Toward Using Node Mobility to Enhance Greedy Forwarding in Geographic Routing for Mobile Ad Hoc Networks[1]

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Abstract—**Node mobility is generally regarded as a hazard for geographic routing, causing a degradation of performance or even persistent routing failures. In this paper we pursue an opposite view where it is possible to take advantage of mobility to enhance greedy forwarding in geographic routing. A concept named *motion potential*, combining node mobility patterns with node position information, is introduced to help make forwarding decisions. Simulation results show that our approach behaves well and competes favorably with conventional geographic routing, especially under the scenario of low network density and high node mobility.**

Keywords-node mobility; greedy forwarding; geographic routing; mobile ad hoc networks and sensor networks

I. INTRODUCTION

Geographic routing is rapidly gaining reputation in the context of wireless ad hoc networks and sensor networks [1], [2] since (1) it does not store global network topology information at each node, which fits well with the resource-limited characteristic of the targeted networks, and (2) it does not require route maintenance, which means node energy can be reserved for data transmission rather than control overhead propagation. Note that the second reason is especially attractive when applying geographic routing to ad hoc networks or sensor networks with mobile nodes such as wildlife tracking sensor networks, military networks, and vehicular ad hoc networks, where unpredictable topology change is a frequent event.

Extensive studies have revealed that the success of geographic routing can be primarily attributed to localized position-based greedy forwarding [2], [3], which uses only local geographic information of direct neighbors and the destination coordinates. When one node, for example N_i, attempts to forward a packet, it makes a local decision and chooses the neighbor closest to the destination as its next hop. By such a strategy, a packet can be delivered to a destination through an optimal path in terms of distance. However, greedy forwarding may not always succeed; it can fail due to encountering a special situation called *local maximum* – no neighbor is closer to the destination than N_i itself. For such a situation, an alternative scheme – perimeter routing – is introduced to help geographic routing exit local maximum. A planar graph is constructed (graph planarization) and the packet is then traversed along this graph (this is also known as face routing) until it reaches either the destination node or a node that is closer to the destination than the node where perimeter forwarding was engaged (in the above case, N_i).

Although perimeter routing theoretically allows recovery from local maximum [1], it is in general much more laborious and consumes more energy of the nodes. Both periodic graph planarization and face routing involve more nodes than greedy forwarding. Furthermore, in the case of low network density, which is common in mobile ad hoc networks and sensor networks with mobile nodes, such a planarization process may fail. Finally, even if a planar graph can be constructed, the potential mobility of nodes may impede face routing by forming an unstable network connectivity graph, ultimately resulting in a degradation of performance or even routing failures [2], [5]. To achieve geographic routing's efficiency in mobile ad hoc networks and sensor networks, two approaches can be considered: (1) extending greedy forwarding with the capability of working under conventional local maximum conditions, thus avoiding perimeter routing; and (2) actively avoiding local maximum conditions. In this paper, we will focus mainly on the first approach.

What we have presented till now shows node mobility as negatively affecting geographic routing. But there is another point of view. In contrast to conceiving methods to alleviate the difficulties caused by node mobility (for example, eliminating location-errors induced by node mobility by predicating a node's location, such as has been done in [5]), our approach tries to take advantage of mobility in the context of geographic routing, especially for those application with loose delay constraints [6]. The simple, but key, observation is that there are two ways to move a packet currently held by some source node: (1) by transmission hops, i.e., forwarding the packet from the source node to another neighbor node, and (2) by physical

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motion of the source node, i.e., letting the packet be carried by the node. Since packet transmission speed is much faster than the speed of mobile nodes, the first approach will produce a shorter end-to-end delay for moving a packet from a source to a destination, even if it requires a long hop-count path. However, long hop-count paths may consume significant system resources, including communication channel bandwidth and node energy. Furthermore, for geographic routing, this approach might simply fail due to local maximums or a lack of any neighbor node at some point along the route path. Naturally, the second approach has the potential to move a packet over a large distance – basically "for free" except for the time delay. In this work, we seek to explore reasonable tradeoffs between hop counts and end-to-end delay to enhance geographic routing in applications that are delay-tolerant. More specifically, our approach looks to leverage node mobility to help forward packets when a local maximum is encountered.

