Self-Adaptive On-Demand Geographic Routing for Mobile Ad Hoc Networks

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***Abstract*—It has been a big challenge to develop a routing protocol that can meet different application needs and optimize routing paths according to the topology changes in mobile ad hoc networks. Basing their forwarding decisions only on local topology, geographic routing protocols have drawn a lot of attentions in recent years. However, there is a lack of *holistic* design for geographic routing to be more efficient and robust in a dynamic environment. Inaccurate local and destination position information can lead to inefficient geographic forwarding and even routing failure. The use of proactive fixed-interval beaconing to distribute local positions introduces high overhead when there is no traffic and cannot capture the topology changes under high mobility. It is also difficult to pre-set protocol parameters correctly to fit in different environments.**

In this work, we propose two self-adaptive on-demand geographic routing schemes which build efficient paths based on the need of user applications and adapt to various scenarios to provide efficient and reliable routing. To alleviate the impact due to inaccurate local topology knowledge, the topology information is updated at a node in a timely manner according to network dynamics and traffic demand. On-demand routing mechanism in both protocols reduces control overhead compared to the proactive schemes which are normally adopted in current geographic routing protocols. Additionally, our route optimization scheme adapts the routing path according to both topology changes and actual data traffic requirements. Furthermore, adaptive parameter setting scheme is introduced to allow each node to determine and adjust the protocol parameter values independently according to different network environments, data traffic conditions and node's own conditions. Our simulation studies demonstrate that the proposed routing protocols are more robust and outperform the existing geographic routing protocol and conventional on-demand routing protocols under various conditions including different mobilities, node densities, traffic loads and destination position inaccuracies. Specifically, the proposed protocols could reduce the packet delivery latency up to 80% as compared to GPSR at high mobility. Both routing protocols could achieve about 98% delivery ratios, avoid incurring unnecessary control overhead, have very low forwarding overhead and transmission delay in all test scenarios.

***Index Terms*—Routing protocols, wireless communication, ad hoc networks, geographic routing, adaptive, on-demand, topology.**

I. INTRODUCTION

There are increasing interests and use of mobile ad hoc networks with the fast progress of computing techniques and wireless networking techniques. In a mobile ad-hoc network (MANET), wireless devices could self-configure and form a network with an arbitrary topology. The network's topology may change rapidly and unpredictably. Such a network may operate in a stand-alone fashion, or may be connected to the larger Internet. Mobile ad-hoc networks became a popular subject for research in recent years, and various studies have been made to increase the performance of ad hoc networks and support more advanced mobile computing and applications [1], [2], [3].

The topology of a Mobile Ad Hoc Network (MANET) is very dynamic, which makes the design of routing protocols much more challenging than that for a wired network. The conventional MANET routing protocols can be categorized as proactive [39] [11], reactive [12] [13] [14] and hybrid [8], [9], [10]. The proactive protocols maintain the routing information actively, while the reactive ones only create and maintain the routes on demand. The hybrid protocols combine the reactive and proactive approaches. The proactive protocols incur high control overhead when there is no traffic, while for on-demand protocols, the network-range or restricted-range flooding for route discovery and maintenance limits their scalability, and the need of search for an end-to-end path prior to the packet transmission also incurs a large transmission delay. These conventional topology-based schemes are normally designed to support long-term and continuous traffic, and would be very inefficient when the data traffic is sporadic such as in a service-oriented application [16], [17], where the nodes are often involved in a long period of services with only occasional data exchanges for collaboration or upon events.

In recent years, geographic unicast [18], [19], [15], [5] and multicast [31], [32], [33], [34] routing have drawn a lot of attentions. They assume mobile nodes are aware of their own positions through GPS or other localization schemes [52], [53] and a source can obtain the destination's position through some kind of location service [37] [4]. In geographic unicast protocols, an intermediate node makes packet forwarding decisions based on its knowledge of the neighbors' positions and the destination's position inserted in the packet header by the source. By default, the packets are transmitted greedily to the neighbor that allows the packet forwarding to make the greatest geographic progress towards the destination. When no such a neighbor exists, perimeter forwarding [18], [19] is used to recover from the local void, in which packets traverse the face of the planarized local topology subgraph by applying the right-hand rule until greedy forwarding can be resumed. As the forwarding decisions are only based on the local topology, geographic routing is more scalable and robust in a dynamic environment.

Even though geographic routing has many advantages and has shown a great potential, the inaccurate knowledge of local geographic topology and destination position can greatly affect routing performance. This not only leads to a larger packet delivery latency and more collisions, but can also result in a routing failure. To obtain the local geographic topology, each mobile node in current geographic routing protocols [19] periodically broadcasts a beacon containing its position. Such a proactive mechanism not only creates a lot of control overhead when there

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is no traffic, but also results in "outdated" topology knowledge under high dynamics (Section III). To obtain more accurate topology, one option is to determine the beaconing cycle by a moving distance threshold, and another option is to increase the beaconing frequency. For example in [19], with a promiscuous use of the wireless network interface, data packets also serve as beacons. However, with this approach, only the positions of the current forwarding nodes get updated more frequently, but they may no longer be the optimal forwarding nodes as topology changes. Both options do not consider the actual traffic conditions and routing requirements, and blindly increasing the beaconing frequency may even generate unnecessary overhead. On the other hand, beaconless schemes have been proposed [7], [47], [23], [24] to find the next-hop forwarders in the absence of beacons before each packet transmission. Although this avoids the overhead of sending periodic beacons when there is no traffic, the search of next-hop forwarder before each packet sending introduces a high overhead and end-to-end delay during packet transmissions [28]. In addition to the problems due to beacons, relying on only one-hop topology information in current geographic routings may lead to non-optimal forwarding and blind forwarding as shown in Section V-B2. Furthermore, it is hard to preset the routing parameters to the correct values for all scenarios, which will impact routing performance.

The goal of our work is to develop *holistic geographic routing schemes* that can adapt to various scenarios to provide efficient and robust routing paths. Specifically, we propose two self-adaptive on-demand geographic routing protocols that can provide transmission paths based on the need of applications. The two protocols share the following features. Firstly, to reduce control overhead, the routing path is built and the position information is distributed on the traffic demand. Secondly, through a more flexible position distribution mechanism, the forwarding nodes are notified of the topology change in a timely manner and thus more efficient routing is achieved. Thirdly, optimization schemes are designed to make routing paths adaptive to the change of topology and traffic, and robust to the position inaccuracy. Fourthly, the routing schemes in the two protocols naturally handle the destination position inaccuracy. Lastly, each node can set and adapt the protocol parameters independently based on the environment change and its own condition.

The two protocols adopt different schemes to obtain topology information. One protocol purely relies on one-hop topology information as other geographic routing schemes, and the other one assumes a hybrid scheme which combines geographic and topology-based mechanisms for more efficient routing. The use of hybrid scheme avoids the performance degradation of conventional geographic routing by not constraining to *local* view of topology, and takes advantage of geographic information to find each next-hop thus significantly reducing the overhead and delay incurred by network-range search of end-to-end path in conventional topology-based on-demand routing.

To summarize, our contributions in this work include:

- Analyzing the effect of outdated topology information on the performance of geographic routing;
- Proposing two novel geographic routing protocols with different schemes to obtain and maintain topology information based on the need of traffic transmissions;
- Introducing route optimization schemes, and to our best knowledge, this is the first geographic routing scheme that adapts the path to the underlying topology change and traffic demand;
- Designing an efficient position distribution mechanism that can adapt its behavior under different dynamics and routing requirements to provide more accurate and updated geographic topology information for efficient routing while reducing unnecessary control overhead;
- Adapting parameter settings in both protocols according to different criteria, such as network environment, traffic demand and node's own condition;
- Handling the inaccuracy of destination position and efficiently avoiding delivery failure.

The rest of this paper is organized as follows. In Section II, we discuss some related work. Section III makes an analysis on the effect of outdated topology knowledge on geographic routing. We provide detailed descriptions of the two protocols in Section IV, and extensive simulation results and performance studies in Section V. Finally, Section VII concludes the paper.

II. RELATED WORK

As far as we know, there are no geographic routing protocols that are adaptive to the demand of traffic transmissions. We will discuss literature work related to geographic routing protocols and on-demand routing protocols for MANET.

The conventional on-demand routing protocols [12] [13] [14] often involve flooding in route discovery phase, which limits their scalability. LAR [15] and DREAM [5] make use of the nodes' position information to reduce the flooding range. In LAR, the flooding of route searching messages is restricted to a *request zone* which covers the *expected zone* of the destination. In DREAM, intermediate nodes forward packets to all the neighbors in the direction of the estimated region within which the destination may be located.

Unlike topology-based routing protocols, geographic routing protocols [19] are based on mobile nodes' positions. Some recent geographic routing studies focus on the improvement and design of forwarding schemes (e.g., [6] [36]), designing routing metric [22], better recovering from local void [29] or analyzing the routing performance [21]. The work in [40], [41], [43] consider the combination of location and other cost factors in routing. Our focus is to address the issues due to the inaccuracy of geographic topology information, and adapt the protocol in various scenarios to improve routing performance. These schemes can work with ours to achieve different objectives. The recovery strategy of our first routing protocol also avoids the reliance of planar graph which may not be available in a practical environment [43]. Tschopp et al. [46] have tried to combine geographic routing and topology-based routing in ad-hoc networks to overcome the shortcomings of both kinds of routing. The work uses a beacon-based algorithm for the embedding of the connectivity graph. However, the unavoidable distortion of the embedding will result in non-optimal routing and even forwarding failure.

The position information has the following three sources which all impact routing performance, with the first two assumed to be known and the third one contained in geographic routing protocols: 1) positioning system (e.g., GPS): each node can be aware of its own position through a positioning system, which may have measurement inaccuracy. 2) location service: every node reports its position periodically to location servers located on one or a set of nodes. The destination positions obtained through these servers are based on node position reports from the previous cycle and may be outdated. 3) local position distribution mechanism: every node periodically distributes its position to its neighbors so that a node can get knowledge of the local topology. Recently the impact of the position inaccuracy from the first source has been studied in [35] [44] [30] and the second one is discussed in [45]. Being an important self-contained part of geographic routing protocols, the design of position distribution mechanism will affect local topology knowledge and hence geographic forwarding, but little work has been done to study and avoid its negative impact. Son et al. [45] conducts a simulation-based study on the negative effect of mobility-induced location error on routing performance. Instead, we make a quantitative analysis on the negative effect. Most importantly, we propose two on-demand adaptive geographic routing protocols that can meet different application and traffic needs and adapt to different conditions. Our routing schemes are designed to be efficient and robust, with adaptive parameter settings, flexible position distributions and route optimization.

