The Effect of Mobility-Induced Location Errors on Geographic Routing in Mobile Ad Hoc and Sensor Networks: Analysis and Improvement Using Mobility Prediction

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Abstract—Geographic routing has been introduced in mobile ad hoc networks and sensor networks. Under ideal settings, it has been proven to provide drastic performance improvement over strictly address-centric routing schemes. While geographic routing has been shown to be correct and efficient when location information is accurate, its performance in the face of location errors is not well understood. In this paper, we study the effect of inaccurate location information caused by node mobility under a rich set of scenarios and mobility models. We identify two main problems, named LLNK and LOOP, that are caused by mobility-induced location errors. Based on analysis via ns-2 simulations, we propose two mobility prediction schemes—neighbor location prediction (NLP) and destination location prediction (DLP) to mitigate these problems. Simulation results show noticeable improvement under all mobility models used in our study. Under the settings we examine, our schemes achieve up to 27 percent improvement in packet delivery and 37 percent reduction in network resource wastage, on average, without incurring any additional communication or intense computation.

Index Terms—Location error, mobility prediction, mobile ad hoc networks, wireless sensor networks.

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1 INTRODUCTION

In anticipation of the broader use of global positioning system (GPS) [1] and other localization schemes, geographic routing is becoming a very attractive choice for routing in mobile ad hoc networks and also in sensor networks. Many geographic routing protocols in ad hoc networks [2], [3], [4], [5] and in sensor networks [19], [20] have been proposed and proven to provide drastic performance improvement over existing ad hoc routing protocols [6], [7], [8], [9]. In addition to the benefits attained from using a geographic routing protocol, the location information itself is important and necessary for many applications. In geographic routing, the packet forwarding decision is solely based on the location information of neighbors and a destination node at the moment of forwarding. Geographic routing protocols have been shown to be correct and efficient with exact location information. The effect of location errors on geographic routing, however, has not been studied before to our knowledge. Hardware nonideality and harsh environment in sensor networks can cause location inaccuracy even without node mobility. This effect is exacerbated with node mobility and harder to resolve because each node may have a different level of location error according to its mobility level. Studying the impact of mobility is not only of relevance for mobile ad hoc networks, but also for sensor networks with mobile nodes (e.g., MSN [21]). Furthermore, it is important to investigate the impact of realistic mobility patterns. Most previous studies on geographic routing have used the random waypoint mobility model that ignores movement correlation among nodes.

In this study, we provide the first study to 1) understand the effect of inaccurate location information caused by node mobility on geographic routing protocols under various mobility models and 2) provide remedies for the identified problems using mobility prediction schemes.

We examine the following three main factors that greatly affect the performance of geographic routing protocols:

1. The freshness of location information: It is not possible to avoid the time gap between the measurement of a location and the time when this information is actually used for a routing decision, in both proactive and reactive routing protocols. This is because of the latency involved in the delivery of location information and also because the time interval between location updates is generally longer than the interpacket arrival times.
2. The speed of mobile nodes in the network: Each mobile node can move at a different speed and the maximum node speed is another critical factor deciding the level of inaccuracy.
3. The mobility pattern of mobile nodes: If the node movement exhibits a different pattern, the effect of node mobility on the geographic routing protocol will be different. Four different mobility models [10]

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are adopted in our work: Random waypoint (RWP), Freeway (FWY), Manhattan (MH), and Reference Point Group Mobility (RPGM).

Based on the simulation results, two major problem types are identified and discussed in this paper: The Lost Link (LLNK) problem and the loop in packet delivery (LOOP) problem. The LLNK problem is related to the link connection problem with neighboring nodes and the LOOP problem is related to the inaccurate location information of destination nodes caused by their mobility.

We present two mobility prediction (MP) schemes to address these problems: neighbor location prediction (NLP) and destination location prediction (DLP). We find that the performance of geographic routing is significantly increased with MP without any added communication overhead.

We evaluate our proposed schemes through ns-2 simulations of the greedy perimeter stateless routing protocol, GPSR [2], [11], using the IMPORTANT [10] mobility tool.

The rest of the paper is organized as follows: In Section 2, we provide background information regarding GPSR and the mobility models used in our work. In Section 3, we discuss the effect of node mobility on geographic routing based on simulation results. In Section 4, we identify two mobility-induced problems. In Section 5, we introduce mobility prediction schemes and discuss related issues. In Section 6, we present results showing performance improvement with mobility prediction. We present concluding comments in Section 7.

2 BACKGROUND

2.1 Greedy Perimeter Stateless Routing (GPSR)

Geographic routing in GPSR [2], [11], or the algorithm described earlier in [24], is a location-based routing protocol for wireless networks, and consists of two packet forwarding modes: greedy packet forwarding and perimeter forwarding. The originator of the data generates a packet that contains the coordinates of the destination node. Initially, the packet is forwarded by greedy packet forwarding in which each node makes a localized routing decision based on the location information of its neighbor nodes as follows: Every node periodically broadcasts a beacon packet within its own radio range which carries a node-id and current location information. Every node which receives a beacon packet stores received information in the neighbor list. Every time a node forwards a packet, it calculates the distances from every neighbor node to the destination node. The neighbor node located closest to the destination node is selected as a next hop. With this localized routing decision, a packet can be delivered to the destination through the optimal path in the distance aspect. However, there are some situations, called *local maxima*, where a node cannot find any node located closer to the destination while there exist sa detour through a neighbor located further from the destination than itself.

When a node finds out a local maximum situation, the packet forwarding mode is changed to perimeter forwarding. The packet then traverses along faces of a planar subgraph using the right-hand rule [2] until it reaches a node that is closer to the destination than the node where greedy forwarding first failed due to the local maximum. At this point, the packet forwarding mode returns to greedy packet forwarding.

2.2 Mobility Models

We adopt a rich set of mobility models for our study. Some of the mobility patterns, apart from the Random Waypoint (RWP) [26] model, that have been studied include the Freeway (FWY), Reference Point Group Mobility (RPGM), and Manhattan (MH). Each of these was chosen to replicate certain mobile node characteristics not previously captured by the RWP model.

2.2.1 Random Waypoint Mobility Model (RWP)

In the Random Waypoint (RWP) mobility model, nodes are randomly placed within the simulation field at starting time. Each node selects a destination randomly, independent of other nodes, to which it moves with a constant speed picked randomly from $[0, V_{max}]$. When a node reaches the destination, it stays there for a given *pause time* before it starts to move to another random destination. The RWP [26] model is simple and easy to use, but it does not take into consideration the following three main characteristics of realistic mobility in ad hoc networks:

1. *spatial correlation* between different nodes where the movement of one node depends on the movement of neighboring nodes,
2. *temporal correlation* for each node where a node's speed and direction depends on its previous movement history, and
3. geographic restrictions where a node's movement may be restricted due to obstacles, buildings, streets, or freeways.

2.2.2 Reference Point Group Mobility Model (RPGM)

In RPGM, the nodes are divided into *groups*. Each group of nodes has a group leader that determines the group's motion behavior. Initially, each member of the group is uniformly distributed in the neighborhood of the group leader. Every node has a speed and direction that is derived by randomly deviating slightly from that of the group leader. The speed deviation is set according to the speed deviation ratio (SDR) and the angle deviation ratio is set according to the angle deviation ratio (ADR) as follows:

$$\begin{aligned} |\vec{V}_{node}(t)| &= |\vec{V}_{reference}(t)| + random() \times SDR \times V_{\max} \\ \theta_{node}(t) &= \theta_{reference}(t) + random() \times ADR \times \theta_{\max}. \end{aligned}$$

In our study, we take SDR = ADR= 0.1. In the above expressions, random() refers to a uniformly distributed random number between $[0, 1]$. RPGM [10], [28] provides high spatial correlation between nodes, which leads to high link durations and less change in the relative network topology.