We propose a refined forwarding approach named *Mobility-based Adaptive Greedy Forwarding* (MAGF). Our approach uses node mobility to dynamically avoid the engagement of perimeter routing by granting the greedy forwarding rule the capability of working efficiently under conventional local maximum situations. A key component of the MAGF rule is a concept called *motion potential*, which combines node mobility attributes with node position information as a metric to be used in selecting a next-hop node. Simulation results are presented that demonstrates the positive impact our method can have on routing performance in terms of route hop count and packet delivery rate, especially under the scenarios of low network density and high node mobility.

II. RELATED WORK

A. Mobility in Ad Hoc Networks

Some pioneering works have studied how node mobility can be used to improve the capabilities of mobile ad hoc networks, especially under Delay-Tolerant Networks (DTN). The methodologies proposed can be collectively referred to as mobility-assisted, encounter-based or store-carry-and-forward routing [6], [12]. One conceptual difference between those previous approaches and our method is that they seek to trade delay for network connectivity while in our approach delay is traded for energy savings.

Our MAGF technique does not employ any special nodes such as ferries or agents as in [13], [14]. All nodes are treated equally. Furthermore, for packet routing, we do not duplicate packets, neither through flooding nor randomized flooding as in [12] [14]. As in standard geographic routing, exactly one copy of a packet is forwarded along a route. In addition, our idea of using both mobility and location information to assist the routing decision (selection of next hop node) in geographic routing is novel and maintains the advantage of making pure localized decisions on packet forwarding rather than requiring any global information.

B. Local Maximum Avoidance

A second category of related work is the techniques used for local maximum avoidance in geographic routing due to local maximum problem's special role – the trigger for perimeter routing. Although this paper shares the basic objective of preventing geographic routing from failing when a local maximum is encountered, we try to achieve this by enhancing greedy forwarding to work efficiently under conventional local maximum conditions, rather than trying to avoid the existence of local maximum problems. Techniques that try to avoid local maximum include the use of location predication [5], correlated street blocking [7], or dynamic potential field [4].

C. Forwarding Rules

A complete taxonomy regarding criteria for next hop selection in position-based routing protocols is provided in [8]. Selection techniques include Random Progress, Most Forward within Radius, Nearest Forward Progress, Nearest Closer, Compass Routing, and Greedy Routing Scheme. Our work is based on the greedy routing scheme, but it enhances that scheme, and other schemes, by considering not only a node's position but also node mobility factors such as speed and motion direction.

Existing approaches build their forwarding rules mostly based on the concept of *progress* [8]. For example, in the greedy forwarding scheme, making progress means forwarding a packet to a node closer to the destination. However, making constant progress cannot be guaranteed [1], [2] since such a "closer neighbor" may not always exist. This constitutes the local maximum problem. In contrast, our approach not only measures absolute progress, but also considers the *potential* for progress based on nodes' mobility patterns. In general, if a node has a very strong tendency for moving toward the destination, even if it currently is not located closer to the destination than the packet holder, we say that this node has a high potential (to become located closer to the destination). Thus, in our approach we will try to use it to delivery a packet to the destination. As a consequence, we have the capability of considering more candidate nodes at each time of forwarding; this naturally enhances the greedy forwarding and avoids the engagement of perimeter routing.

III. ANALYSIS OF LOCAL MAXIMUM SITUATION

To motivate our approach for enhancing greedy forwarding, we first conducted simulation studies to explicitly investigate what factors can affect local maximum problems and how seriously they do so. With the help of this analysis, we can focus our attention on the major issues. The simulations used Greedy Perimeter Stateless Routing (GPSR) [1] as the form of geographic routing protocol.