Authors in [7], [47], [23] and [24] attempted to remove the proactive beacons in geographic routing protocols to reduce overhead. CBF [7] and GeRaF [47] proposed different schemes to avoid contention in selecting the next-hop forwarding nodes. The need of changes at both the MAC layer and the network layer increases the complexity of the two protocols and the uncertainty of the performance. In BLR [23], after a forwarding node broadcasts the data packet, its neighbors in a restricted area will contend for packet relaying. Apart from the inherent unreliability of broadcast, as a data packet is generally much longer than a path search message, the competition in data packet forwarding from multiple neighbors will lead to much higher collision probability. Additionally, since the best next hop may not be located in the restricted area, restricting the forwarding only from nodes in the designated area would lead to non-optimal routing. The contention scheme also cannot guarantee only one neighbor wins for the relaying [7], leading to redundant packet forwarding and more collisions. Therefore, the proposed packet relay method cannot work properly when the traffic load is high. In contrast, our preliminary studies [48] indicate that a higher packet delivery ratio can be obtained if the next-hop relay node can be found before packet forwarding. Instead of sending the control messages to select the forwarder first or purely relying on neighboring nodes to compete in forwarding, BOSS [24] broadcasts the data directly and selects the first node that successfully receives the packet as the next-hop forwarder. Although this may better ensure the packet to be received correctly, similar to BLR [23], broadcasting a larger data packet may increase the probability of collisions when multiple neighboring nodes attempt to transmit packets simultaneously, thus consuming more bandwidth for retransmissions. Different from [24], we set a conservative signal to noise threshold for the received control message to ensure more reliable data transmissions upon channel fading. The reliable unicast transmission can be ensured by MAC layer such as 802.11 which reserves the channel through RTS/CTS to avoid collision. More recently, efforts have been made to address local transmission void [25] by forming planar graph without complete neighbor information or consider energy efficiency along with beaconless transmissions [27], [26].

Although existing beaconless schemes reduce the overhead due to active beacons, the search of the next-hop forwarder for each packet makes the end-to-end delay of these beaconless schemes significantly higher than that of GPSR, i.e., almost ten times as shown in [28]. In contrast, our first protocol only needs to search for the next-hop forwarder when the traffic is initiated or when the cached next-hop forwarder cannot be reached. Our estimation scheme and adaptation scheme work together to timely update the next-hop forwarders for optimal routing. Instead of completely removing beacons, in our second protocol, the beacons are sent based on traffic demand and the beacon periods are adapted based on network topology and relative moving speed between a node and its neighbors. Different from existing beaconless geographic routing schemes which simply consider the forwarding procedures without using beacons, the aim of this paper is to design adaptive and robust packet delivery strategies to suit different network settings and traffic conditions, and ensure routing efficiency as network topology or traffic changes. We also consider parameter adaptation to improve transmission robustness while minimizing the overhead and ensure reliable transmission when the knowledge on the destination position is inaccurate. Our performance studies demonstrate that our algorithms and protocols achieve higher delivery ratio, lower control overhead and delay, and lower redundant transmissions in all scenarios tested, with the variations of mobility, traffic, node density and inaccuracy of destination position. The procedures for finding the next-hop forwarders proposed by existing beaconless schemes may be used with our algorithms and protocols, which will help to support more robust and efficient transmissions in various dynamic conditions.

III. ANALYSIS ON THE IMPACT OF INACCURATE TOPOLOGY KNOWLEDGE ON GEOGRAPHIC ROUTING

A proactive fixed-interval beaconing scheme commonly adopted in existing geographic routing protocols may not only result in a high signaling cost but also outdated local topology knowledge at the forwarding node, which leads to *non-optimal routing* and *forwarding failures*. In this section, we will analyze these negative effects. Note that, for the simplicity of analysis, we consider a reference transmissions range. The reference range can be conservatively calculated with the consideration of potential channel degradation. In our protocol, we consider channel variation due to fading and loss, and a signal is considered to be received only if the measured receiving signal strength is above a target threshold. The neighbors that are not reachable from the MAC layer are also removed from the neighbor table immediately to prevent a transmission failure as discussed in Section IV-C1.

A. Non-optimal Routing

To explain why the outdated local topology knowledge may lead to non-optimal routing, let us look at the example in Fig. 1 (a). Node B just moved into A's transmission range, which is unknown to A before B sends out its next beacon message. Without knowing any neighbors closer to the destination G, A forwards the packet to node C then D by using perimeter forwarding. The greedy forwarding is resumed from D to E until

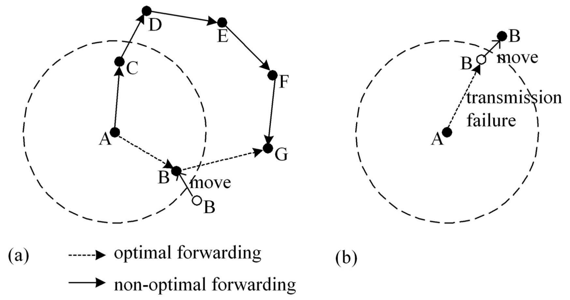

Fig. 1. Negative effects of outdated topology information on geographic routing: (a) non-optimal routing; (b) forwarding failure.

reaching G. The resulted path has five hops, while the optimal path between A and G should have only two hops after B bridges the void between A and G. Due to the lack of timely and larger-range topology information, the inaccuracy of the local topology knowledge greatly affects the geographic routing performance.

B. Forwarding Failures

In the literature work [19], a neighbor's information will be removed if not updated within the timeout interval, which is often set to be multiple beacon intervals. As a result, a node may hold an outdated neighbor information, thus resulting in forwarding failure (e.g., Fig. 1 (b)). This would lead to packet dropping or rerouting [19]. More severely, before detecting the unreachability, the continuous retransmissions at MAC layer reduce the link throughput and fairness, and increase the collisions. This will further increase the delay and energy consumption.

Here we give a quantitative analysis on the probability that a neighbor moves out of transmission range after a timeout interval. For a reference node A, one of its neighbors, node B, moves randomly with an average moving speed v during the period of timeout interval t, and v is uniformly distributed in [0, v_{max}]. Suppose currently B sends a beacon to refresh its position, and the current distance between B and A is z which is uniformly distributed in [0, R], where R is A's reference transmission range. After t, B will move a distance shorter than $r = v_{max} \times t$. We use C_A to represent the neighboring area of node A in relative to its reference range R, and use C_B to represent the moving area of B with a radius r. We calculate the probability P that B is out of C_A after t as follows. There are three cases, $r \leqslant R$, $R < r < 2R$ and $r \geqslant 2R$.

Case 1: (Fig. 2) $r \leqslant R$. When $z \in [R-r, R]$, P equals to the ratio of the shaded area to the area of C_B. The shaded area is:

$$\begin{cases} S = \beta r^2 - \alpha R^2 + zR\sin\alpha, z \in [R-r, \sqrt{R^2-r^2}] \\ S = (\pi-\beta) r^2 - \alpha R^2 + zR\sin\alpha, z \in [\sqrt{R^2-r^2}, R], \end{cases}$$

where

$$\begin{cases} \alpha = \arccos\frac{R^2-r^2+z^2}{2Rz}, z \in [R-r, R] \\ \beta = \arccos\frac{R^2-r^2-z^2}{2rz}, z \in [R-r, \sqrt{R^2-r^2}] \\ \beta = \arccos\frac{r^2+z^2-R^2}{2rz}, z \in [\sqrt{R^2-r^2}, R]. \end{cases}$$

So the expected value of P for case 1 is:

$$E(ratio) = \frac{\int_{R-r}^{R}(r^2\arccos\frac{R^2-r^2-z^2}{2rz} - R^2\arccos\frac{R^2-r^2+z^2}{2Rz})dz}{\int_0^R \pi r^2 dz} + \frac{\int_{R-r}^{R} 0.5\sqrt{2r^2z^2+2R^2z^2+2R^2r^2-z^4-R^4-r^4}dz}{\int_0^R \pi r^2 dz}. \quad (1)$$

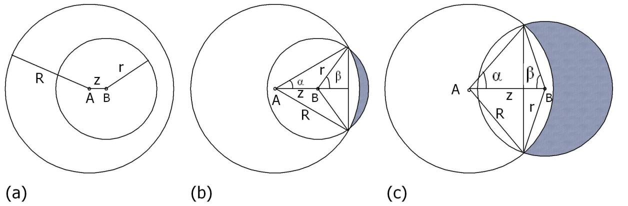

Fig. 2. The relative positions of node A and B ($r \leqslant R$): (a) $z \in [0, R-r]$; (b) $z \in [R-r, \sqrt{R^2-r^2}]$; (c) $z \in [\sqrt{R^2-r^2}, R]$.

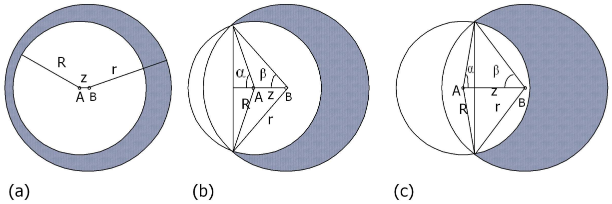

Fig. 3. The relative positions of node A and B ($2R > r > R$): (a) $z \in [0, r-R]$; (b) $z \in [r-R, \sqrt{r^2-R^2}]$; (c) $z \in [\sqrt{r^2-R^2}, R]$.

