. Typically, the routing overhead decreases with increasing transmission range. With a larger transmission range, the frequency of route discovery should be smaller, as wireless links will break less frequently. This factor contributes to a decrease in routing overhead for all three schemes. Our schemes continue to perform better than flooding. However, with a smaller transmission range (200 units in figure 7), performance of our schemes is not much better than flooding. In figure 7(b), LAR scheme 1 performs even worse than flooding. When a node forwards a route request, it broadcasts the request to all its neighbors. With a smaller transmission range, number of neighbors for each node decreases. This factor decreases the probability of a route discovery within the timeout interval, using the initial request zone. Recall that, in this case, our schemes allow the sender to initiate a new route discovery using the flooding algorithm. We believe that this is the reason why LAR schemes do not perform too well when transmission range is small. The different request zones used in the two LAR schemes result in different routing overhead for the two schemes.

The effect of varying the number of nodes is shown in figure 8. Amount of routing overhead for the flooding algorithm increases much more rapidly than LAR schemes, when number of nodes is increased. As noted earlier in the discussion of figure 7(b), smaller probability of success

of route discovery using initial request zone contributes to a larger routing overhead. Similar to the case of small transmission range, the LAR schemes do not perform much better than flooding with a small number of nodes (15 nodes in figure 8).

Figure 9 shows the number of routing packets per route discovery as a function of average speed. As can be seen in the graph, LAR scheme 2 has the smallest number of routing packets per route discovery, and LAR scheme 1 has smaller values than the flooding algorithm.

In the above simulations of LAR scheme 1, we defined the request zone as the smallest rectangle that includes current location of the source node and the expected zone. Recall that the radius of the expected zone for these simulations is obtained using the average speed of the destination node. The numerical results for LAR scheme 1 presented here match closely with those presented in [22], even though the results in [22] were obtained using maximum speed to define the expected zone. The reason for the similarity of these two sets of results is that, in our case, the difference between maximum and average speed is somewhat small. Therefore, similar request zones are used in

(a) Average speed 4.5 units/sec
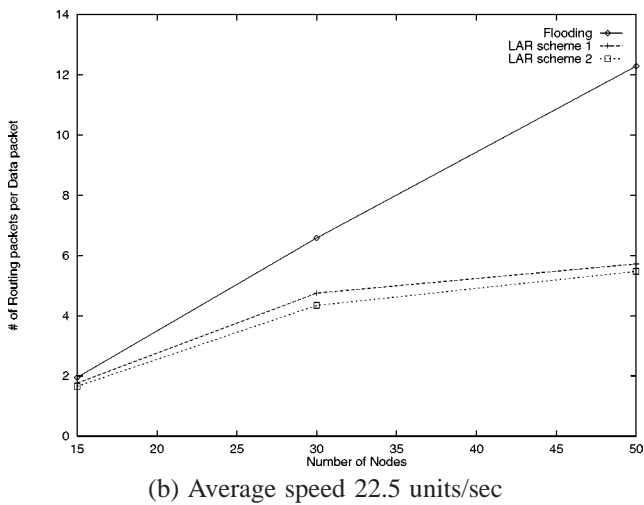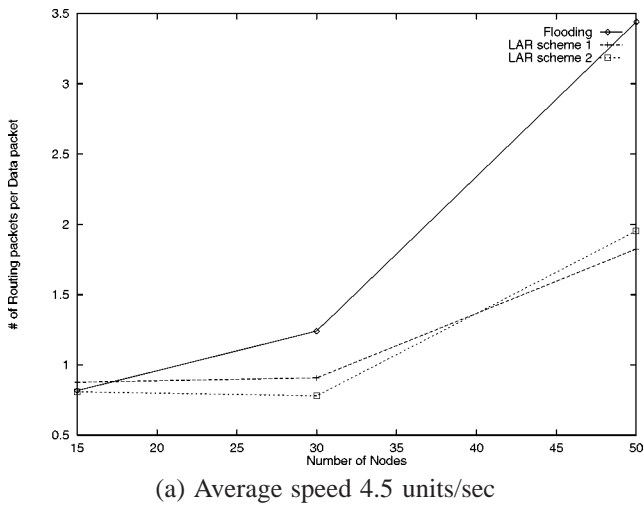