2.2.3 Freeway Mobility Model (FWY)

The Freeway mobility model emulates the motion behavior of mobile nodes on a freeway. An example of the freeway model is shown in Fig. 1. Each mobile node is restricted to its lane on the freeway and the velocity is temporally dependent on its previous velocity. If two mobile nodes on

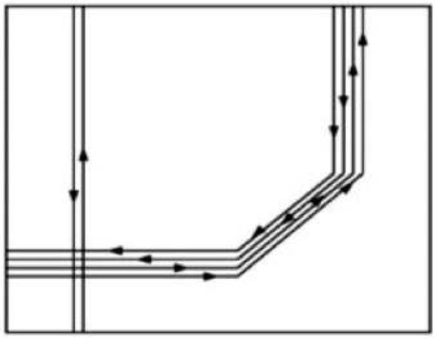


Fig. 1. Freeway model.

the same freeway lane are within the Safety Distance (*SD*), the velocity of the following node cannot exceed the velocity of the preceding node. Due to the above relationships, the Freeway mobility model provides temporal correlation and geographic restriction and, in general, the nodes also exhibit high spatial correlation. In this mobility model, the links between nodes moving in the same direction remain for a relatively long time, while link duration between nodes moving in opposite directions is low [10].

2.2.4 Manhattan Mobility Model (MH)

The Manhattan model emulates the movement pattern of mobile nodes on streets defined by maps. An example of the Manhattan mobility model is shown in Fig. 2. The mobile node is allowed to move along the grid of horizontal and vertical streets on the map. At an intersection, the mobile node can turn left, right, or go straight, with probability 0.25, 0.25, and 0.5, respectively. The probability of turning left is 0.25 and the probability of turning right is 0.25. The velocity of a node at a time slot is dependent on its velocity at the previous time slot and is restricted by the velocity of the node preceding it on the same lane of the street, as in the Freeway model.

Thus, the Manhattan mobility model, similarly to the Freeway model, also exhibits high spatial correlation and high temporal correlation. However, it provides more degrees of freedom for movement than the Freeway model due to street intersections, producing very high relative speed between nodes.

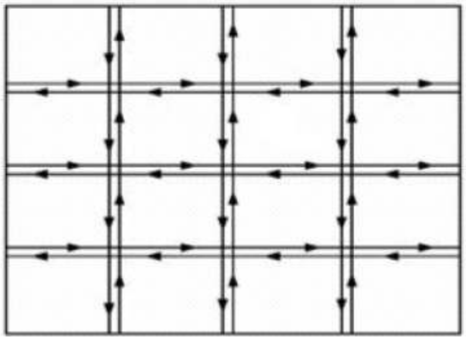


Fig. 2. Manhattan model.

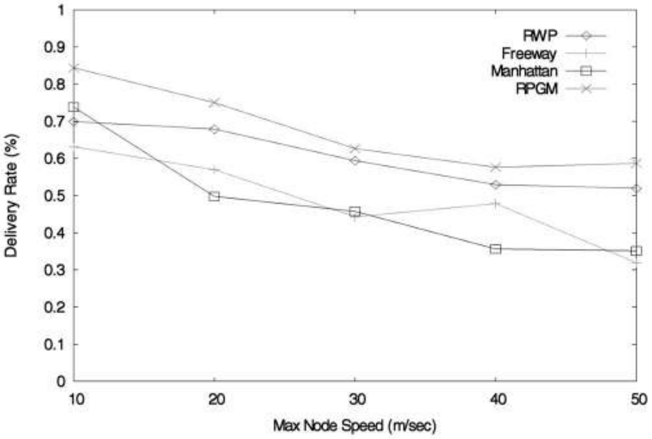


Fig. 3. SDR varying maximum node speed.

3 ANALYSIS OF THE EFFECT OF NODE MOBILITY

To estimate the effect of inaccurate location information caused by node mobility on the geographic routing protocol, we conducted simulations with ns-2 varying the beacon interval and the maximum speed of mobile nodes for each mobility model. GPSR [2], [11] is selected for our simulation because it uses greedy forwarding with face routing and was shown to perform correctly and efficiently with exact location information. It is a widely accepted protocol for geographic routing in mobile ad hoc and sensor networks. Fifty nodes are placed randomly in a 1500m × 300m field and the combination of beacon intervals of 0.25, 0.5, 1.0, 1.5, 3.0, 6.0 seconds and maximum node speed of 10, 20, 30, 40, 50 m/sec are simulated. The IMPORTANT mobility tools presented in [10] are used to generate the mobility models. To filter out the noise in simulation results, five different scenarios are generated for each distinct parameter setting and the results represents the average value.

We introduce several metrics to evaluate different aspects of the performance of the routing protocol:

1. Successful Delivery Rate (SDR): The number of packets successfully delivered to the destination node divided by the total number of packets transmitted.
2. Wasted Transmission Rate (WTR): The number of transmission efforts made for dropped packets during the delivery divided by the total number of packet transmissions.
3. Number of Lost Links (LLNK): The number of link loss events observed during packet forwarding.

SDR represents the level of reliability in packet delivery, while WTR represents the level of wasted resources in the network. The latter metric is particularly important when considering energy-constrained wireless networks.

3.1 Effect of Node Speed

Variation of the node speed means the change in the degree of mobility that affects the error in node location information. The performance of geographic routing protocol that is fully based on location information is closely related to the accuracy of node location information. The general effect of node speed on the performance of GPSR protocol is similar

TABLE 1
The Maximum Performance Difference from Varying Node Speed

Difference	RWP	Freeway	Manhattan	RPGM
SDR (%)	17.9	31.2	38.7	26.7
WTR (%)	22.9	37.2	36.2	13.1
LLNK(#)	749.6	1213.7	1258.5	475.2

for all four mobility models. Fig. 3 shows the effect of node speed on the performance of GPSR routing protocol. The overall performance drops as the maximum node speed increases, but the amount of performance drop is different for each mobility model.

To see the effect of the node mobility on location-based routing protocol for each mobility model, we calculated the difference between the best value and the worst value of each metric in Table 1. Best performance comes from lowest node speed and the worst performance resulted from the highest mobility cases in most of the simulation.

The Manhattan (MH) and Freeway (FWY) models show the biggest performance drop and Random Waypoint (RWP) performs well with increased maximum node speed in the viewpoint of every metric considered. This difference is attributed to the different level of randomness for each mobility model and various levels of vulnerability of the problems caused by the node mobility. By looking at the different causes to the lowered performance (identified in Section 4) and by comparing the different level of performance improvement after applying the remedies (suggested in Section 5) for each problem, the factors that cause different effects of node speed on different mobility model can be easily discovered and understood. This analysis is given at the end the simulation results (in Section 6).

If we look at the performance of GPSR itself on various speed levels instead of the amount of performance drop, the RPGM mobility model consistently outperforms the remaining mobility models in SDR, as seen in Fig. 3. The average number of LLNKs is consistently lower for RPGM (~812 LLNKs) than other mobility models (ranging from 2,366 to 2,586 LLNKs on average), as we can intuitively expect from the greater correlation between the movements of neighbor nodes, and this explains the better performance of RPGM.

While the faster maximum node movement brings a serious performance drop in location-based routing, some interesting results are observed. In Fig. 4, we compare the number of hops in packet delivery calculated before the actual routing (named expected hops) with the actual number of hops used in packet delivery under RWP mobility. Both increased node mobility and increased beacon interval cases are presented. We find that the average number of packets delivered in less-than-expected number of hops increases up to 0.4 percent with increased node mobility, but the increased beacon interval case does not show much difference with this metric. When we normalize these numbers with SDR, about 1 percent packets are delivered in less-than-expected number of hops and no changes for increased beacon interval cases. The average number of packets delivered in more-than-expected number of hops reduces up to 4.3 percent with increased node mobility and increases up to 7.7 percent with increased beacon interval. However, when these values are normalized with SDR, 4 percent more packets are delivered in more-than-expected number of hops for increased node mobility and 7.7 percent more packets are delivered in more-than-expected number of hops for increased beacon interval cases.