Case 2: (Fig. 3) $R < r < 2R$. When $z \in [0, r-R]$ (Fig. 3 (a)), C_B will contain C_A. The expected ratio can be expressed as follows:

$$E(ratio) = \frac{\int_0^{r-R}(\pi r^2 - \pi R^2)dz}{\int_0^{r-R}\pi r^2 dz} = \frac{r^2-R^2}{r^2}. \quad (2)$$

When $z \in [r-R, R]$ (Fig. 3 (b) (c)), the shaded area is:

$$\begin{cases} S = (\pi-\beta) r^2 - (\pi-\alpha) R^2 + zR\sin\alpha, z \in [r-R, \sqrt{r^2-R^2}] \\ S = (\pi-\beta) r^2 - \alpha R^2 + zR\sin\alpha, z \in [\sqrt{r^2-R^2}, R], \end{cases}$$

where

$$\begin{cases} \alpha = \arccos\frac{r^2-R^2-z^2}{2Rz}, z \in [r-R, \sqrt{r^2-R^2}] \\ \alpha = \arccos\frac{R^2+z^2-r^2}{2Rz}, z \in [\sqrt{r^2-R^2}, R] \\ \beta = \arccos\frac{r^2-R^2+z^2}{2rz}, z \in [r-R, R]. \end{cases}$$

Therefore, the overall expected ratio of case 2 is:

$$E(ratio) = \frac{\int_0^{r-R}(\pi r^2 - \pi R^2)dz}{\int_0^R \pi r^2 dz} + \frac{\int_{r-R}^{R}(r^2\arccos\frac{R^2-r^2-z^2}{2rz} - R^2\arccos\frac{z^2+R^2-r^2}{2Rz})dz}{\int_0^R \pi r^2 dz} + \frac{\int_{r-R}^{R} 0.5\sqrt{2r^2z^2+2R^2z^2+2R^2r^2-z^4-R^4-r^4}dz}{\int_0^R \pi r^2 dz}. \quad (3)$$

Case 3: $r \geqslant 2R$. The expected ratio can be calculated similar to Eq. 2 and $E(ratio) = \frac{r^2-R^2}{r^2}$.

According to above three cases, we obtain the numerical results in Table I, where the reference range $R = 250m$. The rows and columns of the table indicate the timeout interval t and the maximum relative moving speed v_{max} respectively.

From the table, due to the loss or delay of beacon messages, the probability that a neighbor moves out of the transmission range of the forwarding node could be very high, especially when the moving speed or the timeout interval is large. Our probability calculation is based on all the one-hop neighbors. The actual greedy-based geographic routing can have even higher probability of transmission failure, as the selected next-hop neighbor is the one closest to the destination and thus closer to the border of the transmission range.

TABLE I
EXPECTED PERCENTAGE OF A NEIGHBOR MOVING OUT OF TRANSMISSION RANGE WITH DIFFERENT t AND v_{max} PAIRS (R=250M).

	4s	6s	8s	10s	12s	14s
10m/s	3.57	5.49	7.51	9.64	11.88	14.27
20m/s	7.51	11.88	16.80	22.43	29.19	38.26
30m/s	11.88	19.51	29.19	42.94	55.38	65.24
40m/s	16.80	29.19	47.37	62.22	72.89	80.07
50m/s	22.43	42.94	62.22	75.00	82.64	87.24

We have shown that the overall impact of routing path inefficiency and outdated location information can result in much higher data packet forwarding and control overhead especially in the high mobility scenarios. To address these issues, we assume various adaptive and optimization schemes to update the node position in a more timely manner while reducing unnecessary overhead, and apply position estimation to avoid transmission failure due to outdated location information.

IV. SELF-ADAPTIVE ON-DEMAND GEOGRAPHIC ROUTING PROTOCOLS

In this section, we present two Self-adaptive On-demand Geographic Routing (SOGR) schemes. In both schemes, we assume every mobile node is aware of its own position (e.g., through GPS or some in-door localization technique), and a source can obtain the destination's position through some kind of location service. We also make use of the broadcast feature of wireless network to improve routing performance and assume mobile nodes enable the promiscuous mode on their network interfaces.

In Section IV-A and IV-B, we will introduce their different reactive topology finding and maintenance schemes, the associated next-hop selection and recovery strategies, as well as their parameter adaptation schemes. Both protocols contain an adaptive route optimization component as presented in Section IV-C, in which the position of a next-hop node is estimated before the transmission to avoid position outdate and transmission failure, and the route is optimized according not only to the topology change but also to the actual data traffic requirements. Additionally, we consider the impact of destination position inaccuracy and discuss the schemes to minimize the delivery failure.

For the convenience of presentation, in the remainder of the paper, except when explicitly indicated, F represents the current forwarding node, D is the destination, N denotes one of F's neighbors, pos_A is the position coordinates of A and $dis_{(A,B)}$ is the geographical distance between node A and B.

A. Scheme 1: SOGR with Hybrid Reactive Mechanism (SOGR-HR)

Without proactive beaconing to distribute local topology, a scheme needs to be designed for a forwarding node to find the path to the destination. In SOGR-HR, the next-hop of a forwarding node is determined reactively with the combination of geographic-based and topology-based mechanisms. By incorporating topology-based path searching, an important benefit of the proposed scheme is to obtain the topology information at a *larger range* when necessary to build more efficient routing path, while general geographic routing protocols are usually constrained by their *local* topology view. Furthermore, the planar-graph based geographic routing strategy becomes unpractical under the real physical channel conditions [43]. The use of topology-based routing recovery scheme in SOGR helps overcome such shortcomings of geographic routing.

1) Geography-based greedy forwarding: Normally a forwarding node F will attempt to forward a packet greedily to a neighbor closest to the destination D and closer to D than itself. When there is no next-hop information cached, F buffers the packet first and broadcasts a request message $REQ(D, pos_D, pos_F, h)$ with the hop number $h = 1$ to restrict the searching range to its one-hop neighbors. If a neighbor node N closer to D than F sends back a REPLY, F will record N as the next-hop to D with the transmission mode set as *greedy* and unicast the data packet to N. If another REPLY from a node N' arrives later, F updates its next-hop to N' if N' is closer to D than N, and ignore the reply otherwise.

REG has a small size and a higher probability of being transmitted successfully. To avoid transmission failure of data packets on bad channel, a node will reply only if the received signal to noise plus interference ratio of its received REQ is above a conservative threshold set higher than the target decoding need. Further, to avoid collisions, a neighbor N waits for a backoff period before sending back the REPLY and the pending REPLY will be cancelled if it overhears either a REPLY from another neighbor closer to D than itself or the packet sending by F with the next-hop closer to D than N, indicating that F has already received a REPLY without being overheard by N. To make sure the neighbor closer to D responds sooner and suppresses others' REPLYs, the backoff period T_{bf}^N should be proportional to $dis_{(N,D)}$ and bounded by the max value $h \times I_{bf}$, where I_{bf} is a protocol parameter, and the hops h is set to 1 in greedy forwarding. The backoff period for a node N is calculated as:

$$T_{bf}^N = \alpha \times h \times I_{bf} \times \left(1 - \frac{dis_{(F,D)} - dis_{(N,D)}}{h \times R}\right), \tag{4}$$

where R is the reference transmission range of mobile nodes. If multiple neighbors have very similar distances to D, their reply messages may collide. To address this issue, we introduce a parameter α, which is set to 1 when F sends out the first search message to ensure that the nodes closer to D reply earlier, and set to a random number between 0 and 1 during recovery forwarding (presented next) to avoid reply collisions from neighbors that are of equal distance to D. After F broadcasts the first REQ message, if multiple neighbors have similar closest distance to D and collide in their replying while F gets a reply from a node that has a larger distance to the destination, the protocol will still function properly although the next-hop found is not the one closest to the destination. A node closer to D than the current next hop can send a CORRECT message later to F through the optimization process discussed in Section IV-C. If all the reply messages are lost, a neighboring node is given a further opportunity of sending back its REPLY during the recovery forwarding.

2) Topology-based recovery forwarding: If F does not receive any reply within $1.5 \times h \times I_{bf}$, F will initiate a recovery process. There may be two reasons for F to fail in getting any reply message: 1) The reply messages from all its neighbors are lost; 2) F may not have neighbors closer to D, resulting in a local "void". Without knowing the local topology, the recovery schemes [19], [18], [50], [51] based on planar structure cannot be used to address the local void problem. Also, the planar-graph based geographic routing strategy becomes unpractical under the real physical channel conditions [43]. Instead, SOGR-HR uses a recovery strategy with expanded ring search (which is normally used in path finding in topology-based routing protocols [13] [12]) to address both issues, and build a more efficient path to recover from the local void by taking advantage of larger range topology information.

In a recovery process, F increases its searching range to two hops. Since the absence of a REPLY on the first try may be caused by the loss of REQ or REPLY message due to collisions, whenever a REQ reaches a one-hop neighbor that is closer to D than F, the neighbor sends back a REPLY after a backoff period according to Eq. 4 with $h = 1$. Otherwise, the one-hop neighbor of F continues broadcasting the REQ to its own one-hop neighbors. When a second-hop neighbor of F gets this REQ and is closer to D, it sends a REPLY following the reverse path of the REQ message, with the backoff period calculated from Eq. 4 at $h = 2$. Different from that in greedy forwarding, the α here is set to a random number between 0 and 1 for both one-hop neighbors and two-hop neighbors to avoid potential reply collisions from neighbors that have similar distance to the destination. When a REPLY is sent by a two-hop neighbor, the intermediate nodes record the previous hop of the REPLY as the next-hop towards D with the transmission mode set as *recovery*. On the other hand, when the REPLY is originated from a one-hop neighbor of F, F set the transmission mode to be *greedy*. To avoid overhead, an intermediate node drops a REPLY if it already forwarded or overheard a REPLY from a node closer to D than the current replier. F then unicast the data packet to the detected next hop with the corresponding transmission mode.

If the route searching fails with $h = 2$, F may expand the searching range again by increasing the value of h until it reaches Max_{hops}. Instead of searching for an end-to-end path as in the conventional topology-based routing, the position information is used to guide the searching and selection of relay node(s) towards the destination. As the recovery forwarding is only triggered when needed and the relay nodes can generally be found within a small range (i.e., two hops from our performance studies), the path searching overhead and delay are much smaller than that in conventional topology-based routing.

3) Adaptive parameter settings: As the network traffic and topology are dynamic, it is difficult to pre-determine optimal parameters for good performance in all scenarios. SOGR-HR has two parameters set adaptively, I_{bf} and I_t, the intervals for setting the backoff time in Eq. 4 and for determining the position caching period respectively. A larger I_{bf} leads to a larger backoff interval and therefore a larger next-hop searching delay, while too small a backoff interval gives the first replier less time to suppress others' REPLYs, leading to a larger control overhead. Hence, I_{bf} is determined by F according to its neighbors' distribution relative to D, and is inserted in its REQ message. I_{bf} for D is initialized as Ref_{bf}. During each one-hop route searching process for D, F counts the number of REPLYs it received (denoted as n) and decides I_{bf} as follows:

$$\begin{cases} I_{bf} = I_{bf} + \Delta_{bf}, n > 1, \\ I_{bf} = I_{bf} - \Delta_{bf}, n = 1, \end{cases} \tag{5}$$

where Δ_{bf} is the adjustment granularity. The updated I_{bf} is used in the next route searching process for D.