(b) Average speed 22.5 units/sec

Figure 8. The number of RPs per DP versus number of nodes (transmission range 300 units).
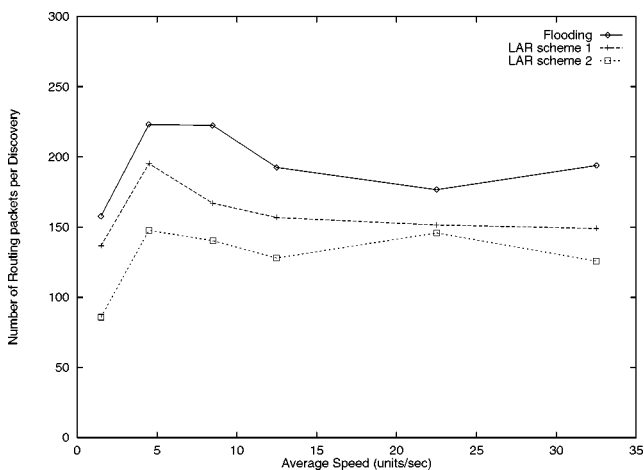


Figure 9. The number of RPs per discovery versus speed (for 30 nodes and transmission range 300 units).



Figure 10. The number of RPs per DP versus parameter $\alpha$ (for $\beta = 0$) (for 30 nodes and transmission range 300 units).



Figure 11. The number of RPs per DP versus parameter $\beta$ (for $\alpha = 1$) (for 30 nodes and transmission range 300 units).

both cases (also, note that, even if the destination is within 1 transmission range outside the request zone, it may still receive the route request message from a node within the request zone). In general, this would not be true, and re-
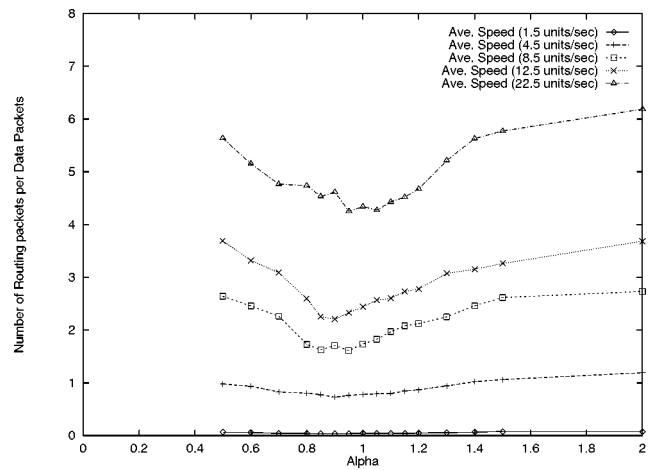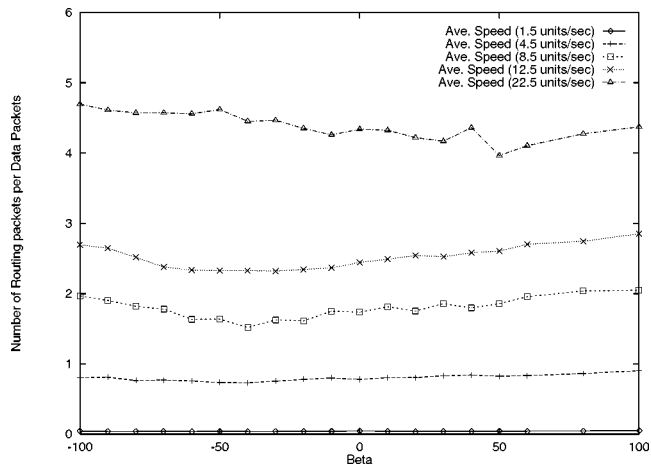
sults obtained using average speed to define the expected zone may significantly differ from those obtained using the maximum speed. In particular, if there is a large enough probability that the actual speed may significantly exceed the average speed, then using average speed may result in poorer results (because the request zone may exclude the actual current location of the destination with non-negligible probability).