From these statistics, we find that the increased node mobility and longer beacon interval has a bad influence on the geographic routing in terms of the average number of hops for packet delivery metric. One result that draws our attention is the number of packets delivered in less-than-optimal hops. This number is slightly increased (~1 percent) with increased node mobility, while the SDR decreases. In our experiment, 1 percent of the packet could be considered to have a positive side of node mobility, where the destination node moves toward the source and it is fortunate enough to be one of the packet forwarders that is closest to the destination node from the previous forwarder. As discussed above, the overall effect of node mobility is still negative to geographic routing because more packets (~4 percent) are delivered in more-than-optimal hops with increased node mobility.

The result teaches us that the positive side of node mobility can be utilized somewhat to improve the routing performance and, more importantly, some node mobility which used to have a negative effect on geographic routing can be converted to lose its negative impact of mobility like a packet drop. This observation supports the necessity of

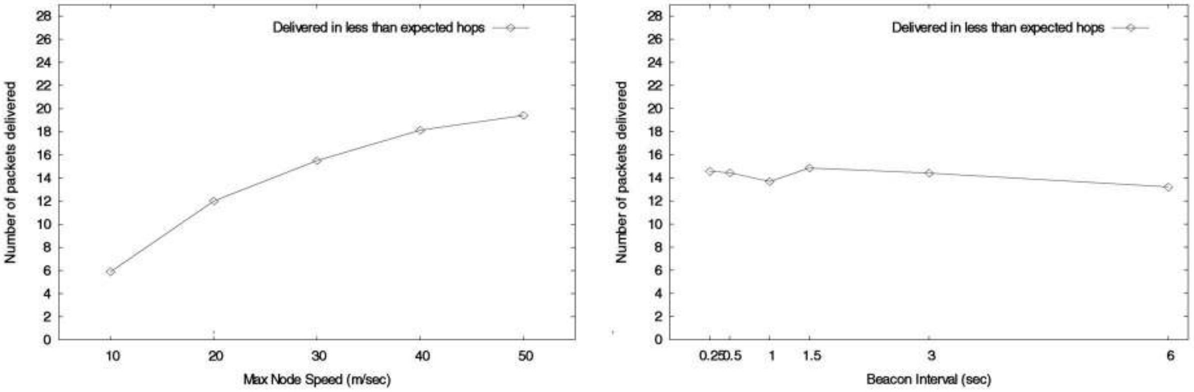


Fig. 4. Number of packets delivered in less than expected hops.

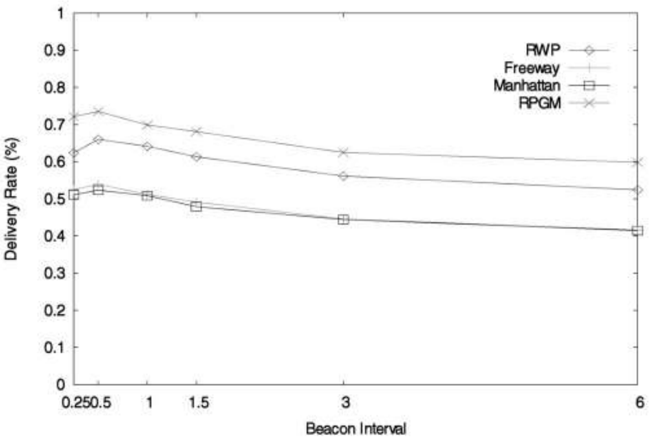


Fig. 5. SDR varying beacon interval.

the second part of our suggested mobility prediction scheme, called destination location prediction (DLP).

3.2 Effect of Beacon Interval

Frequency in beacon packet transmission is closely connected with the freshness of the location information used for routing protocols. Performance is evaluated at six different beacon intervals and overall performance is generally better with smaller beacon interval. The simulation results on the effect of using different beacon intervals are presented in Figs. 5 and 6. The performance drop caused by longer beacon interval is smaller (~12.7 percent in SDR) than performance drop by increased mobility (~28.6 percent) under our experiment settings.

The simulated geographic routing protocol GPSR performs best when the beacon interval is 0.5 rather than when the beacon interval is 0.25, which is the shortest beacon interval we examine. This holds for every metric (SDR, WTR, LLNK) and every mobility model we simulated (see Table 2). When we compare the number of drops for each reason of packet drop between these two beacon intervals, simulations with beacon interval 0.25 show many more packet drops caused by buffer overflow (indicated by IFQ in the ns-2 [12] trace file). The number of drops result from other reasons, such as drop by no route (NRTE), by TTL expiration (TTL), by routing loop (LOOP), does not show much difference on the other hand.

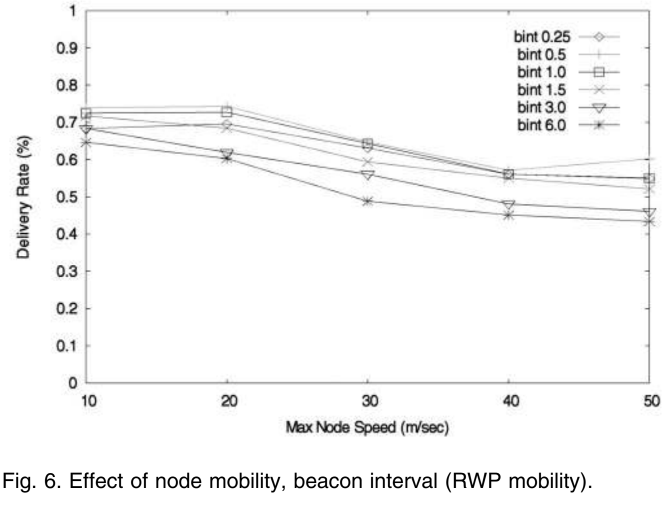


Fig. 6. Effect of node mobility, beacon interval (RWP mobility).

TABLE 2
Maximjum Performance Difference
from Varying Beacon Intervals

Difference	RWP	Freeway	Manhattan	RPGM
SDR (%)	13.6	12.2	10.9	13.8
WTR (%)	22.6	17.5	12.2	16.7
LLNK(#)	722.6	837.1	636.5	235.1

This result shows that frequent beacons may cause network congestion and lead to deteriorated performance of geographic routing as well as wastage of network resources.

4 IDENTIFIED PROBLEMS (CAUSED BY MOBILITY)

Inaccurate location information caused by node mobility produces bad performance of geographic routing protocol as we have shown. Through further analysis, we identify two main problems [25] that account for the performance degradation, namely, LLNK and LOOP problems, described next.

4.1 Lost Link (LLNK) Problem

The greedy forwarding mode in GPSR always forwards a packet to the neighbor that is located closest to the destination node. Each node searches its neighbor list to find a node that meets this condition and forwards a packet to this selected next hop neighbor. However, the selected next hop node may not exist within the radio range even though it is listed as a neighbor. This situation is defined as a lost link (LLNK) problem and can be caused by one of the following two reasons:

1. Node mobility: There is a higher probability of packet transmission failure if greedy forwarding is used to forward the packets. Even with a small outward node movement of the intended receiver, connection between the sender and the receiver can be broken.
2. Asymmetry in a communication link: GPSR assumes link symmetry between neighboring nodes. However, this may not be true in many real wireless network environments. Asymmetric communication links exist when there are nodes with different radio ranges, due to environmental effects or node mobility. Link asymmetry is a common problem in wireless sensor networks where low-power radios are used. These problems are illustrated in Fig. 7.