The interval I_t is the caching time of a position value, sent with messages REQ, REPLY, and data packets. Both REQ and REPLY messages carry the message senders' position pos, and a data packet contains the packet forwarder's position. Setting I_t too low may lead to more frequent path discovery and increase the delivery delay and control overhead, while setting it too high will result in outdated information and routing failure. To take into account node mobility, in our simulation, a receiving node j adapts the caching time of the position of the sending node i based on the relative velocity between i and j, $v_{i,j}$, as

$$I_t = min\{I_{t,max}, max\{I_{t,min}, Dis_t/v_{i,j}\}\}, \tag{6}$$

where Dis_t is a moving distance threshold for timeout. This ensures a node to keep a more updated position of a neighbor for which it has a higher relative moving speed. Node j can estimate $v_{i,j}$ according to the recent two positions of i and j and the time interval between them. The parameter I_t is bounded by the range $[I_{t,min}, I_{t,max}]$ to avoid too frequent position information invalidation and too long a timeout interval for relatively slowly-moving nodes or static nodes.

B. Scheme 2: SOGR with Geographic-based Reactive Mechanism (SOGR-GR)

SOGR-GR depends only on one-hop neighbors' positions to make greedy and perimeter forwarding like other geographic routing protocols [19]. However, it adopts a reactive beaconing mechanism which is *adaptive* to the traffic need. The periodic beaconing is triggered only when a node overhears data traffic from its neighbors the first time. The beaconing is stopped if no traffic is heard for a pre-defined period. A forwarding node may broadcast a request (REQ) message to trigger its neighbors' beaconing when necessary, and the neighbors will have random backoff before broadcasting a beacon to avoid collision. With the neighbor topology information, SOGR-GR takes the same local void recovery method as existing geometric routing protocols to avoid the need of extra searching as in SOGR-HR. In addition, similar to SOGR-HR, the important protocol parameters of SOGR-GR are also set adaptively for optimal performance.

1) Adaptive position distribution: To make the beacon sending on demand, every node keeps three time values t_{req}, $t_{reqHeard}$ and t_{bc}, in which t_{req} records the time when the latest REQ or data packet was sent out, $t_{reqHeard}$ is the time when the latest REQ or data transmission was heard, and t_{bc} saves the last beaconing time. A REQ message or a data packet also serves as a beacon since it contains the forwarder's position.

Whenever a node receives a REQ or overhears a data transmission from its neighbor, it broadcasts a BEACON carrying its position if $t_{cur} - t_{bc} \geq I_{bc}$, where t_{cur} is the current time and I_{bc} is the beaconing interval. This is to ensure that the periodic beaconing is only triggered by the first heard REQ or a data packet after a silent period. The interval I_{bc} is bounded within $[I_{bc,min}, I_{bc,max}]$ as described in the following subsection. To avoid synchronous beaconing from multiple neighbors, the BEACON sending time is jittered by a random delay smaller than the interval I_{jitter}. After a beacon is sent at time t, at the next beaconing time $t + I_{bc}$, the node sends a beacon only when $t_{cur} - t_{reqHeard} < I_{bc}$; otherwise, it keeps silence, so that beaconing is stopped when there is no traffic for a period.

If a node is idle for a period of time, it needs to obtain an update on the neighbor positions to avoid transmission failure as a result of using outdated information. Before forwarding a packet, if $t_{cur} - t_{req} \geq I_{bc,min}$, F sends out a REQ to trigger its neighbors' beaconing, and delays its forwarding decision for a period $3 \times I_{jitter}$ to collect the neighbors' positions; otherwise, F makes a forwarding decision directly based on the existing local topology information.

2) Adaptive parameter settings: The main parameters in SOGR-GR are I_{bc} and I_t. A node can decide its I_{bc} according to different rules, for example, its remaining energy or moving speed. Like I_t setting in SOGR-HR, in our simulation, the I_{bc} of a node i is determined according to the maximum relative moving speed between node i and its active neighbors, v_i^M, as follows:

$$I_{bc} = min\{I_{bc,max}, max\{I_{bc,min}, Dis_{bc}/v_i^M\}\}, \tag{7}$$

where I_{bc} is limited to be within $[I_{bc,min}, I_{bc,max}]$ to avoid too frequent beaconing or too long beaconing interval from certain "lazy" nodes. I_t is the caching time of position information and is set as $2 \times I_{bc}$.

C. Route Adaptation and Optimization with Both Schemes

With the movement of nodes, the cached topology information gets outdated and the routing path may become inefficient. Our route optimization schemes adapt the path according to topology change and traffic conditions. Specifically, motivated by the analysis in Section III, the validity of the cached topology information is evaluated before packet forwarding to avoid *forwarding failure* due to outdated neighbor information, and the routing path is optimized with the cooperation of the forwarding node and its neighbors to avoid *non-optimal routing* due to the inaccuracy in topology knowledge. The optimization mechanisms are applicable to both protocols. For the convenience of presentation, we mainly describe these mechanisms based on SOGR-HR.

1) Validity estimation of next hop: In SOGR-HR, after a route searching phase (Section IV-A), the current best next hop, say C, is cached for a period when there is no significant topology change to reduce the delay and control overhead for route searching. Node C may move out of the transmission range of F or may be no longer the best next hop. Before forwarding a packet, F verifies the validity of C as the next hop.

F estimates the current position of C $(x,\ y)$. Since the position estimation algorithm is not the focus of the paper, in our simulation, we used a simple linear estimation method as presented in Eq. 8, and certainly more sophisticated estimation method in the literature (for example, considering link quality or using more accurate mobility model) can be used for a better estimation to further improve performance.

$$\begin{cases} x = x_{new} + (x_{new} - x_{old})(t_{cur} - t_{new})/(t_{new} - t_{old}), \\ y = y_{new} + (y_{new} - y_{old})(t_{cur} - t_{new})/(t_{new} - t_{old}). \end{cases} \tag{8}$$

where $(x_{new},\ y_{new})$ and $(x_{old},\ y_{old})$ are C's newest two positions recorded by F with t_{new} and t_{old} as their recording time, and t_{cur} is the current time. $(x_{new},\ y_{new})$ will be used as the estimated position when $(x_{old},\ y_{old})$ is unavailable or outdated. If C's estimated position is out of F's transmission range, or is no longer closer to D when the transmission mode is *greedy*, a route searching process will be triggered to find a valid next hop. Sometimes, a neighbor cannot be reached even when it is within the estimated transmission range of F due to poor link condition. In this case, forwarding failure can be detected by the MAC layer protocol, and the unreachable next hop will be removed.

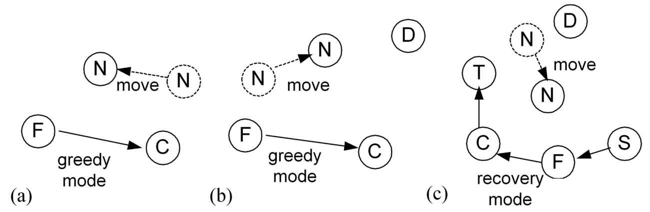

Fig. 4. Route optimization: (a) case 1; (b) case 2; (c) case 3.

Similarly, in SOGR-GR, before F forwards a data packet, the neighbors' positions are estimated. Invalid neighbors' information is removed. The forwarding decision is then made based on neighbors' estimated positions. Similarly to SOGR-HR case, the unreachable neighbors detected by MAC layer due to bad links will be removed from the neighbor table to avoid future transmission failures.

2) Optimization for the forwarding path: In SOGR-HR, due to the local topology change, the cached next hop C may no longer be the best one towards D. To achieve more optimal routing, F's neighbors monitor whether F makes correct forwarding decisions and help to improve transmission path *opportunistically*.

After F forwards a packet to C which continues the forwarding towards D, a neighbor N overhears both transmissions and gets pos_F, pos_C and pos_D. A packet forwarded using the recovery mode will also carry the position of the node (say node S) where the recovery forwarding is originated, pos_S. If N determines that it is a more optimal next hop than C, it sends to F a message $CORRECT(pos_N, D)$ asking it to change its next hop to N. We consider three route optimization cases, using examples in Fig. 4. With $mode_{(A,B,D)}$ representing the forwarding mode from A to B towards a destination D, the criterion for N to send a CORRECT message in each case is as follows:

1) Case 1: (Fig. 4 (a)) N is the destination of the packet. When N moves into F's transmission range, F should forward the packet directly to N.
2) Case 2: (Fig. 4 (b)) $mode_{(F,C,D)} = greedy$. When another node N is currently closer to D than C is, i.e. $dis_{(N,D)} < dis_{(C,D)}$, node N will inform F which will set its new next hop to N.
3) Case 3: (Fig. 4 (c)) $mode_{(F,C,D)} = recovery$. There are two cases: a) F is the last hop of the *recovery* mode, so $dis_{(C,D)} < dis_{(S,D)}$. If $dis_{(N,D)} < dis_{(C,D)}$, F should forward its future packets to N for a more optimal route. b) F is not the last hop of the *recovery* forwarding, so $dis_{(S,D)} \leq dis_{(C,D)}$. If $dis_{(N,D)} < dis_{(S,D)}$, it means F should forward the packet to N and N can resume the greedy forwarding. Overall, if $dis_{(N,D)} < dis_{(S,D)}$ and $dis_{(N,D)} < dis_{(C,D)}$, N needs to send a CORRECT to F.

Through this process, more optimal routing can be achieved. In case 2 and 3, to avoid that multiple neighbors detect non-optimal forwarding simultaneously and send CORRECT messages to F at the same time, the CORRECT message will also be sent with backoff and suppressed as that done for REPLY message with $h = 1$. Without a recovery forwarding phase as for next-hop finding, the parameter α is set as a random number between 0 and 1 to further reduce message collision from nodes with similar distance to D.

There is also another possibility for the recovery forwarding. Suppose *recovery* forwarding starts at F, F sets its next hop to C in order to reach node T which is closer to D than F. Since F is not aware of the positions of non-neighboring nodes on the recovery path to T, a node on the recovery path should notify F with an ERROR message whenever it detects that its next hop is unreachable. T should also notify F if it is no longer closer to D than F is, and F will start a new route searching process.