When simulating LAR scheme 2, we used $\alpha = 1$ and $\beta = 0$. As explained in section 3.3, $\alpha$ and $\beta$ can be varied to tune the request zone's size. Figures 10 and 11 show how $\alpha$ and $\beta$ can affect the routing overhead of LAR scheme 2. In figure 10, the number of routing packets per data packet becomes optimal in the interval between $\alpha = 0.8$ and $\alpha = 1.2$, when $\beta = 0$. On the other hand, the effect of varying the parameter of $\beta$ from $-100$ to $100$ units seems to be negligible in figure 11. This may be because the variation of $\beta$ is relatively small, as compared with the transmission range of mobile hosts, 300 units.

### 4.3. Impact of location error

As noted at the end of the previous section, the location of a node estimated using GPS may include some error, say $e$, which causes each estimated coordinate ($X$ and $Y$) to be in error by at most $e$ units. In the above simulations, we assumed $e = 0$. Figure 12 shows how the location error affects routing overhead (i.e., number of routing packets per data packet).

In figure 12, our schemes continue to perform better than flooding for the chosen parameters (i.e., average speed, number of nodes, transmission range). Typically, routing overhead for LAR schemes increases with increasing location error. However, although it is hard to see in figure 12(a), the curve for LAR scheme 1 is not monotonically increasing. Note that the number of routing packets (RP) per data packet (DP) at $e = 75$ is smaller than that at $e = 50$. Figure 12(b) plots the relative increase in the routing overhead of LAR schemes 1 and 2, when location error is nonzero, as compared to when the er-

ror is 0. Observe that the increase in routing overhead is small.

With a larger location error, the size of request zone increases – in figures 13(a) and (b) area of the request zone is plotted as a fraction of the 1000 unit × 1000 unit network area. Increase in request zone size usually contributes to an increase in routing overhead. However, routing overhead, when location error is increased, may also decrease. This is because, when the size of request zone is larger, the probability that the discovery will succeed on the first attempt is larger, which can result in smaller number of RPs per DP.

LAR schemes use location information to attempt to improve routing performance. Intuition suggests that, when location error is very large, such schemes would not be very effective. Further work is needed to determine at what location error levels proposed LAR schemes become ineffective.
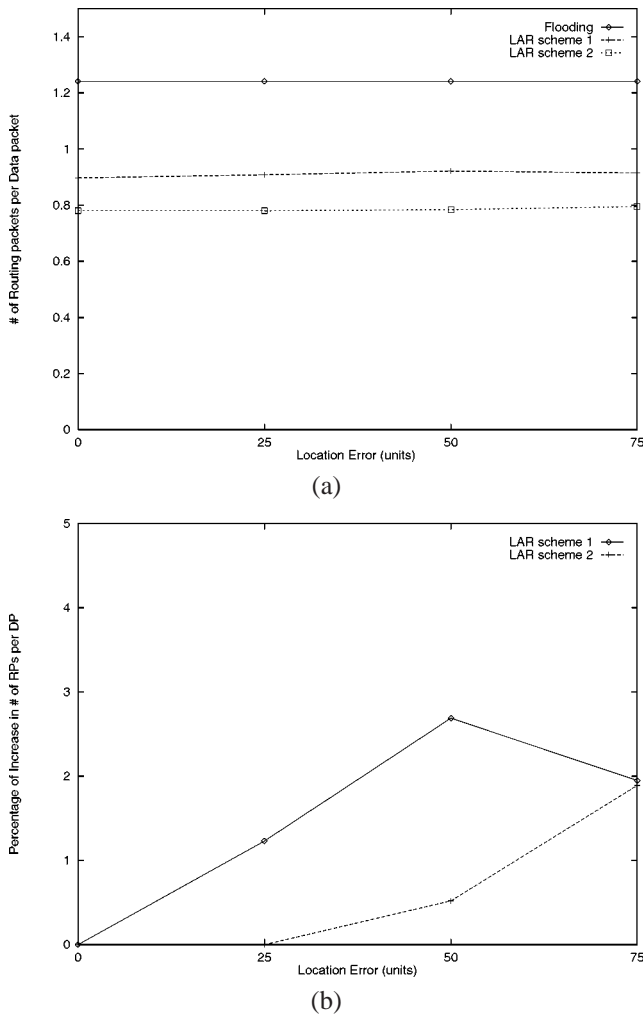