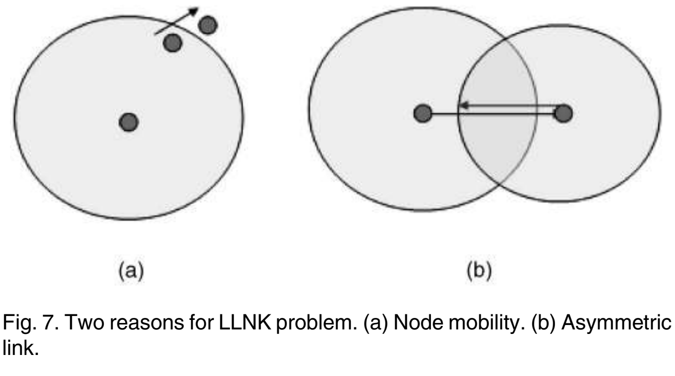


Fig. 7. Two reasons for LLNK problem. (a) Node mobility. (b) Asymmetric link.

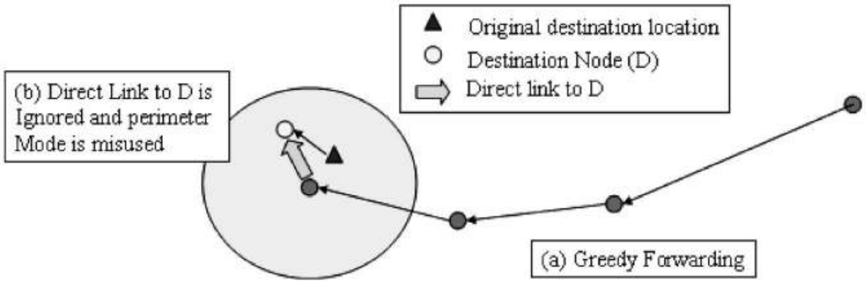


Fig. 8. An example case of LOOP problem

4.2 LOOP Problem

With GPSR, a packet is forwarded toward the coordinate of the destination stored in the packet header and identification of a node is meaningless until the packet reaches the destination node in greedy forwarding. Consider the case when a destination node moves away from its original location and another becomes a node located closest to the original coordinate of the destination. This situation is misunderstood as a local maximum by GPSR protocol and perimeter mode forwarding is used to resolve this problem.

However, in this situation, packets normally get dropped unless the destination node comes back to near the original location and becomes the closest node to the destination location of the packet again. Perimeter forwarding generates wasteful loops in this situation and we label these situations LOOP problems, as shown in Fig. 8.

5 MP: IMPROVEMENT ON GEOGRAPHIC ROUTING

We introduce a mobility prediction (MP) scheme for geographic routing that does not require any additional communication or serious calculation. MP consists of two subschemes, named neighbor location prediction (NLP) and destination location prediction (DLP).

5.1 Related Work on Mobility Prediction

There have been some prior research efforts for mobility prediction. In [13], a mobility prediction scheme in wireless networks and its application to several unicast [14], [15] and multicast [16] routing protocols are introduced. The suggested mobility scheme is employed to calculate the duration of a link connection time. Route expiration time (RET) before the predefined route becomes unavailable and can be attained based on the valid link duration, better packet delivery, and reduced overhead are achieved. The mobility prediction scheme in [13] assumes clock synchronization in the network and constant node speed and movement direction. The suggested scheme is effective when nodes exhibit a nonrandom traveling pattern.

Predictive location-based QoS routing scheme is introduced in [18]. This suggested predictive routing scheme utilizes the location resource update protocol for distribution of location information. An update packet contains timestamps, node coordinates, direction and velocity of node mobility, and resource information. Broadcast flooding is used to deliver update packets from each node to every other node in the network. The frequency of update packet broadcasting can vary according to the velocity of the node and two different types of update packet are used to indicate the level of predictability. The location prediction scheme is used to estimate a new location at the expected delivery time of the packet. The collected node mobility information from periodic update packet is used to estimate expected location of neighbor. A delay prediction scheme based on a source routing assumption is introduced to estimate the location of the destination node. The source routing approach is selected because each node in the network has the global knowledge of the whole network topology and estimated packet delivery time can be calculated based on the selected source route.

Similarly, [17] suggests a mobility prediction scheme that proactively constructs a route for robust and efficient packet delivery. A virtual grid space, where every node stays inside, is introduced and a unique grid-id is given for each grid. The movement pattern of a node is identified based on the previous node movement represented by a sequence of grid-ids stored in the node movement cache. Recent node movement is compared with identified movement pattern via pattern matching to predict the next node movement. The probability of next node movement is calculated and used to cope with node mobility beforehand. Assumptions on virtual grid space and the nonnegligible amount of required storage, computation, and communication limit the applicability the proposed scheme.

A DFS-based QoS routing algorithm [27] estimates the duration of a link connection between neighboring nodes based on the exchanged node location information. This is called a connection time and this estimation method uses the speed vectors and the directional vector information calculated with a neighbor location history. The purpose of this connection time estimation is to find a QoS path similar to [13], [18], but the way to calculate the estimated location to neighbor nodes is similar to our NLP scheme. The main difference is that the QoS routing algorithm [27] estimates the duration time (t) of the link connection, which could be relatively longer future, and the estimation accuracy is dependent both on the frequency of location updates and connection estimation, and the NLP scheme predicts the current position of the neighbor nodes only based on at most two location update intervals old information.

Our mobility prediction scheme is composed of two prescriptions to the problems we identified in Section 4. The schemes we suggest are referred to as neighbor location prediction (NLP) and destination location prediction (DLP).

5.2 Neighbor Location Prediction (NLP)

A neighbor location prediction scheme is introduced as a solution to the LLNK problem (described in Section 4.1). To avoid the bad next-hop node selection, which may result in LLNK problems, the current locations of neighbor nodes are estimated at the moment of packet routing decision with

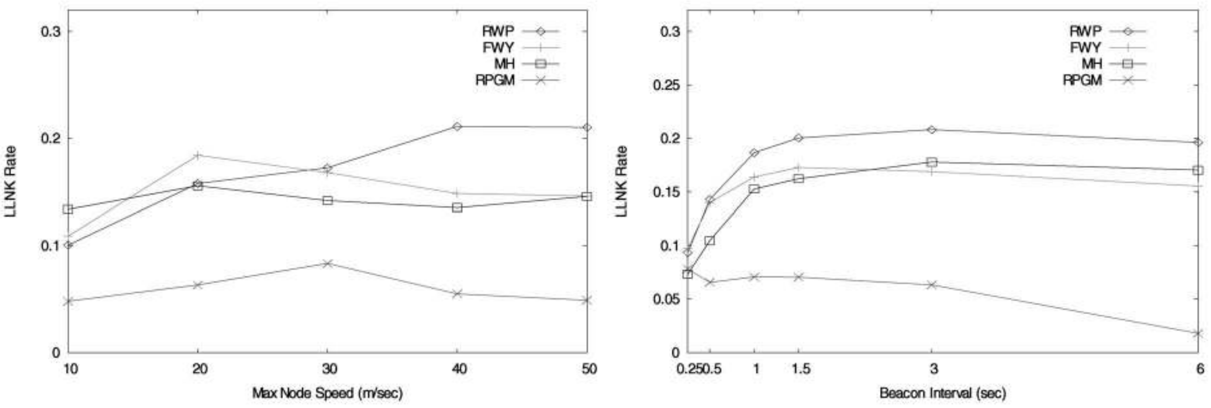


Fig. 9. Percentages drop in LLNK with NLP scheme. The higher value in each graph indicates more savings from LLNK with the NLP scheme.