SOGR-GR assumes similar route optimization schemes. When N detects a non-optimal forwarding from F, it indicates that F may have an outdated pos_N, so N will broadcast a BEACON message. The BEACON will also be backoffed and suppressed as the CORRECT message described above. The non-optimal forwarding in SOGR-GR has three similar possible cases as described above.

3) Handling inaccurate destination position: In geographic routings, a source gets the position of the destination through a location service [37] [4]. As a location server often tracks the nodes' positions in the network through a periodic position update, its information on a node's position may not be accurate and the inaccuracy could be big if the update interval is large for a reduced overhead. Suppose the position of the destination node D that the source obtained from the location server is pos_{inac}, while D is currently located at pos_D. As discussed in [45], in the existing geographic routing [19], pos_{inac} completely guides the packet forwarding without considering D's identification. At the last hop towards pos_{inac}, even if D is the neighbor of the last hop, unnecessary forwarding may still be executed if D is not the node closest to pos_{inac} until the packet happens to reach D or is finally dropped.

SOGR-HR and SOGR-GR are robust to the destination position inaccuracy by nature. Suppose F is the last hop towards pos_{inac}, in SOGR-HR, as long as D is located in the route searching range of F, F will build the path to D. In SOGR-GR, F will forward the packet directly to D if D is its neighbor. Furthermore, in the case 1 of the optimization process (Section IV-C2), D will notify its neighbors whenever it detects that a neighbor didn't forward the packet directly to it. These can handle the case that D is within the transmission range of any node on the forwarding path towards pos_{inac}. Although the inaccuracy of location service is normally smaller than a transmission range [37], if the inaccuracy is too large to reach D by using the above methods, the last hop will start a limited-range search for D. Our simulation results show that the two protocols are robust to the destination position inaccuracy.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of SOGR-HR and SOGR-GR with various moving speeds, node densities, traffic loads and destination position inaccuracies.

TABLE II

VALUES USED IN SOGR-HR AND SOGR-GR'S ADAPTIVE PARAMETER SETTINGS.

	values	protocol
Ref_{bf}	10ms	SOGR-HR
Δ_{bf}	2ms	SOGR-HR
Dis_t	300m	SOGR-HR
$[I_{t,min}, I_{t,max}]$	[10s,30s]	SOGR-HR
Dis_{bc}	150m	SOGR-GR
$[I_{bc,min}, I_{bc,max}]$	[5s,15s]	SOGR-GR

A. Simulation Overview

We implemented SOGR-HR and SOGR-GR within the Global Mobile Simulation (GloMoSim) [38] library. Although various schemes have been proposed to address different issues, very few literature studies provide complete protocol design that can be followed for implementation. As our protocols are on-demand and geography-based, for performance evaluations, we compare our protocols with the classic topology-based on-demand routing protocol AODV [12], LAR [15], an on-demand routing protocol utilizing position information to restrict the flooding range of route searching, and the geographic routing protocol GPSR [19]. Besides demonstrating the efficiency and robustness of our protocols in dynamic scenarios, we further confirm the benefit of using geographic routing.

We run simulations using the AODV and LAR1 codes carried with the simulator. We also implemented GPSR [19] in GloMoSim according to the NS-2 code [20]. The GPSR implementation followed the specification in [19] with MAC-layer failure feedback (notification from the MAC layer when a neighbor is unreachable), interface queue traversal (the packets addressed to the unreachable neighbor are removed from the interface queue and passed back to the routing layer for rerouting) and promiscuous use of the network interface (data packets also serve as beacons by carrying the forwarder's position) which were also applied in SOGR-HR and SOGR-GR. We set GPSR's beacon interval as 1.5s with neighbor table timeout interval set as $4.5 \times 1.5s = 6.75s$ according to [19]. Table II lists the initial values or constraints we used in SOGR-HR and SOGR-GR for parameter setting. As all the parameters are adaptive and adjusted at each forwarding, the initial values are not critical. The parameter I_{jitter} in SOGR-GR is set to 10ms. The reference distance threshold Dis_{bc} for a beacon update in SOGR-GR is set to be smaller than the transmission range. The timeout reference distance Dis_t for SOGR-HR is set to be double Dis_{bc} so that the timeout periods for SOGR-HR and SOGR-GR are comparable. The initial backoff interval Ref_{bf} and the minimum and maximum backoff intervals are set to consider some message propagation and queuing delay, and to avoid potential collision. We restrict the searching range of SOGR-HR to two hops by setting Max_{hops} as two because in most cases nodes closer to the destination can be found within this range and a larger searching range will result in a bigger control overhead.

The simulations were run with 300 nodes randomly distributed in an area of $3000m \times 1500m$. We chose a rectangular network area to obtain a longer path. The movement of nodes follows the improved random waypoint mobility model [49]. The moving pause time was set as 0 second, the minimum speed was 0

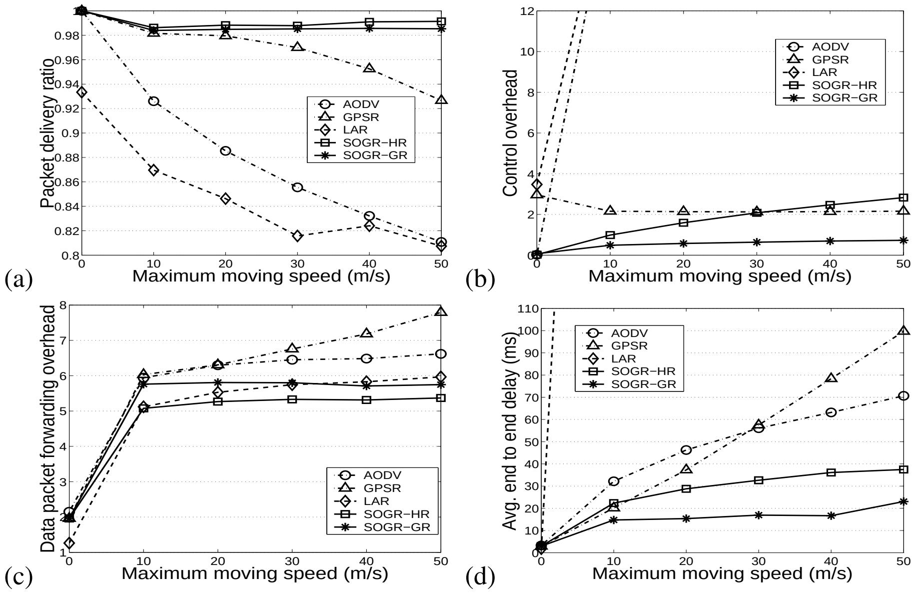

Fig. 5. Performance with different maximum moving speeds (300 nodes, $3000m \times 1500m$, 30CBR): (a) packet delivery ratio; (b) control overhead; (c) average number of data packet forwarding; (d) average end to end delay.

m/s and the default maximum speed was 20 m/s except in the performance evaluation of the impact of mobility. We set the MAC protocol and radio parameters as [9] according to the Lucent WaveLAN^{TM} card, which operates at a data rate 11Mbps and radio frequency 2.4GHz with a reference transmission range 250m. The physical channel follows the Rayleigh model, and a packet is considered to be received only when its received SNR is above a threshold. IEEE 802.11b was used as the MAC layer protocol to coordinate medium access and resolve collisions. Each simulation lasted 900 simulation seconds. A traffic flow was sent at 8 Kbps using CBR between a randomly chosen source and destination pair with packet length 512 bytes. By default, 30 CBR flows are used in the simulations, except when evaluating the impact of traffic load. Each CBR flow starts at a random time between 10s and 15s so that the reference proactive protocol GPSR has enough time to accumulate topology information, and ends at 890s to allow the emitted packets to reach destinations. A simulation result was gained by averaging over 20 runs with different seeds to increase the confidence of the results.

We study the following metrics:

1) *Packet delivery ratio*: The ratio of the packets delivered to those originated by CBR sources.
2) *Control overhead*: The total number of control message transmissions (the forwarding of a control message at each hop is counted as one control transmission) divided by the total number of data packets received.
3) *Average number of data packet forwarding per delivered packet*: The total number of data packet forwarding accumulated from each hop (including rerouting and retransmissions due to collisions) over the total number of data packets received. Both the non-optimal routing and rerouting due to unreachable next hop will increase the forwarding overhead.
4) *Average end to end delay*: The average time interval for the data packets to traverse from the CBR sources to the destinations.

To demonstrate the effectiveness of our algorithms and protocols in supporting robust communications under various conditions, we have performed extensive simulations with the variations of mobility and thus the rate of network topology changes, node density, traffic load, and the accuracy level of the destination position. In each performance study, only the parameter to evaluate is varied, and the remaining parameters are set to the default values.

B. Simulation Results

1) Effect of moving speed: We study the impact of mobility on the performance of various protocols by varying the maximum moving speed from 0m/s to 50m/s. In Fig. 5 (a), the delivery ratios of the two topology-based protocols drop quickly as the moving speed increases. As mentioned previously, the scalability of LAR and AODV is limited by the involved network-range or restricted range flooding. The end-to-end paths obtained during route discovery phases are easily broken under network dynamics resulting in packet droppings, although a smaller-range recovery may be initiated after routing failure at the cost of retransmissions and extra control overhead. In contrast, the geographic routing protocols determine the next hop based only on the knowledge of local topology, and can hence respond to the mobility faster. Therefore, all three geographic routing protocols have much higher delivery ratios. SOGR-HR and SOGR-GR maintain a high delivery ratio around 99% even in a highly dynamic environment, while the delivery ratio of GPSR drops quickly when the maximum moving speed is higher than 20m/s. The stable performance of SOGR-HR and SOGR-GR demonstrates the effectiveness of their adaptive schemes in response to changes of network topology as a result of mobility. When mobile nodes move faster, the local topology information advertised through fixed-interval beaconing in GPSR is more vulnerable to be invalid. While in SOGR-HR and SOGR-GR, the adaptive parameter settings and more flexible position distributions will intelligently generate necessary control messages to distribute position information and better track mobility.