(a)



(b)

Figure 12. For 30 nodes, average speed 4.5 units/s, and transmission range 300 units: (a) the number of routing packets per data packet versus location error, (b) percentage increase in the number of routing packets per data packet versus location error.
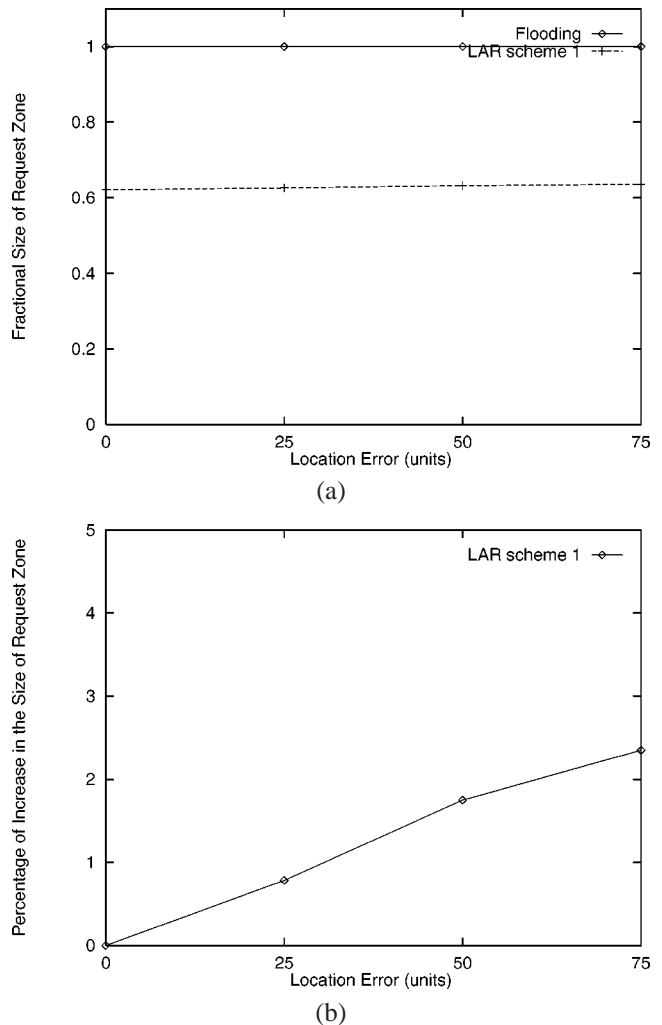


(a)



(b)

Figure 13. For 30 nodes, average speed 4.5 units/s, and transmission range 300 units: (a) size of request zone versus location error, (b) percentage increase in the size of request zone for the LAR scheme 1. Note that size of the request zone for the flooding scheme is always constant (the entire network).