Previous work has suggested that two factors have major impact on local maximum problems: network density and node mobility [2], [5]. Our preliminary study focused on these two factors and employed 2400m×2000m random topologies. The nodes in this environment moved with a speed ranging from 0 to v m/s, where v is the parameter we used to decide the maximal node mobility ($v \in \{0, 5, 10, 15, 20\}$). Every node will randomly change its motion direction each t seconds ranging from 2 to 20. We assume all nodes have the same transmission range of 250m. To obtain different network density, the number of nodes is varied from 50 to 250 in steps of 50. We introduce a term called *Route Discovery Task* to refer to the task of discovering a route from a given source node to a given destination node. In this simulation, the source and destination are both randomly selected. Note that within this paper we employ the Random Way Point [10] mobility pattern due to its simplicity and generality. The idea here is to shed light on general situations involving mobile nodes rather than any specific situations. The more we confine a node's mobility pattern the more the result will only reflect the efficiency/deficiency of the evaluated algorithm under that specified situation.

Simulation-based relationships between different network configurations and the occurrence of local maximums (LM) are established in Figures 1 and 2. Figure 1 focuses on network density, while Figure 2 focuses on node mobility. To aggregate the individual simulation runs, 1200 route discovery tasks were conducted for each network configuration and the results were averaged. In Figure 1, the max speed (v) of nodes is set to 10 while in Figure 2 the number of nodes is set to 150. Note that we currently ignore the "no-neighbor induced LM" curve in Figure 1. Its usage will be discussed later in Section 4.

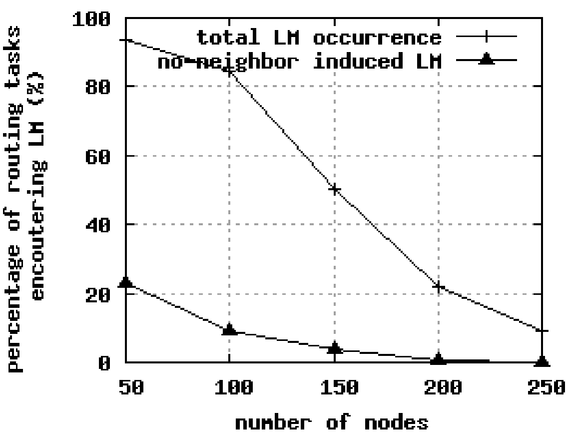


Figure 1. Network density's effect on local maximum (LM)

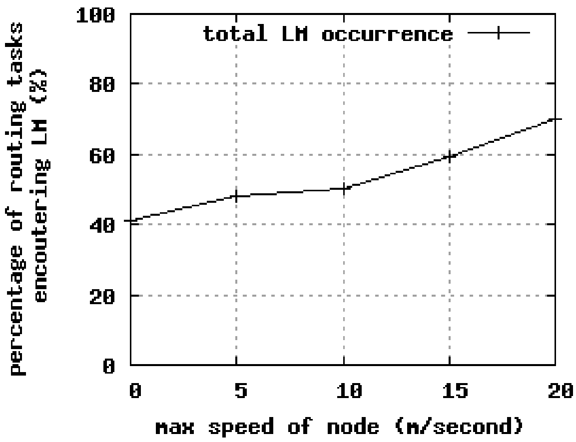


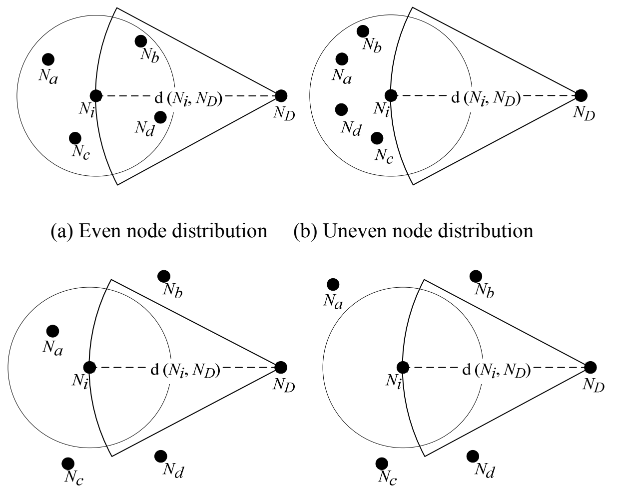
Figure 2. Node mobility's effect on local maximum (LM)