The use of adaptive position update in the two SOGR protocols

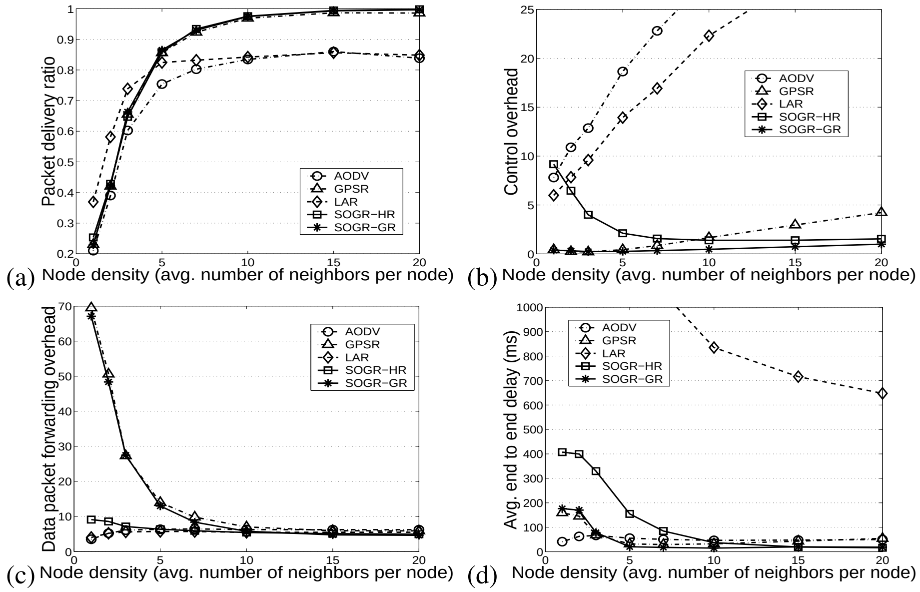

Fig. 6. Performance with different node densities (3000m × 1500m, 20m/s, 30CBR): (a) packet delivery ratio; (b) control overhead; (c) average number of data packet forwarding; (d) average end to end delay.

is verified by Fig. 5 (b), where both SOGR-HR and SOGR-GR intelligently generate more control messages to capture the topology changes as mobility increases. With a fixed beaconing interval, GPSR has unnecessary control overhead when the mobility is low, and suffers from outdated topology knowledge when the mobility is high. SOGR-HR is seen to generate a slightly higher control overhead than SOGR-GR. In SOGR-HR, whenever the next hop is invalid, the forwarding node will start a new route search phase; while in SOGR-GR, the forwarding node just needs to select another valid next hop from its neighbor table without incurring extra control overhead. The increase of mobility leads to a higher chance of path breakage and thus a higher number of path search messages. As a result, the control overheads of AODV and LAR are significantly higher with the increase of mobility.

As expected, GPSR needs more packet forwarding to deliver a packet as shown in Fig. 5 (c), due to its non-optimal routing and rerouting caused by the outdated local topology knowledge and the longer routing path during perimeter forwarding. The number of forwarding increases almost linearly with the increase of moving speed. As AODV and LAR usually search for the shortest path to the destination, they have fewer forwarding. SOGR-HR has the fewest forwarding in most cases, and both SOGR-HR and SOGR-GR have much fewer forwarding under high mobility as compared to GPSR. These are due to their use of more efficient position distribution mechanisms to reduce the rerouting of undeliverable packets and route optimization schemes to adapt the route more quickly to the topology changes. SOGR-GR has a little more forwarding than SOGR-HR because as GPSR, the perimeter forwarding in SOGR-GR may introduce more packet forwarding, while by considering topology at a larger-range during recovery forwarding, SOGR-HR can build more efficient routing path without being constrained to one-hop information.

In Fig. 5 (d), LAR and AODV are seen to have a longer end-to-end delay due to more frequent path breakage and the time required to re-build the path before packet forwarding in traditional on-demand routing protocols. In GloMoSim implementations, when there is no route available, AODV will remove the undelivered packets immediately, while LAR will buffer the packets until the route is available (possibly as a result of node mobility) or the buffer is full, so LAR has a much longer delay than AODV (the high delay of LAR is also observed in [42]). The end-to-end delay of GPSR increases almost linearly as mobility increases due to its outdated topology knowledge and thus higher chance of rerouting and non-optimal routing. At the highest mobility, its delay is more than four times that of SOGR-GR and 2.5 times that of SOGR-HR. Both SOGR protocols achieve much smaller delay with use of various adaptive and path optimization strategies to track the topology changes in a timely manner. SOGR-HR has a slightly longer delay than SOGR-GR as SOGR-HR will start a new next-hop search whenever the next hop is invalid.

In summary, the two SOGR protocols are robust to the quick topology change under high mobility, and can distribute the position information more timely and adaptively in response to different mobility levels. With more updated position information, better path finding strategy and various optimization schemes, both SOGR-HR and SOGR-GR have much fewer redundant transmissions and lower end-to-end delay as compared to GPSR. The delivery ratio of GPSR reduces quickly at high mobility due to the lack of updated positions of neighbors and its inefficient routing. As expected, the two conventional on-demand protocols could not react fast to the topology change, and incur higher control overhead and end-to-end delay.

2) Effect of node density: Since geographic routing is sensitive to node density and performs better in dense networks, we also study density impact by varying the node density from average only one neighbor per node to twenty neighbors per node.

In Fig. 6, all the routing protocols have higher delivery ratios under a higher density, and the three geographic routing protocols perform better at a higher node density. LAR has a slightly higher delivery ratio in a sparse network as it buffers the packet until the route is available at the expense of an extremely long delay

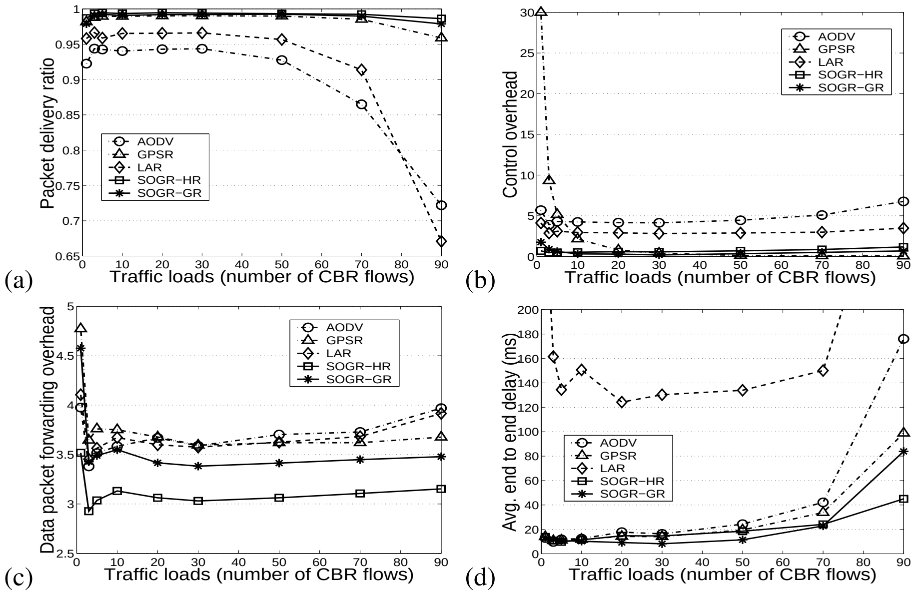

Fig. 7. Performance with different traffic loads (90 nodes, $1500m \times 1000m$, 20m/s): (a) packet delivery ratio; (b) control overhead; (c) average number of data packet forwarding; (d) average end to end delay.

(Fig 6 (d)), while the remaining protocols drop packets earlier if no route is available. The topology-based routing protocols generally have a lower delivery ratio as a result of larger number of control messages and hence collisions as observed in Fig. 6 (b).

In Fig. 6 (b), all the three geographic routing protocols have low control overheads when the node density is larger than average two neighbors per node with SOGR-GR having the lowest overhead, while the overheads of the two topology based protocols rise sharply due to their use of network-range flooding of path search messages and the flooding overhead is larger in a higher density network. Compared to SOGR-GR and GPSR, SOGR-HR has a higher overhead when the node density is low, as the forwarding node will increase the searching range more frequently. While for SOGR-GR and GPSR, the perimeter forwarding is based on the local topology information saved in the neighbor table, and hence will not cause any extra control overhead. At high density, however, the control overhead of GPSR is more than double those of SOGR-HR and SOGR-GR. GPSR uses fixed-interval beaconing and the total number of beacon messages will increase as the number of network nodes increases, while both SOGR protocols assume reactive routing mechanism and adaptive parameter setting to reduce control overhead.

In Fig. 6 (c), it is seen that the lower overhead of GPSR and SOGR-GR in a sparse network is at the expense of more data packet forwarding. This is because both the greedy and perimeter forwarding of GPSR and SOGR-GR are fully "stateless". Every node just forwards packets according to its one-hop topology knowledge even if there is no route from source to destination. Therefore, many packets are dropped after having traversed a long way. While for AODV and LAR, only when the path is available through route searching, the packets will be forwarded, so they have a relatively higher control overhead but fewer packet forwarding overhead as shown in Fig. 6 (b) (c). Due to the hybrid mechanism adopted, SOGR-HR makes a better balance between control overhead and packet forwarding overhead. Only when the forwarding node finds a node closer to the destination within its Max_{hops} neighbor range, it will forward data packets. Hence, in a sparse network, SOGR-HR has up to 86% lower packet forwarding overhead than GPSR and SOGR-GR, with more path searches. In SOGR-HR, the larger range topology information obtained from the topology-based mechanism improves its performance in sparse networks, as the packets will be dropped as early as possible when the destination is unreachable.

For all three geographic routing protocols, packets often traverse a longer path to reach the destination in a sparse network as a recovery forwarding has to be used more frequently. As a result, their end-to-end latency is longer in a sparse network as shown in Fig. 6 (d). From Fig. 6, their overall performance improves quickly when the node density increases until to a dense network where they keep a better performance.

In summary, all geometric protocols could achieve higher delivery ratio and much lower control overhead under a higher network density compared to topology-based on-demand routing protocols. By making a better tradeoff between path searching overhead and forwarding efficiency, SOGR-HR achieves a significant lower packet forwarding overhead compared to GPSR and SOGR-GR in a sparse network.

3) Effect of data traffic loads: As the scalability problem of the simulator prevented us from simulating a higher traffic load in a larger network, to study the performance of various traffic loads, we simulated a 90-node network with range $1500m \times 1000m$, and increased the traffic loads until 90 CBR flows.