NLP. Estimates are based on the recent beacon information received from neighbor nodes. The neighbor list includes the following additional fields for neighbor location estimation: last beacon time (LBT), node speed in the direction of the x-axis (Sx) and y-axis (Sy). When a node receives a new beacon from a neighbor, the current time is stored in LBT together with the location of the neighbor. The beacon receiver searches its neighbor list for previous beacon information from the same neighbor. If previous beacon information from the same neighbor is found in the neighbor list, current node speed of the neighbor, which consists of Sx and Sy, is calculated when it receives a new beacon packet from the same neighbor as follows.

The previous location and beacon time of a neighbor stored in the neighbor list is denoted by (x1, y1, PBT) and the same information found in the last beacon packet for the same neighbor is denoted by (x2, y2, LBT). The current node speed Sx and Sy of the neighbor is calculated as follows:

$$\mathrm{Sx} = (\mathrm{x2} - \mathrm{x1})/(\mathrm{LBT\text{-}PBT}) \text{ and}$$
$$\mathrm{Sy} = (\mathrm{y2} - \mathrm{y1})/(\mathrm{LBT\text{-}PBT}).$$

The current location of a given neighbor node (Xest, Yest) is estimated whenever a node looks up a neighbor list for routing decision based on the calculated node speed and the amount of time passed since LBT:

$$\mathrm{Xest} = \mathrm{x2} + \mathrm{Sx} * (\mathrm{Current\ Time} - \mathrm{LBT})$$
$$\mathrm{Yest} = \mathrm{y2} + \mathrm{Sy} * (\mathrm{Current\ Time} - \mathrm{LBT}).$$

Our linear location prediction scheme is simple, but yet reasonable when the beacon interval and the time since LBT are both relatively small.

The transmission range information of each node is also incorporated in our NLP scheme to avoid the problem caused by asymmetric link resulting from an inherent difference in transmission power among deployed nodes and also from node mobility. We assume each node knows (or estimates) its approximate radio range and does not forward a packet to a neighbor node that is currently located outside of its range based on the estimated position to avoid LLNK. With NLP, a packet is forwarded to a neighbor node that meets the following two conditions:

1. a neighbor node that has a closest distance to a destination node from the estimated location of a neighbor node and
2. the distance to a neighbor node is less than the transmission range of a forwarding node.

The neighbor list is reconstructed by incorporating the transmission range information and using the estimated neighbor location information obtained from this simple calculation. The NLP technique is then used to blacklist neighbor nodes that are estimated to be out of the communication range at the moment of packet forwarding. The LLNK problem is greatly reduced for all mobility models in our simulation when using the NLP scheme. The average percentages drop in the number of LLNKs only with the NLP scheme is 17.5 percent for RWP, 15.2 percent for FWY, 14.3 percent for MH, and 6 percent for RPGM mobility models in the scenarios we examined.

Fig. 9 shows the degree of reduction in the percentages of LLNK after incorporating the NLP scheme under different mobility models. The RWP mobility model benefits the most with the NLP scheme overall. The RPGM scheme shows relatively less improvement in LLNK due to its high spatial correlation between nodes. Even though there are more LLNK problems with increased node mobility, the NLP cures more LLNK problems and keeps the percentages of the LLNK reduction similar for the increased node speed scenarios. The RWP model earns more savings at higher node speed, but the FWY and MH do not show incremental benefits from the NLP scheme at increased node speeds. Very low temporal correlation between nodes moving in opposite directions in the FWY model, and the higher degree of freedom with sharp direction change and quite high relative speed between nodes in MH cause a higher probability of getting relatively accurate location estimation from the NLP. The effectiveness of the NLP scheme is dependent on the randomness of node mobility and the frequency of location updates.

5.3 Destination Location Prediction (DLP)

The second part of our mobility prediction scheme is a solution to the LOOP problem (described in Section 4.2), which turns out to be the most serious problem for greedy forwarding. A great number of packets get dropped even when those are delivered to a neighbor node of the destination node. Packet drop after forwarding it to a

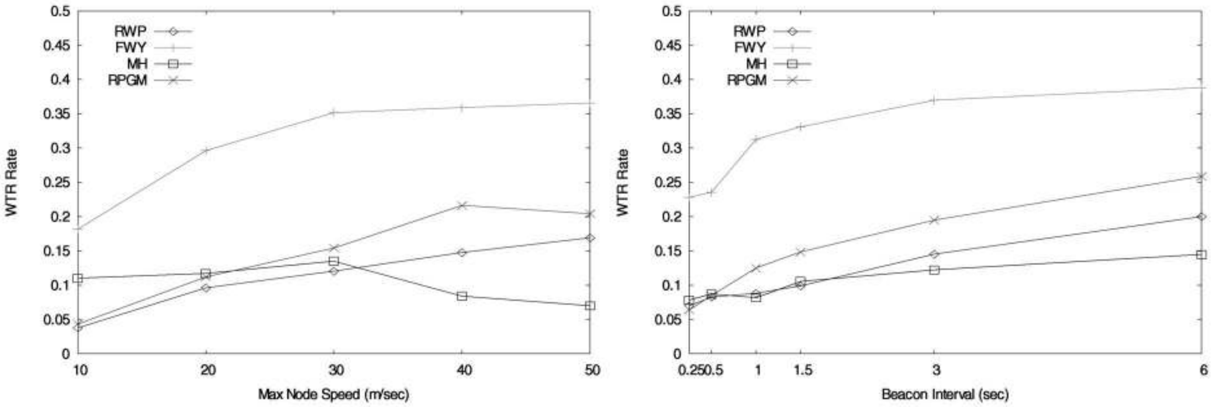


Fig. 10. The reduction in WTR with the DLP scheme. The value in each graph indicates additional savings in WTR with the DLP scheme in addition to NLP scheme.

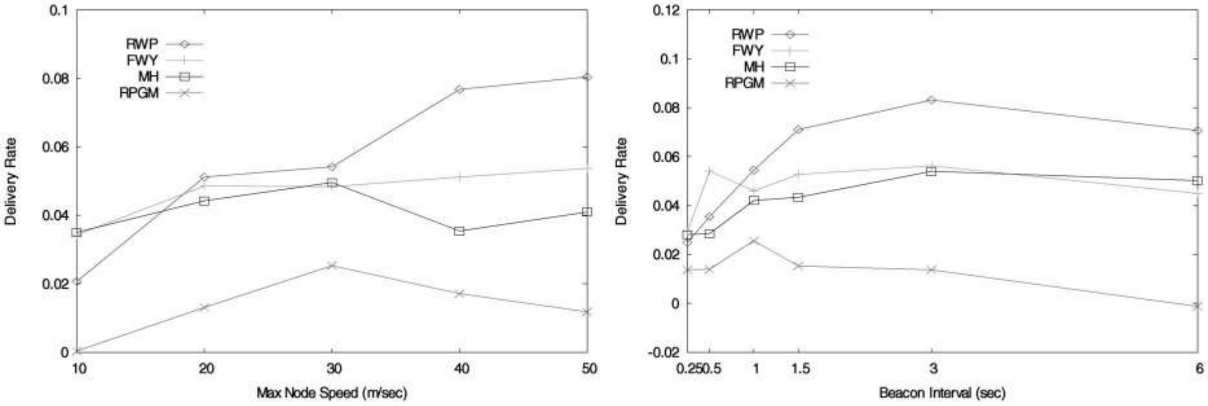


Fig. 11. The improvement in SDR with the NLP scheme.