An instant observation is that network density dominates the local maximum problem. When the network was sparsely connected (50 nodes in the environment), more than 1100 out of the 1200 route discovery tasks encountered local maximum problems. Even after we increased the density three times to 150 nodes in the environment, more than half of the route discovery tasks still reached a local maximum situation. When it comes to the evaluation of node mobility, the situation is slightly different, although higher node mobility undoubtedly results in higher occurrences of local maximums. Changing from a static network (0m/s) to one with moderate node mobility (10m/s), causes only a 15.3% increase in terms of local maximum occurrence. Even when we double the node mobility to 20m/s, there is merely a gain of 11.6% of local maximum problems. The quantitative simulation we provided here is consistent with the qualitative evaluation in [3], [5], [8] and [9].

Increasing network density seems an effective way to avoid engagement of perimeter routing. However, the luxury of increasing this density is not always available. Thus, we now turn our attention to an approach for enhancement of greedy forwarding by exploiting node mobility. We want greedy forwarding still to be workable under a local maximum situation.

IV. ENHANCEMENT OF GREEDY FORWARDING

Since we have no control over the objective external environment, a good idea is to rethink the geographic routing algorithm itself. An insightful observation of the localized greedy forwarding is that every time a node attempts to forward a packet, it only considers at most half of its neighbors, assuming nodes are distributed evenly in the environment. For example, in Figure 3(a), when node N_i attempts to forward a packet, it only considers N_b and N_d. Note that the circle in the figure represents a node's communication range. However, even node distribution is a vulnerable assumption, especially for ad hoc networks and sensor networks with mobile nodes. Node mobility can cause instances of "skewed" networks, as shown in Figure 3(b). Furthermore, even if the node distribution could be guaranteed to be even, low network density can result in situations as shown in Figure 3(c) or Figure 3(d). Conventional geographic routing protocols will treat each of the cases (b), (c) and (d) as instances of local maximum, and thus greedy forwarding would halt.



(a) Even node distribution (b) Uneven node distribution

(c) Sparse network 1 (d) Sparse network 2

Figure 3. Candidate analysis for greedy forwarding

To avoid entering perimeter routing mode, we would like to see if we can use the nodes N_a, N_b, N_c, and N_d in case (b), or node N_a in case (c), to continue greedy forwarding. Of course the answer should be yes if it is possible for those neighbors to carry the packet towards N_D. However, before we spend more effort on these cases, we should first convince ourselves that the situation shown in Figure 3(d) is not the main cause of local maximum problems.

We now refer again to the simulation result shown earlier in Figure 1. We name those local maximum that were caused by situations similar to the case shown in Figure 3(d) "no-neighbor induced local maximum." The result shown in Figure 1 is that the instances of "no-neighbor induced local maximum" only contribute a very small fraction of the total local maximum occurrence (no more than 26.4%). Thus, it appears to be worthwhile to consider the cases shown in Figure 3(b) and (c). To help better describe our approach, let us first define three important concepts: *progressive region*, *potential region* and *motion potential*.

A. Progressive Region and Potential Region

Figure 4 is used to define the concepts of progressive region and potential region. The circular region (denoted as C_i) with center N_i is used to represent the communication range for node N_i. Now consider node N_D as the center of another circle C_d (partially shown) whose perimeter intercepts node N_i. A sector of circle C_d is shown and has the property that all nodes on the arc of this sector, including node N_i, lie the same distance from N_D. Note that all the nodes within N_i's communication range that are closer to N_D (than node N_i itself) are located within the shadowed area. This is also the intersection of the two circular regions C_i and C_d. We name this shadowed area as the *progressive region* since forwarding packets to nodes in this region is considered as making progress in terms of routing towards the destination [8]. Similarly, we denote the non-progressive region portion of the circular region C_i as the *potential region*. Forwarding packets from node N_i to nodes in the potential region would not traditionally be considered as making "direct progress" toward the destination. But these potential region nodes might still be potentially helpful for the route discovery task, as we will see.