Fig. 7 indicates that all three geographic routing protocols have delivery ratios higher than 95% even with a very heavy traffic load. As a data packet also carries the position of its sender, the increase of traffic could help quickly update the positions of nodes, which enables better forwarding node selection and mobility handling. These mitigate the side effect as a result of load increase. The delivery ratios of SOGR-HR and SOGR-GR are over 98% with various traffic loads, while GPSR's delivery ratio drops faster in a heavy traffic network, as its rerouting and non-optimal routing increase the transmission load and cause more packet droppings due to more collisions or

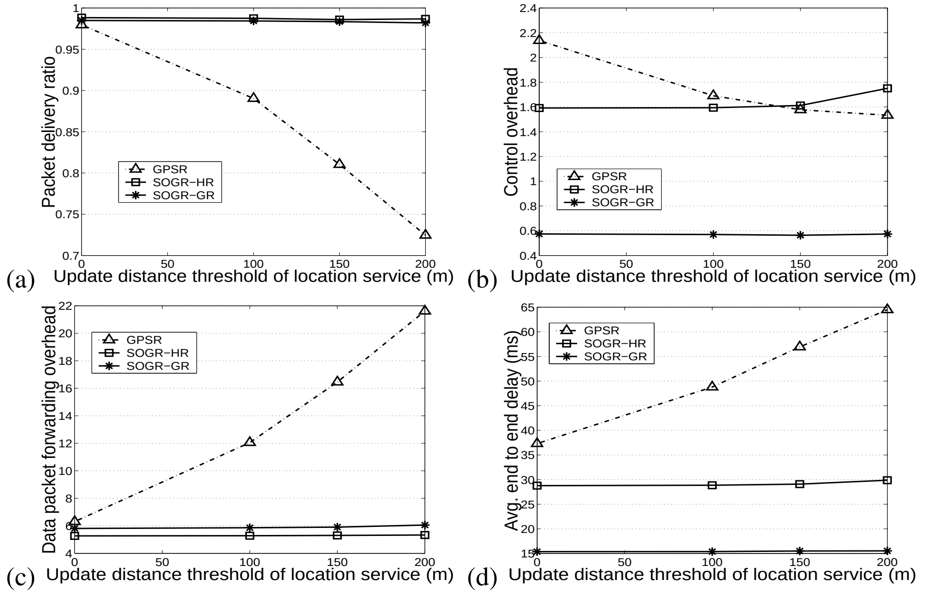

Fig. 8. Performance with different update distance thresholds of location service (300 nodes, $3000m \times 1500m$, 20m/s, 30CBR): (a) packet delivery ratio; (b) control overhead; (c) average number of data packet forwarding; (d) average end to end delay.

transmission queue overflows. SOGR-GR has a slightly lower delivery ratio than SOGR-HR at high traffic load due to its use of longer paths during perimeter forwarding, which results in more forwarding (Fig. 7 (c)) and higher transmission load thus collisions. The delivery ratios of AODV and LAR drop quickly under heavy load as a result of transmission collisions and increased retransmissions, as confirmed by Fig. 7 (c).

In Fig. 7 (b), as expected, GPSR has a very high control overhead under a relatively low traffic load because its proactive beaconing mechanism generates control overhead even when there is no routing requirement. While SOGR-HR and SOGR-GR keep very low control overhead under all the traffic loads and the overhead increases slightly when the traffic load increases. Their on-demand routing mechanisms only generate control messages as needed.

In Fig. 7 (c), the geographic routing protocols do not have a significantly higher packet forwarding overhead, as the accuracy of the local topology information increases with traffic. However, when the traffic load is low, GPSR has both a much higher packet forwarding overhead and a much higher control overhead. Its proactive fixed-interval beaconing scheme not only introduces unnecessary signaling overhead, but also could not update the position timely when needed.

SOGR-HR and SOGR-GR also keep lower end-to-end delays with various traffic loads as shown in Fig. 7 (d). SOGR-HR has a slightly longer delay than SOGR-GR in most cases as explained earlier in Section V-B4. When the traffic load increases from 70 flows to 90 flows, however, both GPSR and SOGR-GR have faster delay increases than SOGR-HR, as their longer recovery path are more vulnerable to delay caused by the longer transmission queue under high traffic load. The delays of AODV and LAR increase significantly at heavy load due to their increased number of retransmissions.

Overall, all geographic routing protocols could achieve higher delivery ratios under a heavy traffic as compared to conventional topology-based on-demand routing protocols. Compared to GPSR, both SOGR protocols could achieve low control overhead under all the traffic tested due to their use of adaption schemes, while GPSR has both high control overhead and high packet forwarding overhead in a light load scenario due to its use of proactive fixed-interval-based beaconing scheme for node position update.

4) Effect of destination position inaccuracy: Since performance issues relevant to location service are not the focus of this paper, in our simulation, we use a location database to simulate a location service with which a source could obtain a destination's position. In order to study the impact of inaccurate destination position due to location service, we set the moving distance threshold for location update in the location database as 100m, 150m and 200m according to [37] and conducted simulations on the three geographic routing protocols.

The simulation results shown in Fig. 8 verify our analysis in Section IV-C3. The performance of GPSR degrades significantly with the increase of inaccuracy in destination position. Due to the misguiding of pos_{inac}, much more packets of GPSR are dropped (Fig. 8 (a)) as more unnecessary perimeter forwarding are triggered, which results in a higher packet forwarding overhead and longer delivery latency (Fig. 8 (c)(d)). As data packets also serve as beacons, more packet transmissions reduce the number of regular control messages as seen in Fig. 8 (b). As the inaccuracy of the destination position increases, SOGR-HR and SOGR-GR still keep a good performance due to their use of more efficient destination finding schemes and path optimization schemes, with SOGR-HR having a slight increase in its control overhead and delivery latency. This is because with larger destination position inaccuracy, the path built towards pos_{inac} is less optimal relative to pos_D, which will be detected by the optimization process and trigger the forwarding node to perform route searching more frequently to adjust its path towards pos_D.

Therefore, SOGR-HR and SOGR-GR are robust to the inaccuracy of destination positions and support more reliable packet delivery, while GPSR has a quick decrease of delivery ratio, and increase of packet forwarding overhead and delay as the inaccuracy increases.

VI. CONCLUSIONS

In this work, we have developed efficient and robust geographic routing schemes that can be applied for *applications with different traffic patterns* and *adapt to various scenarios* to provide efficient routing paths and improve routing performance in a dynamic resource-constrained wireless ad hoc network. Specifically, we propose two self-adaptive on-demand geographic routing protocols SOGR-HR and SOGR-GR. The two protocols adopt different schemes to obtain and maintain local topology information. SOGR-GR purely relies on one-hop topology information for forwarding as other geographic routing schemes; SOGR-HR combines both geographic and topology-based mechanisms for more efficient path building.

The two protocols are designed with the following features: 1) Both protocols incorporate routing parameter adaptations, where each node can determine and adjust its protocol parameter values independently according to mobility, node distributions, and data traffic conditions; 2) To avoid unnecessary control overhead, both protocols distribute topology information and search for routing path only when there is traffic; 3) To alleviate the negative effects of outdated local topology information on geographic routing, more efficient position distribution mechanisms are included to update the local topology in time and adaptively based on traffic demand, and position estimation is used to remove outdated topology records; 4) Optimization schemes are applied so that a forwarding node and its neighbors can collaborate to adapt the path to both topology change and traffic demand and thus improve transmission path opportunistically; 5) Both proposed routing schemes could better deal with the inaccuracy of destination position and its resulting routing inefficiency and failure.

The simulation results demonstrate that our protocols are very robust in a dynamic mobile ad hoc network, and can efficiently adapt to different scenarios and perform better than existing geographic routing protocols and conventional on-demand protocols under various environments, including different mobility, node densities, traffic loads and destination position inaccuracies. Specifically, compared to GPSR, both SOGR protocols are much more robust to quick topology changes and the inaccuracy of destination positions, and could reduce the end-to-end delay up to 80% in high mobility scenario. Both proposed routing protocols could achieve about 98% delivery ratios, avoid incurring unnecessary control overhead, have very low forwarding overhead and transmission delay in all test scenarios. Additionally, SOGR-HR makes a better balance between control overhead and routing path efficiency in a sparse network and in a light-load scenario, and could reduce the packet forwarding overhead up to 86% and 41% respectively without incurring unnecessary control overhead.

VII. DISCUSSIONS AND FUTURE WORK

The focus of this paper is to design adaptive geographic routing protocols to achieve higher performance in a dynamic wireless ad hoc network and meet the need of various applications which may have different traffic patterns. The neighbor detection is based on measured control message strength among neighbors and hence considers the impact of channel fading. The adaptive position update messages will help maintain the topology and prevent from potential routing failure under topology changes, as a result of mobility or channel degradation. The protocols can be extended to incorporate various cost factors considered in the literature work [40], [41], [43] to provide further performance improvement. The next-hop relay node selection can base on both geographic information and conditions of transmission channels. We will investigate the performance of our protocols by incorporating more factors in the future work.

REFERENCES

[1] Y. C. Tseng , S. Y. Ni, and E. Y. Shih. Adaptive Approaches to Relieving Broadcast Storms in a Wireless Multihop Mobile Ad Hoc Network. *IEEE Transactions on Computers*, Vol. 52, No. 5, May 2003. pp. 545 - 557.

[2] Yanli Cai, Wei Lou, Minglu Li, Xiang-Yang Li. Energy Efficient Target-Oriented Scheduling in Directional Sensor Networks. *IEEE Trans. on Computers*, 58(9), Page(s):1259 - 1274, Sept. 2009.

[3] Weigang Wu, Jiannong Cao, Jin Yang, and M. Raynal. Design and Performance Evaluation of Efficient Consensus Protocols for Mobile Ad Hoc Networks. *IEEE Trans. on Computers*, 56(8), Page(s):1055 - 1070, Aug. 2007.

[4] I. Abraham, D. Dolev and D. Malkhi. LLS: a locality aware location service for mobile ad hoc networks. In *Workshop on Discrete Algothrithms and Methods for MOBILE Computing and Communications (DialM)*, 2004.

[5] S. Basagni, I. Chlamtac, V. Syrotiuk and B. A. Woodward. A distance routing effect algorithm for mobility (DREAM). In *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM)*, pages 76–84, 1998.