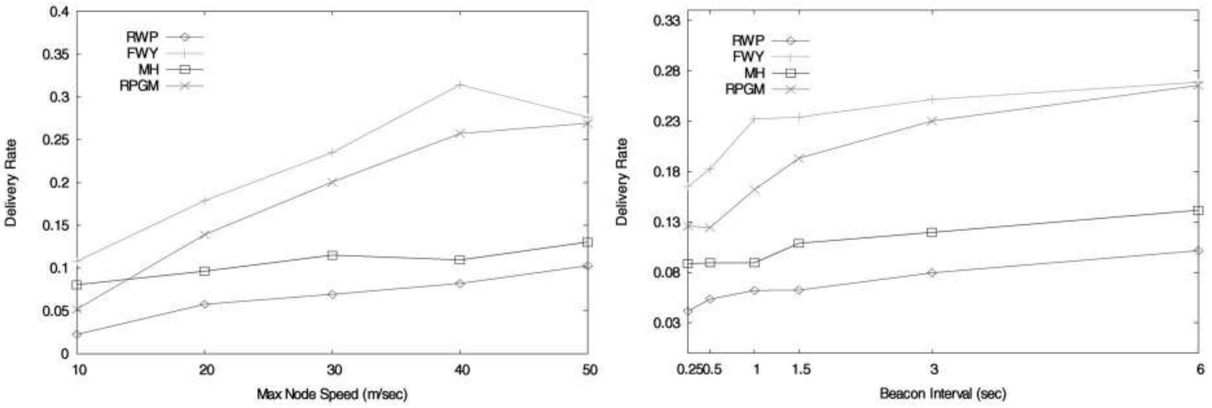


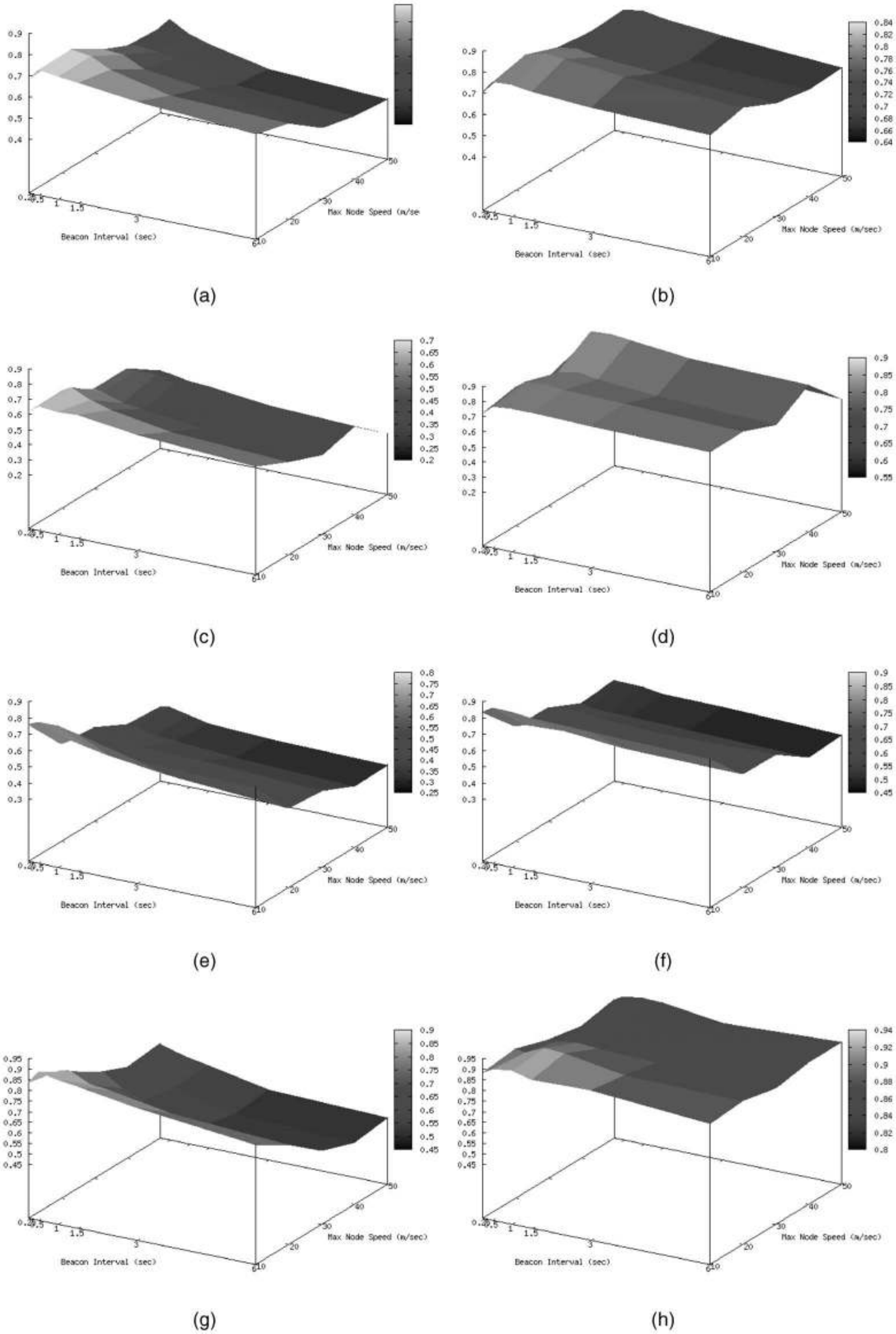
Fig. 12. The improvement in SDR with the MP (NLP plus DLP) scheme.

neighbor of a destination node is the most undesirable thing to do with packet routing because it means more wastage of energy and bandwidth in the network.

To avoid this kind of problem and to increase the chance of packet delivery for the case when the destination node is moved out of its original location, a destination location prediction (DLP) scheme is proposed as a second part of MP. With DLP, each node searches its neighbor list for the destination node before it makes a packet forwarding decision based on the location information of the destination.

If the destination node exists in the neighbor list and is located within the transmission range of the packet holder, the packet is forwarded directly to the destination node without further calculation for finding a closest neighbor to the destination. LOOP problems can be overcome by utilizing the identification information of nodes as well as location information. A significant amount of lost packets and wasted network resources can be saved by avoiding misjudgment on the local maximum situation. With DLP, the destination node movement toward the nodes in the delivery path and within the transmission ranges of those packet forwarder does not cause negative effects on geographic routing or can even be utilized in a positive way.

The improved performance from the effect of the DLP can be shown by checking the change in WTR metric value.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 13. SDR comparison: with MP and without MP for RWP, FWY, MH, and RPGM. (a) SDR without MP (RWP model). (b) SDR with MP (RWP model). (c) SDR without MP (FWY model). (d) SDR with MP (FWY model). (e) SDR without MP (MH model). (f) SDR with MP (MH model). (g) SDR without MP (RPGM model). (h) SDR with MP (RPGM model).

With NLP, WTR reduced 7 percent in RWP, 6 percent in FWY, 5 percent in MH, and 2 percent in RPGM by reducing LLNK problem. After applying the DLP scheme, an additional reduction of 12 percent in RWP, 31 percent in FWY, 10 percent in MH, and 15 percent in RPGM can be attained in WTR. This significant improvement in WTR with DLP proves the reduction of the number of the packet drops near the destination location involved in LOOP problem.

Fig. 10 shows the reduction in WTR for different mobility models. The FWY model shows the best performance improvement with DLP. The combination of 1) the higher probability of finding other than the destination node

TABLE 3
The Effect of Node Speed and Beacon Interval (bint) on the Performance of GPSR with and without MP: The Number in the Table Indicates the Difference between the Best SDR and the Worst SDR

mobility	change in	SDR w/o MP	SDR w/ MP
RWP	node speed	18%	10%
	bint	14%	7%
FWY	node speed	31%	20%
	bint	12%	7%
MH	node speed	39%	35%
	bint	11%	4%
RPGM	node speed	27%	5%
	bint	14%	3%

located closest to the original destination node location and 2) the higher probability of finding the destination node still within the range of one of the packet forwarding node for the FWY and RPGM model, due to their geographic restrictions in their mobility, explain the better savings in the WTR with DLP scheme. Even with longer beacon interval cases, the amount of the reduction in WTR keep increasing with the DLP under our experiment settings. The NLP scheme reduces the probability of a packet drop in the middle of packet forwarding. Based on improved link reliability with NLP, the performance gain from DLP can be further improved.