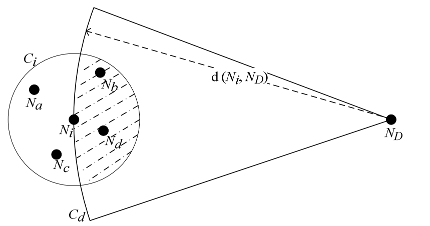


Figure 4. Progressive region and potential region

Assuming the geographic coordinates can be presented as points and adopting set theory, we can formally define the two regions as follows:

Progressive Region = $\{(x, y) \mid d((x, y), N_D) < d(N_i, N_D)$ & $d((x, y), N_i) < r(N_i)\}$ and

Potential Region = $\{(x, y) \mid d((x, y), N_D) \geq d(N_i, N_D)$ & $d((x, y), N_i) < r(N_i)\}$

where d(A,B) represents the distance between points *A* and B, and r(N_i) is the communication range of node N_i. We will see shortly how the two regions work together.

B. Motion Potential

The key component of our adaptive greedy forwarding algorithm is the concept of a node's *motion potential*, which depends on motion-pattern parameters of the node (such as speed and direction) and on the location of a destination. Intuitively, at some time *t*, the motion potential associated with a node N_i measures the "strength" for node N_i to move closer to a specified destination N_D and therefore become positioned in direct communication range of N_D. A forwarding decision will select nodes with higher motion potential, as discussed below.

According to some node's current motion pattern (speed and direction), there are two basic situations to consider: (1) The node can move into communication range of the destination; and (2) The node cannot move into communication range of the destination. Assuming that nodes move with positive speed, we can understand that these two cases depend on the node's current direction of travel. If a node is traveling directly towards the destination, it would fall into case (1) and it should have a high-valued motion potential. In contrast, if a node were traveling directly away from the destination, it would fall into case (2) and should have a relatively low-valued motion potential.

For purpose of simple comparison, we could just assign nodes in case (1) a motion potential score of 1, and assign nodes in case (2) a motion potential score of 0. This would give a higher motion potential score (and thus priority) to those nodes of case (1). But, this simple, binary-valued assignment is too coarse-grain, i.e., it does not distinguish multiple nodes in either case. Therefore, we propose the following quantitative model of motion potential. The *motion potential* of some node N_i for some destination node N_D is defined as:

$$MP(N_i, N_D) = \begin{cases} 1+\dfrac{v_i}{\cos\theta * b-\sqrt{a^2-\sin^2\theta * b^2}}, & 0 \le \theta < \arcsin(\dfrac{a}{b}) \\ \dfrac{\theta}{\pi}, & \arcsin(\dfrac{a}{b}) \le \theta \le \pi \end{cases} \tag{1}$$

where a = $r(N_D)$, b = $d(N_i, N_D)$, and v_i is the current speed of node N_i. Parameter θ models the node's motion direction; it represents the angle formed by the line segment connecting N_i and N_D, and the current motion vector of node N_i. So, $0 \le \theta \le 180$. The condition $\arcsin(\frac{a}{b})$ is used to classify the two cases identified before. In other words, it defines the critical angel that determines if the node can move into communication range of the destination. We can use Figure 5 to help explain the MP function. The destination N_D is located at point D.