# 5. Variations and optimizations

## 5.1. Alternative definitions of request zone

In this paper, we consider two ways of defining a request zone. Several other alternatives may be conceived. For instance, in the rectangular request zone of LAR scheme 1, sender node S may be on the border of the zone (refer figure 4(a)). Instead, one may define a larger rectangle as the request zone. Also, in LAR scheme 1, the sides of the rectangle are always parallel to the $X$ and $Y$ axes. It is possible to remove this restriction when defining the rectangular region. For instance, one side of the rectangle may be made parallel to the line connecting the location of node S to previous location of D – this approach would often result in a smaller request zone (see figure 14).

In our simulation for the two LAR schemes, the request zone is expanded to the entire network space when a sender using our algorithm fails to find the route to a destination within a timeout interval. This simple strategy of expanding the request zone causes performance degradation of LAR schemes with a smaller transmission range and number of nodes. This scheme may be improved by increasing the request zone gradually.

Definition of a request zone is also dependent on how much information regarding the mobile hosts is available. We assume that only average speed of the nodes is known. It is interesting to consider situations wherein additional information may be available (for instance, direction of movement).

## 5.2. Adaptation of request zone

Accuracy of a request zone (i.e., probability of finding a route to the destination) can be improved by adapting the request zone, initially determined by the source node S, with up-to-date location information for host D, which can be acquired at some intermediate nodes. Let us consider the case that node S starts search of a destination node D within a request zone $Z$ at time $t_1$, which is based on location information about D learned by S at time $t_0$. Let us assume that the *route request* includes the timestamp $t_0$, because
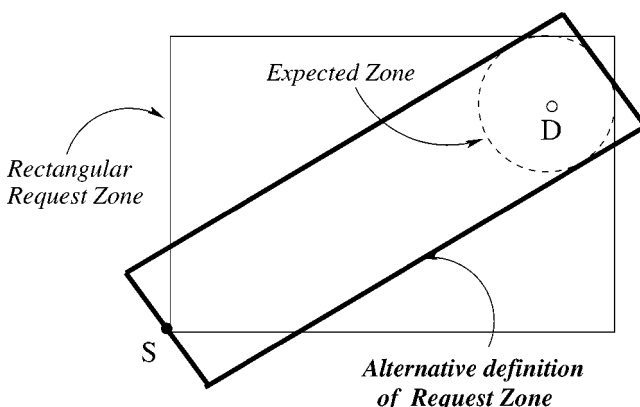
the location of node D at time $t_0$ is used to determine the request zone. Also, location of node S and the time $t_1$ when the request is originated are also included. Now suppose that some intermediate node I within $Z$ receives the route request at time $t_2$, where $t_1 < t_2$. More recent location information for D may potentially be known by node I (as compared to node S), and the expected zone based on that information may be different from previous request zone $Z$. Therefore, request zone initially determined at a source node may be adapted at node I.

For instance, when using LAR scheme 1, node I may determine the expected zone using more recent location information for node D, and define the adapted request zone as the smallest rectangle containing node S and the new expected zone for node D. Similarly, when using LAR scheme 2, node I may calculate distance from the more recent location of destination D that it knows, and use this distance in the decision rule (to decide whether to discard a route request) of scheme 2.
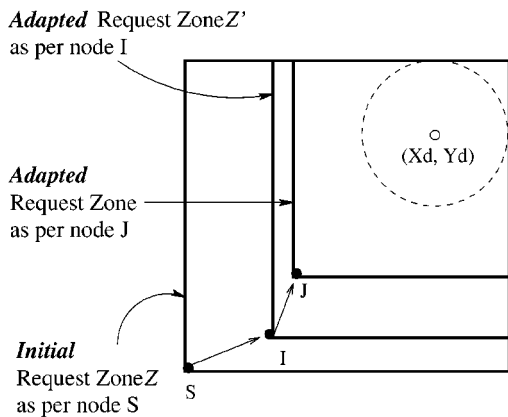
## 5.3. Another adaptation of request zone