Figs. 11 and 12, respectively, show the improvement in SDR attained with only the NLP scheme and with DLP scheme applied to the NLP only scheme (i.e., MP). The degree of SDR improvement with NLP and DLP is similar for RWP, but the other remaining three mobility models show much better improvement when DLP is combined together with NLP. The differences in spatial correlation, temporal correlation, and geographic restrictions as explained earlier in this section result in the differences in SDR for different mobility models and under different scenarios simulated.

6 SIMULATION RESULTS WITH MP

With MP (NLP plus DLP), the successful packet delivery rate (SDR) is improved to 12.3 percent for RWP, 26.9 percent for FWY, 14.7 percent for MH, 19.8 percent for RPGM, and the SDR levels up even with higher mobility and longer beacon interval. Fig. 13 clearly shows the effect of the MP on the performance of the geographic routing protocol for different mobility models.

In other words, the impact of faster node movement and infrequent beacon interval has greatly reduced after applying the mobility prediction scheme to GPSR. Table 3 shows the reduced variation in SDR with increased node

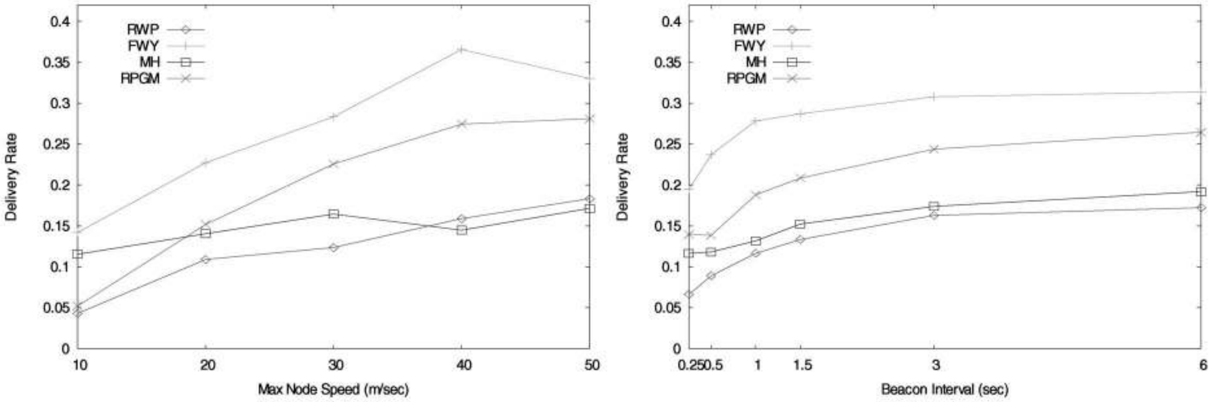
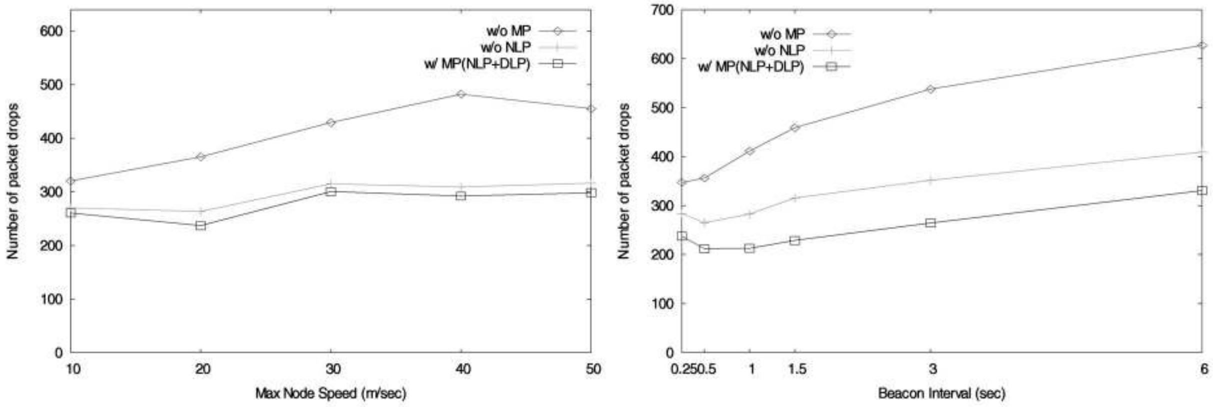
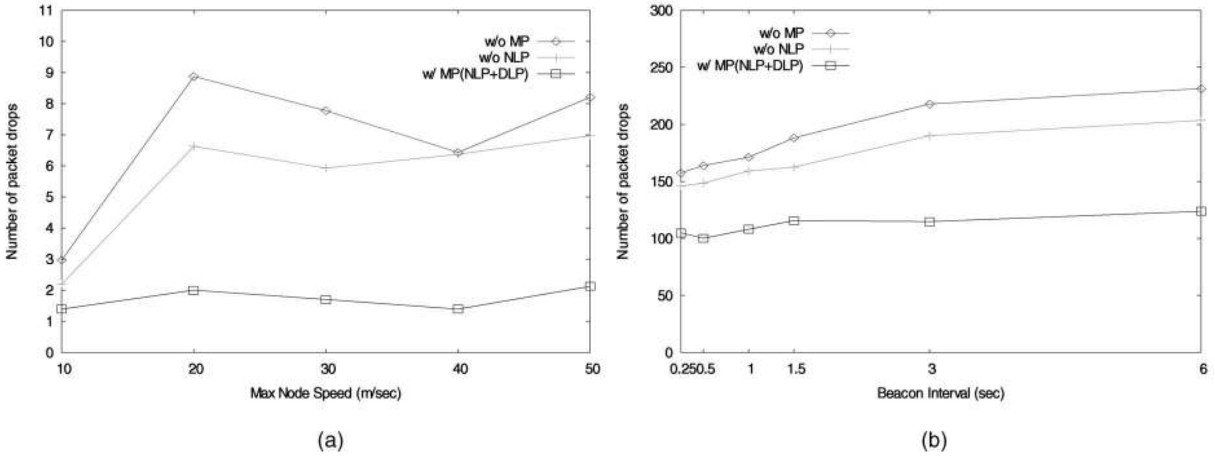


Fig. 14. The improvement gained in SDR with the mobility prediction scheme. The value in each graph indicates the SDR improvement from the original geographical routing scheme without mobility prediction.