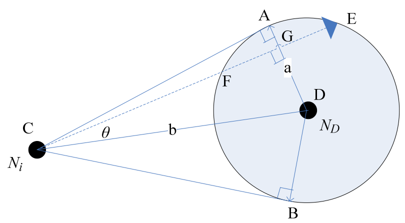


Figure 5. Illustration for motion potential

As shown in Figure 5, assuming that node N_i, currently located at point C, is moving towards point E, θ is represented by ∠ECD and ∠ACD is the critical angel (or ∠BCD in the other direction). If θ is smaller than ∠ACD, node N_i can move into the circular region according to its current motion pattern and the motion potential is calculated by the upper portion of formula (1), instead of simply assigning all nodes in case (1) a value of "1" before. In this case, we are dividing the current speed v_i by the distance needed (line segment CF) for N_i to move into the circular region, which essentially models how fast N_i can enter that region. Otherwise, the lower portion of formula (1) is used. We quantitatively define the motion potential in this case to give higher score to nodes with a smaller motion angle (θ) toward N_D. Thus, if there are no neighbor nodes that show a potential for moving into range of the destination, the selection of a next-hop node will be such that it prevents the packet from deviating from N_D drastically, anticipating making progress during the next forwarding decision. What we have adopted here is exactly the same as the strategy used in compass routing [11]. Note that the "1+" term in the upper portion of formula (1) is used to facilitate comparison. Since the lower portion always produces a value less than 1, we can guarantee that once there is some node that can move into direct communication range of N_D, the priority of that node will be higher than those nodes that cannot enter the direct communication range of N_D.

C. *Mobility-based Adaptive Greedy Forwarding (MAGF)*

For simplicity, we will mainly be concerned with a static destination node. However, such an assumption can be relaxed, as we will mention later.

To enhance the capability of greedy forwarding, our approach considers nodes in both the progressive region and the potential region in performing a localized forwarding decision. In general, whenever a node attempts to forward a packet, it will first search the progressive region and pick the node in the progressive region that is the closest to the destination – this is consistent with the approach of conventional geographic routing. However, if there are no nodes in the progressive region, nodes in the potential region are then considered using the concept of motion potential. The motion potential of each node in the potential region is calculated based on formula (1), and the node with the highest potential will be chosen to carry the packet forward.

Consider again the situation in Figure 3(a). When node N_i attempts to forward a packet, node N_d will be chosen as the next-hop node since N_d is located in N_i's progressive region, and when compared to all other nodes in that region, it is closet to the destination. For the case of Figure 3(b), which is regarded as local maximum by conventional geographic routing, our MAGF approach will cause N_i to calculate the MP value of nodes N_a, N_b, N_c, N_d and N_i itself, and then choose the one with the highest motion potential to serve as the next-hop node.

Note that there are two cases that deserve special attention when considering the above general description of the approach. Case 1: What does MAGF do if node N_i has the highest motional potential among all nodes in the potential region (this includes the situation shown in Figure 3(d))? Case 2: Is it possible to encounter a temporary loop in the routing path when using potential region nodes; and if so, how to resolve this problem?

For Case 1, MAGF regards this as a local maximum situation and adopts a default time-period for caching the packet. This means that N_i continues to carry the packet during this time period, anticipating meeting some neighbor that it can pass the packet to in the near future. More specifically, N_i will cache the packet and periodically check its neighbors (i.e., those nodes in communication range) in an attempt to use the localized forwarding decision procedure given previously. The *caching time* (T_{cache}), which is the maximal time for holding any packet in a node's cache, can be adjusted according to particular system design issues, such as the average speed of nodes. If a packet has not been forwarded by the time the caching time expires, the packet will be dropped and the route discovery for this packet is considered to have failed.

For Case 2, we can observe that it is possible for a temporary loop to be formed if we consider a situation like that shown in Figure 3(c). Assume that node N_i will choose N_a as its next-hop node, due to N_a's motion potential. After N_a receives this packet, N_a will now likely find that N_i is in its progressive region and thus N_a will seek to forward the packet back to node N_i. The main reason this kind of looping might occur is that when using packet forwarding, packets travel much faster than nodes.