Even though the LAR scheme 2 does not explicitly specify the request zone, the request zone at node S can be thought to be implicitly defined as a circle of radius $\alpha\mathrm{DIST_s} + \beta$. As the route request packet is propagated to various nodes, this implicit request zone is adapted by an intermediate node I as a circle of radius $\alpha\mathrm{DIST_i} + \beta$, as shown in figure 15(a). On the other hand, in LAR scheme 1 the request zone is specified explicitly by the source S, and the request zone is not modified by any intermediate nodes. We can improve the performance of LAR scheme 1 by having the request zone be adapted at an intermediate nodes I, such that the request zone for the request propagated by node I includes the current location of I and the expected zone of the destination D. For instance, in figure 15(b), when node I receives the route request from the source S and forwards the request to its neighbors because I is within the request zone $Z$ (defined by S), it can replace $Z$ by an adapted request zone $Z'$ before forwarding the request. By applying the same reasoning when node J receives the route request message from node I, the request zone can be again adapted.

Generalizing the above idea, although a rectangular shape is used for the request zone in LAR scheme 1, any other form may also be used. For instance, figure 15(c) shows the case when the request zone is defined as a cone rooted at node S, such that angle made by the cone is large enough to include the request zone – the angle made by the cone may be chosen by some other heuristic as well (for instance, if the angle is always chosen to be 90 degrees, this scheme would become similar to that in figure 15(b)). Similar to adaptation of the rectangular request zone in figure 15(b), the cone-shaped request zone may also be adapted as shown in figure 15(c). This approach using cone-shaped region is analogous to the approach used in [3] to deliver data to a destination node. The significant



Figure 14. Alternative definitions of request zone for LAR scheme 1.
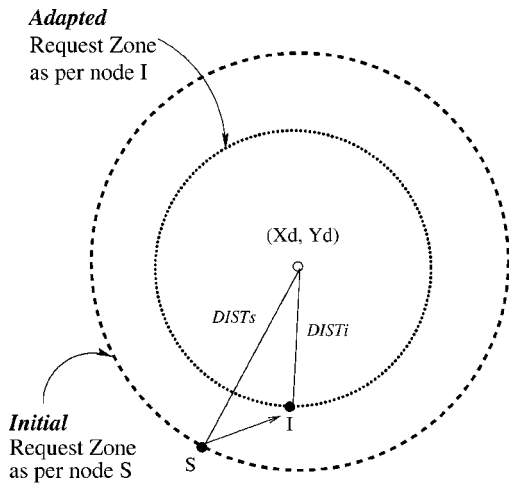
(a) Adaptation of *Implicit* Request Zone
for LAR scheme 2 : ***Circular Shape***



(b) Adaptation of ***Rectangular Shaped*** Request Zone
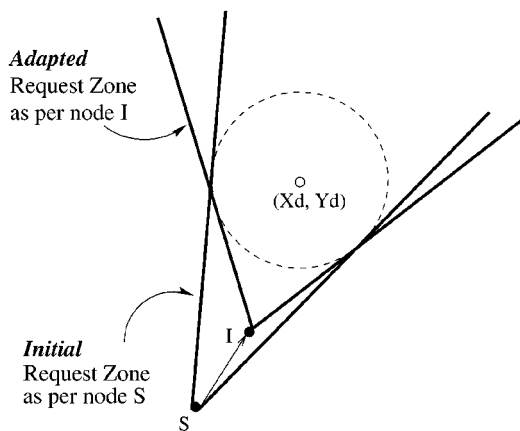


(c) Adaptation of ***Cone-Shaped*** Request Zone

Figure 15. Explicit adaptation of request zone for LAR scheme 1.

difference between the two approaches is that we use the cone-shaped regions for route discovery, not for data delivery. Also, our scheme does not require periodic broadcast of location information, unlike [3].