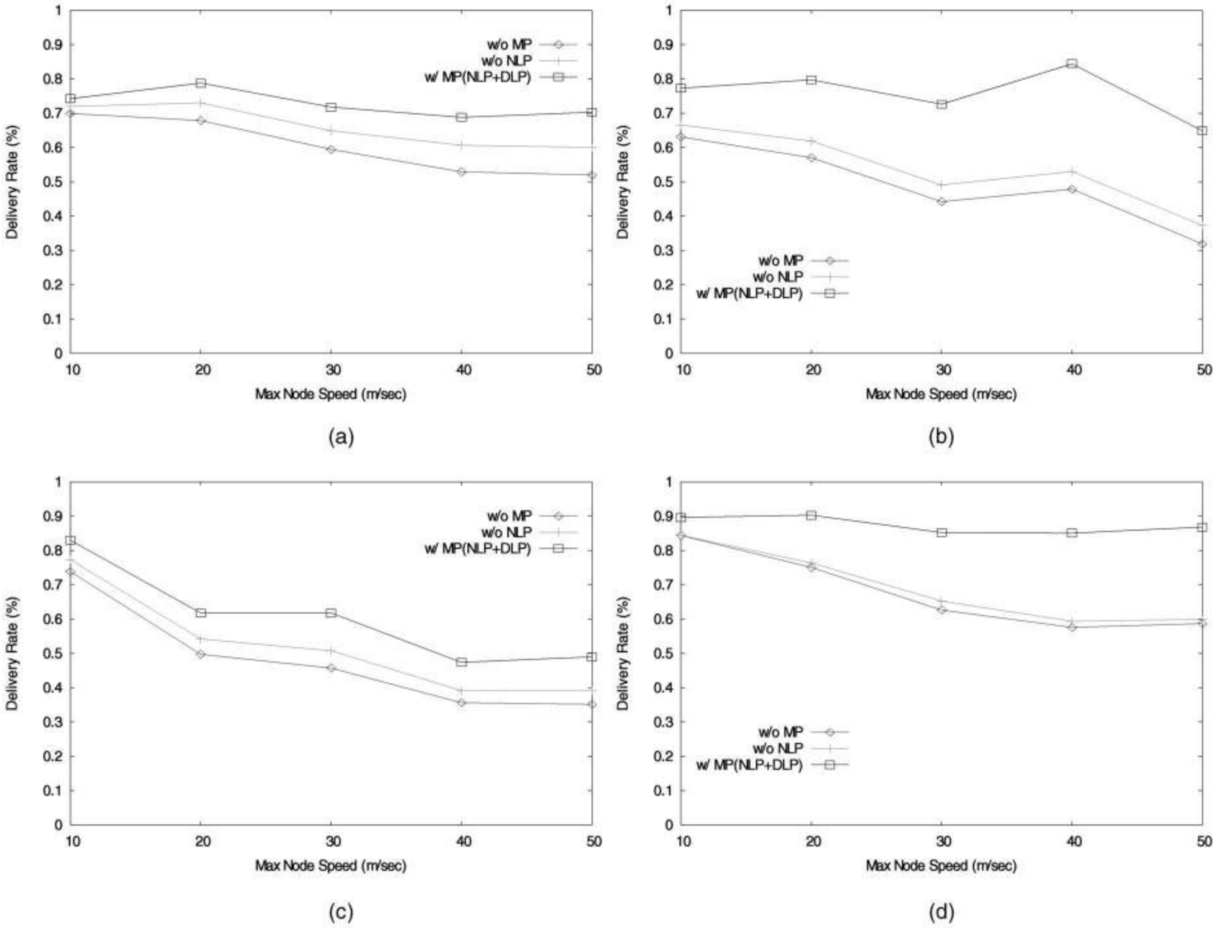
(a) (b)

Fig. 15. The number of packet drops caused by ARP. (a) Drop by ARP under RWP mobility. (b) Drop by ARP under Freeway mobility.



(a) (b)

Fig. 16. Number of drops by NRTE and TTL. (a) Drop by TTL under RPGM mobility. (b) Drop by NRTR under Manhattan mobility.



(a) (b) (c) (d)

Fig. 17. SDR under four different mobility models with different mobility prediction schemes: without MP, with NLP, and with MP (NLP puls DLP). (a) SDR under RWP. (b) SDR under FWY. (c) SDR under MH. (d) SDR under RPGM.

speed and beacon interval with mobility prediction scheme and Fig. 14 presents the improvement details with mobility prediction for each mobility model under the variation of two main parameters: node speed and beacon interval.

To identify the actual effect of each component in MP, the causes of packet drops in our simulations are analyzed. As discussed earlier, the NLP is a scheme to reduce the number of LLNK caused by inaccurate neighbor location information. Broken link connection delays the packet forwarding process in the queue. Packet drops caused by the delay in the ARP process (indicated by ARP in the ns-2 trace file) are closely related to LLNK problem.

Fig. 15 shows the change in the number of packet drops caused by ARP and it proves that the number of packet drops by ARP greatly decreased, especially with the NLP scheme.

The DLP is a scheme introduced to fix the LOOP problem caused by the mobility of the destination node. Fig. 16 shows example improvements achieved with DLP in the number of packet drops caused by no route (NRTE) and TTL expiration (TTL). Packet drops caused by routing NRTE and TTL are closely related to the LOOP problem and exhibit conspicuous improvement with DLP. Packet drops caused by Loop (LOOP) and MAC layer callback timer (CBK) also show similar improvement with DLP in our simulations.

Fig. 17 shows the performance improvement achieved with both the NLP and the DLP for each mobility model. From the different level of effectiveness gained from each mobility prediction scheme, the cause of different levels of performance degradation shown in Table 1 can be explained.

Significant improvement in SDR of the FWY and RPGM mobility model with DLP indicates that those two mobility model has severely affected by the LOOP problem. In the FWY model, the movement of nodes is restricted on the freeway lane and the probability of the packet drop being resolved with DLP becomes high. Due to the group mobility pattern, packet loss problem of RPGM is mainly caused by the LOOP problem rather than LLNK and resolved very well with DLP. The improvement of SDR in the MH mobility model is also high with DLP, but not as good as the FWY and RPGM models. This difference can be explained with higher probability of destination node being unreachable in the MH model. RWP mobility model shows the similar improvement in SDR from both the NLP and DLP scheme.

7 CONCLUSION AND FUTURE WORK

Geographic routing in the presence of mobility is receiving considerable attention in both ad hoc and sensor networks. In this paper, we have presented the effect of inaccurate location information caused by node mobility in geographic routing protocols and identified two major problems caused by node mobility: LLNK and LOOP problems. We have also proposed a two-part mobility prediction scheme to address these two revealed problems. For our simulation, we chose three main factors:

1. maximum node speed,
2. beacon interval, and
3. mobility pattern that affects the performance of geographic routing to clarify the effect of these factors on the performance of location-based routing protocols.

The general effects from varying maximum node speeds and beacon intervals are similar for all the studied mobility models. However, the levels of effect are somewhat different. Increased node mobility causes more effect on FWY and MH mobility models. The longer beacon interval deteriorates the performance of RWP and RPGM slightly more. These differences are attributed to the differences between the mobility models.

Both the negative and positive sides of node mobility could be found in our simulation results. Identification of two major problems caused by mobility-induced location error and the discovery of the positive effect of node mobility are some of the main contributions of our study. The LLNK problem is caused by the movement of neighbor nodes and asymmetry in communication link. The LOOP problem is caused by the movement of a destination node. A positive effect of node mobility is utilized by DLP.

Our proposed mobility prediction scheme is comprised of neighbor location prediction (NLP) and destination location prediction (DLP) schemes. Each component is introduced to settle down the LLNK and the LOOP problem. With NLP, the number of lost link problems can be significantly decreased by estimating the actual location of neighbor nodes based on latest movement and by excluding nodes located outside of a sender's radio transmission range. With DLP, unnecessary packet drops near the destination can be avoided and the positive side of node mobility is exploited while the negative effect is mitigated.

With the combination of these two schemes in GPSR, the performance in both SDR and WTR is significantly improved. For the FWY model, we got the best improvement of 27 percent when more packets are delivered to the destinations and 37 percent of wasted transmission effort is reduced with suggested mobility prediction scheme in our simulations.

Other than the saved network resources with MP, we could pursue further savings. As seen in Fig. 4, the negative effect of increased beacon time is alleviated even with a high level of node mobility. Economical exchange of beacon can be achieved with MP when the small loss in the level of reliability is less significant than the level of wastage in network resource (e.g., sensor networks).

In our future work, we aim to collect supplementary information from previous node movements to build more sophisticated mobility prediction schemes. The location estimation scheme will be combined with a stability factor for each link to help the sender make better routing decisions and will be applied for location services [22], [23] as well as other geographic routing protocols. We also plan to investigate the relationship between node density and the performance of geographic routing protocol under more realistic mobility models of ad hoc and sensor networks.

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