To reduce such chances of unproductive packet forwarding, our MAGF scheme adopts the following rule: If a node N_i wants to forward a packet to a potential region node, N_k, selected according to the previously discussed forwarding criterion, it will instruct N_k to hold the packet for a small time period, Δt . During this time period, the packet will be carried by N_k and rely on N_k's mobility to move the packet toward the destination. This mode of "carrying the packet" will end either when Δt expires, at which time greedy localized forwarding resumes, and N_k looks for a next-hop node; or when N_k happens have entered the direct communication range of the destination, in which case this route discovery task is successfully finished. Intuitively, Δt is based on an estimate of how long it will take for N_k to become positioned closer to the destination than N_i, given both nodes' current mobility patterns. To achieve this objective, the following function is introduced:

$$\textit{position difference} = \mathrm{d}(\mathrm{LP}(N_i,t), N_D) - \mathrm{d}(\mathrm{LP}(N_k, t), N_D) \qquad (2)$$

where LP(A,t) is a location predication function that returns the predicated location of node A after a time frame of length t, based on the current mobility pattern (speed and direction) of A. A value of 0 for *position difference* in the above function is of great interest since it defines the time period t at which nodes N_i and N_k will be located the same distance from the destination. As a consequence, we denote this value t as T_0 and use it to construct Δt as follows: $\Delta t = T_0 + T_{cache}$. Thus, when a potential region node receives a packet from some source node, it will carry that packet long enough to allow it to first "catch up" with the source node, and then even eventually achieve a position closer to the destination. By doing so, we can successfully eliminate all two-node formed temporary loops (as illustrated in Case 2 above).

However, it is also possible that a node N_m can be chosen as a next-hop node by the current packet holder N_i even though N_m has previously forwarded this packet. This is possible because N_m's mobility can move it to a new location that is viewed as favorable by our routing algorithm. However, unlike the case when such a loop is formed in traditional static network routing, we believe this case of "reuse" of N_m can be productive since this reuse can still help us achieve progress in terms of routing the packet toward the destination. More sophisticated measurements (e.g., long-term mobility pattern predication) may be helpful in this situation to further enhance performance. We currently leave that topic to future work.

Recall that we assumed the destination node is static. To relax this assumption, we can again use location predication. For example, the concept of destination location predication (DLP) in [5] is shown by simulation to behave efficiently regarding destination node mobility and can be integrated into our approach; but this is outside the scope of this current paper.

V. SIMULATION RESULTS

The simulation environment used to study the behavior of the adaptive greedy forwarding technique was set to be identical with that used in Section 3. We set the caching time to 15 seconds. The two primary features of interest in our study were packet delivery rate and average hop count.

Figure 6 shows results for packet delivery rate. Figure 6(a) reveals that with the increasing of network density, packet delivery rate also increased quickly – an observation that is consistent with previous qualitative evaluation. We found that our adaptive greedy forwarding scheme behaved somewhat better than conventional geographic routing, especially when network density was relatively low.

When it came to evaluating the effect of node mobility on delivery rate (See Figure 6(b)), we found that unlike conventional geographic routing's difficulty in dealing with high node mobility, our approach actually allowed for an increase in the delivery rate when nodes moved faster.

This supports our idea of considering node mobility when making forwarding decisions.