### 5.4. Propagation of location and speed information

Initially, in ad hoc network environments, a node may not know the physical location (either current or old) of other hosts. However, as time progresses, each node can get location information for many hosts either as a result of its own route discovery or as a result of message forwarding for another node's route discovery. For instance, if node S includes its current location in the route request message, and if node D includes its current location in the route reply message, then each node receiving these messages can know the locations of nodes S and D, respectively. In general, location information may be propagated by piggybacking it on any packet. Similarly, a node may propagate to other nodes its average speed (or some other measure of speed). In our simulations, we assume that average speed is constant and known to all nodes. In practice, the speed distribution could be time-variant.

### 5.5. Local search

In our protocol, any intermediate node I detecting routing failure (due to a broken link) informs the source node S by sending a *route error* packet (see figure 16(a)). Then, S initiates a new route discovery (using a request zone), to find a path to the destination D. As we have already seen, if we use location information, routing messages can be reduced by limiting propagation of route request packets to the request zone determined (implicitly or explicitly) by node S, as shown in figure 16(b). Figure 16(c) shows how this scheme may be improved to reduce the size of request zone as well as latency of route re-determination for node D. This can be done by allowing any intermediate node I detecting route error to initiate a route discovery using a request zone based on its own location information for node D. Such a *local search* may result in a smaller request zone (as shown in figure 16(c)) because node I may be closer to D than S. Smaller request zone could reduce routing overhead. The time to find the new path to D may also be reduced, as a smaller request zone is searched.

### 5.6. Combining with time-to-live (TTL)

In DSR [18], route discovery using expanding ring search has been suggested as one optimization over flooding. In this approach, a source initially sends a route request with setting its time-to-live (TTL) field to 1. If no route reply is received for some time, the source increases the TTL to a larger value and tries again. Although both TTL and LAR schemes limit the spread of route request messages, their behavior is quite different. In fact, the LAR protocols may also be used in combination with the
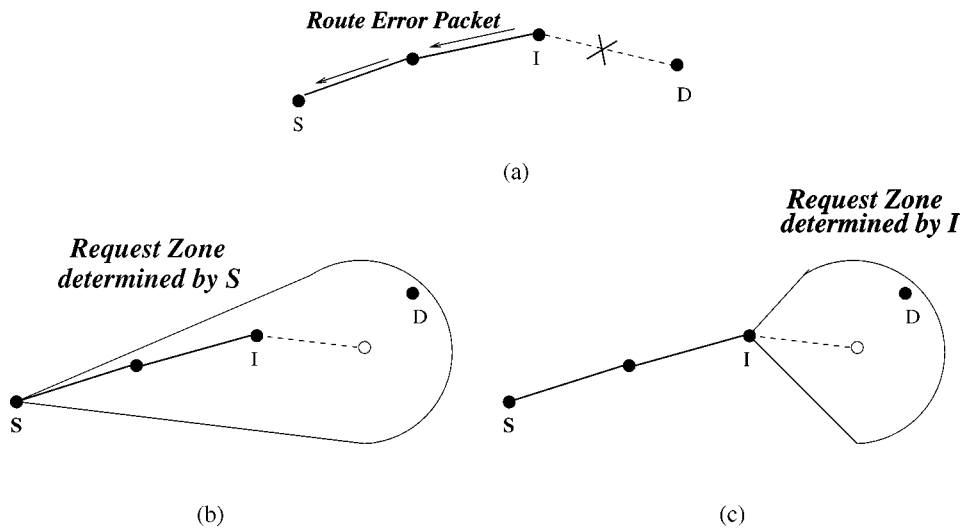
Figure 16. Local search to re-establish a broken route.

TTL optimization. By setting the TTL to some reasonable number, the source can bound the number of hops the request packet will travel. Therefore, even if a node exists within the request zone defined by the LAR scheme, it will drop the packet when it is over TTL hops away from the source.

### 5.7. Use of directional antennas

The LAR protocol lowers routing overhead by reducing the number of nodes that will receive and forward a route request message. However, the basic LAR approach is still limited in a sense due to the broadcast propagating nature of mobile ad hoc networks. In general, MANET nodes are assumed to have *omnidirectional* antennas for wireless communication [7]. This assumption implies that any request message broadcast by a node will reach all its neighbors, even if some of these neighbors are outside the intended request zone. This may be improved upon by using directed antennas.