[6] L. Blazevic, S. Giordano and J.-Y. L. Boudec. Self organized terminode routing. *Cluster Computing Journal*, 5(2):205–218, 2002.

[7] H. Fussler, J. Widmer, M. Kasemann, M. Mauve and H. Hartenstein. Beaconless position-based routing for mobile ad-hoc networks. *Tech. Rep. TR-03-001, Dept. Math. and Comp. Science, Unive. Mannheim, Germany*, 2003.

[8] Z. Haas, M. Pearlman and P. Samar. Zone routing protocol (ZRP). *Internet draft, draft-ietf-manet-zone-zrp-02.txt*, July 2002.

[9] V. Ramasubramanian, Z. J. Haas and E. G. Sirer. Sharp: A hybrid adaptive routing protocol for mobile ad hoc networks. In *Proc. ACM MOBIHOC 2003*, June 2003.

[10] R. Beraldi and R. Baldoni. A Caching Scheme for Routing in Mobile Ad Hoc Networks and Its Application to ZRP. *IEEE Transactions on Computers*, Vol. 52, No. 8, Aug. 2003. pp. 1051 - 1062.

[11] P. Jacquet, P. Muhlethaler and A. Qayyam. Optimized link-state routing protocol. *IETF MANET Internet draft*, March 2002.

[12] C. Perkins, E. M. Royer and S. Das. Ad hoc On-Demand Distance Vector (AODV) Routing. *IETF RFC 3561*, July 2003.

[13] D. B. Johnson, Y. Hu and D. A. Maltz. The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4. *IETF RFC 4728*, February 2007.

[14] H. Rangarajan and J. J. Garcia-Luna-Aceves. Using labeled paths for loop-free on-demand routing in ad hoc networks. In *Proc. ACM MOBIHOC*, May 2004.

[15] Y. Ko and N. Vaidya. Location-aided routing (LAR) in mobile ad hoc networks. In *Wireless Networks*, Judy 2000.

[16] X. Xiang and X. Wang. A Scalable Geographic Service Provision Framework for Mobile Ad Hoc Networks. In *IEEE International Conference on Pervasive Computing and Communications*, White Plains, New York, March 2007.

[17] M. Li and Y. Liu. Underground Coal Mine Monitoring with Wireless Sensor Networks. In *ACM Transactions on Sensor Networks*, Volume 5 Issue 2, March 2009.

[18] P. Bose, P. Morin, I. Stojmenovic and J. Urrutia. Routing with guaranteed delivery in ad hoc wireless networks. In *Wireless Networks*, Springer Netherlands, Volume 7, Number 6, pages: 1572-8196 Nov. 2001.

[19] B. Karp and H. T. Kung. Greedy perimeter stateless routing for wireless networks. In *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM)*, pages 243–254, August 2000.

[20] B. Karp. Greedy perimeter stateless routing (GPSR). *http://www.icir.org/bkarp/gpsr/gpsr.html*.

[21] F. Kuhn, R. Wattenhofer, and A. Zollinger. An Algorithmic Approach to Geographic Routing in Ad Hoc and Sensor Networks. *IEEE/ACM Trans. on Networking*, 16(1), Page(s):51 - 62, Feb. 2008.

[22] Y. Li, Y. Yang, and X. Lu, Routing Metric Designs for Greedy, Face and Combined-Greedy-Face Routing. *Proc. IEEE INFOCOM 09*, Page(s):64 - 72, Apr. 2009.

[23] M. Heissenbttel, T. Braun , T. Bernoulli, and M. Wlchli BLR: Beacon-less routing algorithm for mobile ad-hoc networks. *Elsevier's Comp. Commun. Journal*, 27(11):1076–1086, July 2003.

[24] J. A. Sanchez, R. Marin-Perez, and P. M. Ruiz, BOSS: Beacon-less on demand strategy for geographic routing inwireless sensor networks. *The 4th Internatonal Conference on Mobile Ad-hoc and Sensor Systems*, pp. 110, 2007.

[25] S. Ruhrup, H. Kalosha, A. Nayak, and I. Stojmenovic, Message-Efficient Beaconless Georouting With Guaranteed Delivery in Wireless Sensor, Ad Hoc, and Actuator Networks. *IEEE/ACM Transactions on Networking*, 18(1), pp. 95 - 108, Feb 2010.

[26] H. Zhang and H. Shen, Energy-Efficient Beaconless Geographic Routing in Wireless Sensor Networks. *IEEE Transactions on Parallel and Distributed Systems*, 21(6), pp. 881 - 896, June 2010.

[27] M. Jain, M. K. Mishra, and M.M. Gore, Energy aware beaconless geographical routing in three dimensional Wireless Sensor Networks. *First International Conference on Advanced Computing*, pp. 122 - 128, Dec. 2009.

[28] J. A. Sanchez, P. M. Ruiz, and R. Marin-Perez, Beacon-less geographic routing made practical: challenges, design guidelines, and protocols. *IEEE Communications Magazine*, 47(8), pp. 85 - 91, Aug. 2009.

[29] F. Zhang, H. Li, A. Jiang, J. Chen and P. Luo, Face Tracing Based Geographic Routing in Nonplanar Wireless Networks. *Proc. IEEE INFOCOM 07*, Page(s):2243 - 2251, May 2007.

[30] Y. Kim, R. Govindan, B. Karp and S. Shenker. Lazy cross-link removal for geographic routing. In Proceedings of the 4th International Conference on Embedded Networked Sensor Systems (Sensys), 2006.

[31] X. Xiang, X. Wang, and Y. Yang, Supporting Efficient and Scalable Multicasting over Mobile Ad Hoc Networks. In *IEEE Transactions on Mobile Computing*, vol 10, No. 4, pp. 544-559, April 2011.

[32] X. Xiang, X. Wang, and Y. Yang, Stateless Multicasting in Mobile Ad Hoc Networks. In *IEEE Transactions on Computer*, vol. 59 no. 8, pp. 1076-1090, Aug. 2010.

[33] X. Xiang, X. Wang and Z. Zhou, Robust and Scalable Geographic Multicast Protocol for Mobile Ad Hoc Networks. In *Proceeding of IEEE INFOCOM*, minisymposium, Anchorage, Alaska, May 2007.

[34] X. Xiang and X. Wang. An Efficient Geographic Multicast Protocol for Mobile Ad Hoc Networks. In *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Niagara-Falls, Buffalo, New York, June 2006.

[35] Y. Kim, J.-J. Lee and A. Helmy. Modeling and analyzing the impact of location inconsistencies on geographic routing in wireless networks. *Mobile Computing and Communication Review*, 8(1), 2004.

[36] F. Kuhn, R. Wattenhofer, Y. Zhang and A. Zollinger. Geometric ad-hoc routing: Of theory and practice. In *Int. Symposium on the Principles of Distributed Computing (PODC)*, 2003.

[37] J. Li, J. Jannotti, D. S. J. D. Couto, D. R. Karger and R. Morris. A scalable location service for geographic ad hoc routing. In *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM)*, pages 120–130, 2000.

[38] X. Zeng, R. Bagrodia and M. Gerla. GloMoSim: A Library for Parallel Simulation of Large-scale Wireless Networks. In *Workshop on Parallel and Distributed Simulation*, pages 154–161, 1998.

[39] C. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *Proc. ACM SIGCOMM*, 1994.

[40] K. Seada, M. Zuniga, A. Helmy, and B. Krishnamachari. Energy efficient forwarding strategies for geographic routing in wireless sensor networks. In *ACM Sensys 2004*, Baltimore, MD, Nov. 2004.

[41] S. Lee, B. Bhattacharjee, and S. Banerjee. Efficient geographic routing in multihop wireless networks. In *ACM MobiHoc*, 2005.

[42] T. Camp, J. Boleng, B. Williams, L. Wilcox and W. Navidi. Performace comparison of two location based routing protocols for ad hoc networks. In *IEEE INFOCOM*, June 2002.

[43] Y. Kim, R. Govindan, B. Karp, S. Shenker. Geographic routing made practical. In *Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation*, 2005.

[44] K. Seada, A. Helmy and R. Govindan. On The Effect of Localization Errors on Geographic Face Routing on Sensor Networks. In *Proceedings of the Third IEEE International Workshop on Information Processing in Sensor Networks (IPSN)*, 2004.

[45] D. Son, A. Helmy and B. Krishnamachari. The effect of mobility-induced location errors on geographic routing in ad hoc networks: analysis and improvement using mobility prediction. In *Proc. WCNC 2004*.

[46] D. Tschopp, S. Diggavi, M. Grossglauser and J. Widmer. Robust Geo-Routing on Embeddings of Dynamic Wireless Networks. In *IEEE INFOCOM*, May 2007.

[47] M. Zorzi and R. R. Rao. Geographic random forwarding (GeRaF) for ad hoc and sensor networks: Energy and latency performance. *IEEE Trans. Mobile Computing*, 2(4), Oct.-Dec. 2003.

[48] X. Xiang, Z. Zhou and X. Wang. Self-Adaptive On Demand Geographic Routing Protocols for Mobile Ad Hoc Networks. *IEEE INFOCOM07*, minisymposium. Anchorage, Alaska, May 2007.

[49] J. Yoon, M. Liu, and B. Noble. Random Waypoint Considered Harmful. *Proc. IEEE INFOCOM 03*, 2(4), Apr. 2003.

[50] X.-Y. Li, G. Calinescu, P. Wan, and Y. Wang. Localized Delaunay Triangulation with Applications in Wireless Ad Hoc Networks. *IEEE Transactions on Parallel and Distributed Systems*, 14(10), pages 1035-1047, Oct. 2003.

[51] Y. Wang, X.-Y. Li, W. Song, M. Huang, and T. A. Dahlberg. Energy-Efficient Localized Routing in Random Multihop Wireless Networks *IEEE Transactions on Parallel and Distributed Systems (TPDS)*, 2011.

[52] Z. Yang, Y. Liu, and X.-Y. Li. Beyond Trilateration: On the Localizability of Wireless Ad-hoc Networks. *IEEE/ACM Transactions on Networking*, 18(6) pages. 1806 - 1814, Dec. 2010.

[53] W. Xi, Y. He, Y. Liu, J. Zhao, L. Mo, Z. Yang, J. Wang, and X.-Y. Li. Locating Sensors in the Wild: Pursuit of Ranging Quality. *ACM Sensys*, 2010.

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