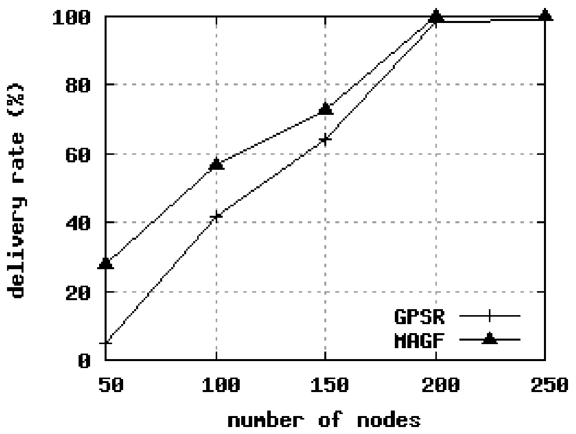


Figure 6(a). Network density vs. delivery rate

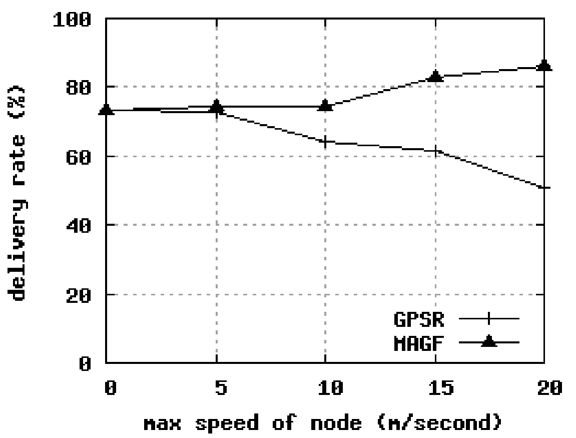


Figure 6(b). Maximal node speed vs. delivery rate

Figures 7(a) and 7(b) show results for average hop count. It is obvious that when network density increases, the average hop count for each route decreases (see Figure 7(a)). This is because packet forwarding is able to make constant progress without using any low-efficiency, long detours, like that needed for face routing in conventional geographic routing. Furthermore, we saw that our MAGF strategy for dealing with local maximum problems resulted in a much smaller hop count. Figure 7(b) shows that by increasing node mobility, conventional geographic routing consumed more hop counts, while our forwarding scheme actually shortened the route. This is because our MAGF approach explicitly considers node mobility.

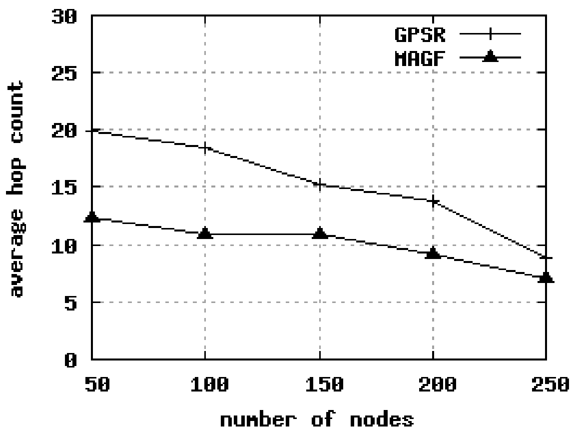


Figure 7(a). Network density vs. average hop count

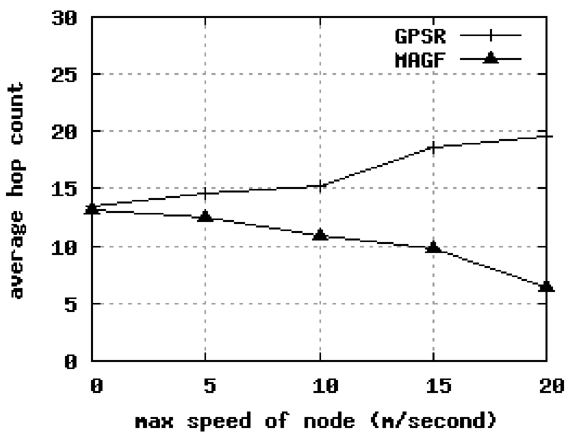


Figure 7(b). Maximal node speed vs. average hop count

VI. CONCLUSION

Previous research has discussed the fact that node mobility can have a negative effect on conventional geographic routing performance. Here, we explored how node mobility might be exploited to create enhanced greedy forwarding techniques for geographic routing. A refined greedy forwarding scheme based on geographic routing was provided. Simulation results showed that this scheme behaved well in terms of average hop count and packet delivery rate, especially when node mobility is at a high-level. The produced computation overhead is limited, and since we do not perform planar graph construction, the complexity of next-hop node selection for our MAGF approach should be identical to that of greedy forwarding scheme and no more than that of standard GPSR.

Two key tasks for future work include the following: (1) In our approach, we actually have traded delay for energy consumption. Further study (both theoretically and by simulation experiments) on how MAGF impacts routing delay and delivery time under different network densities and node mobility patterns would be useful; and (2) The next-hop selection rule is based on our novel concept named motion potential, and we observed that the accuracy of motion potential is partially decided by a node's mobility pattern. It is possible for some nodes to have constantly evolving and shifting mobility patterns. For these nodes we need more sophisticated motion potential calculation methods so that motion potential scores can have sufficient predictive power.

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