For instance, in figure 17, let us assume that node S needs to determine a route to node D so it broadcasts a route request packet. Let us also assume that LAR scheme 1 is used for this route discovery phase with omnidirectional antennas. With LAR scheme 1 based on the viewpoint of S, the request zone is defined as the rectangle in which only node S, A, B and D are included. Nodes C and E do not need to receive any route request packets, because they are both outside the request zone. However, due to the broadcast transmission properties of wireless networks, node C receives a route request packet from node S whose transmission range covers C as well as A. Similarly, the request message will be forwarded to node E, via node A, unnecessarily. (In fact, when node A forwards the route request, all it neighbors B, C, E, and S, will receive the request.) This inherent limitation can be mitigated by using *directional antennas*. A directional antenna is an antenna in which the radiation pattern is not omnidirectional. LAR
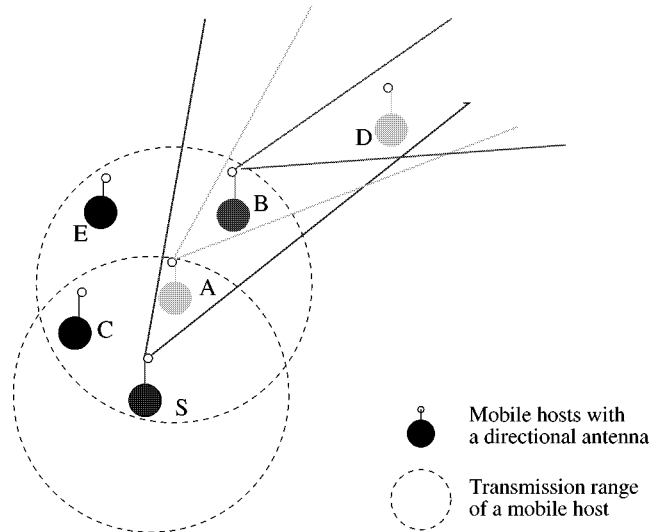


Figure 17. LAR with directional antennas.

protocols, particularly those using the optimizations in figure 15, make it possible to utilize directional antennas for routing in MANET.

Again, assume that node S having a directional antenna initiates a route discovery phase for node D. Based on the previous location information of D, route request packets may only be directed at a small group of mobile nodes (see figure 17). Therefore, in this scenario, node C does not receive the request packet from S even though C is a neighbor of S. When node A forwards the route request (originated by node S), it applies a similar criteria. Continuing in this fashion, intuitively, an extention of LAR protocols with directional antennas will substantially decrease the cost of ad hoc routing.

### 5.8. Clock synchronization

For the LAR scheme 1, we assumed clock synchronization between the nodes. However, our approach can be eas-

ily extended to the case when clocks are unsynchronized. When a node X receives location information for another node Y (for instance, in a route reply packet), node X would timestamp the information as per its local clock. This information can be used in a future route discovery, as described in LAR scheme 1. This approach is likely to perform as well as in the case of synchronized clocks, because message delivery delays are likely to be relatively small. LAR scheme 2 does not need synchronized clocks, which may be considered to be an advantage over scheme 1.

## 6. Conclusion

This paper describes how location information may be used to reduce the routing overhead in ad hoc networks. We present two location-aided routing (LAR) protocols. These protocols limit the search for a route to the so-called request zone, determined based on the expected location of the destination node at the time of route discovery.

Simulation results indicate that using location information results in significantly lower routing overhead, as compared to an algorithm that does not use location information. We also suggest several optimizations on the basic LAR schemes which may improve performance. Further work is required to evaluate efficacy of these optimizations, and also to develop other ways of using location information in ad hoc networks, for instance to improve performance of reactive algorithms such as TORA [27,28], or to implement location-based multicasting [21].

## Acknowledgements

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