SSR: Segment-by-Segment Routing in Large-Scale Mobile Ad Hoc Networks

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***Abstract*—Location-based routing in Mobile Ad hoc NETworks (MANETs) does not need to use pre-computed routes for forwarding packets thus scales very well. However, location-based routing suffers from two major problems: hole-induced local optimum and mobility-induced location errors. To solve these problems, in this paper, we propose a Segment-by-Segment Routing (SSR), which is a combination of location-based routing and topology-based routing. It maintains a *k*-hop vicinity routing table for each Cluster Head (CH), and uses location-based routing between neighboring *k*-hop vicinities while applies topology-based routing in the *k*-hop vicinity. The *k*-hop vicinity routing table provides useful reachability information used by an avoidance-based strategy to deal with holes, and helps to achieve the degree of tolerance of location inaccuracy with *k*-hop long radio transmissions. Comparative analysis shows that the proposed protocol outperforms the well-known GPSR routing protocol in terms of reliability, tolerance of location inaccuracy, and communication complexity, with a little larger cost in control messages.**

***Index Terms*—MANETs, routing, anchor, segment, hole avoidance**

I. INTRODUCTION

It is very challenging to design an efficient routing protocol for Mobile Ad Hoc NETworks (MANETs) since the Mobile Nodes (MNs) in a MANET have limited resources and move arbitrarily. Existing routing protocols in MANETs can be classified into two major groups: topology-based routing and location-based routing [12]. The topology-based routing protocols use the network topology information to compute and maintain routes. They can be further classified into proactive, reactive, and a hybrid of the two schemes. A survey of topology-based routing can be found in [16]. Topology-based routing does not scale well due to the large overhead incurred in computing the routes which heavily relies on the state of the links in the network, particularly if the link state changes dynamically and the MN may be broken down due to the limited battery.

Location-based routing, also called position-based routing or geographic routing, has become more and more popular in recent years. It usually assumes that a link between two nodes exists as long as one node resides in the transmission range of another node. A node makes the packet forwarding decision primarily based on the location of the destination and the locations of the node's one-hop neighbors. No pre-computed routes are used for forwarding packets, thus the scalability of location-based routing is very high.

Location-based routing is done in a greedy way in which a node forwards a packet to a neighbor closer to the location of the destination. But it cannot guarantee the packet delivery when there is a hole along the forwarding direction, resulting in the local optimum problem. The

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local optimum is a situation where an intermediate node has no neighbor with progress toward the destination while a valid route to the destination still exists. A hole is a void region in MANETs where no MNs reside, which can be caused by the distribution, mobility, or the breakdown of MNs. The readers are directed to reference [5] for a good understanding of the impact of holes on location-based routing.

Furthermore, location-based routing protocols heavily rely on a location service to provide the accurate location information for a destination. However, it is very difficult for the location service to maintain accurate location information all the time [2]. The effect of mobility-induced location errors on location-based routing in both MANETs and wireless sensor networks has been analyzed in [19], where the Lost Link problem and the Loop problem in packet delivery are discussed.

Therefore, we observed that there are two major problems in location-based routing: hole-induced local optimum and mobility-induced location errors. On the other hand, there are two problems in topology-based routing: large overhead and weak scalability. The observations motivated us to design new protocols to achieve a good trade-off against these problems by combining the advantages of both location-based routing and topology-based routing. In this paper, we propose a novel, cluster-based hybrid protocol, called *Segment-by-Segment Routing (SSR)*. It maintains a *k*-hop vicinity routing table for each Cluster Head (CH), and uses location-based routing between neighboring *k*-hop vicinities while applies topology-based routing in the *k*-hop vicinity. The protocol works as follows: the CH selects a sub-path leading to an MN in its *k*-hop vicinity by using topology-based routing; and the ending MN of the sub-path is determined by also using location-based routing. This sub-path is called *segment*. That is, a next segment is selected in each routing decision rather than selecting a next hop node in other routing protocols. Since the routing is performed in a segment-by-segment manner rather than hop-by-hop; the *Segment-by-Segment Routing* (SSR) is thus named.

The main idea behind SSR is that each CH maintains a routing table of those CHs which reside in its *k*-hop vicinity. Here, *k* is a system parameter. If *k* equals to one, it is a location-based routing, and if *k* approximates to the network diameter, it is a proactive topology-based routing. By maintaining the *k*-hop vicinity routing tables, both problems of hole-induced local optimum and mobility-induced location errors can be easily solved without too much routing overhead.

There are two differences between the proposed SSR protocol and other hybrid reactive-proactive routing protocols [10,11,13,17]. Firstly, the vicinities maintained by the CHs are changeable in SSR because of the system parameter *k*, while zones are fixed in [11,13,17] and have different sizes in [10]. It seems that the fixed zones are not adaptive to dynamic mobile environment, and the different sizes scheme is rather complicated because each node continuously makes decision on the zone radius and changes them thereafter. Secondly, location-based routing is performed in the reactive parts of SSR, while topology-based routing is also used in the latter. SSR is a well-blended combination of location-based routing and topology-based routing, this combined scheme has seldom occurred in the literature.

The SSR protocol has four desirable properties: (1) the short delay, (2) the high reliability, (3) the high degree of tolerance of location inaccuracy, and (4) the good scalability. The remainder of the paper is organized as follows. Section II gives an overview of existing routing protocols in MANETs. Section III describes our network model. Section IV presents the design of the proposed SSR protocol. Section V describes the comparative analysis with the well-known GPSR routing protocol. Finally, Section VI concludes this paper.

II. RELATED WORK

A typical example of proactive routing is the Destination-Sequenced Distance-Vector (DSDV) protocol [15], where each node maintains a routing table maintaining routes for all available destinations. The node periodically broadcasts its

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routing table, and broadcasts updates immediately when its routing table changes. In order to avoid possible routing loops, DSDV adds sequence numbers to routing updates. DSDV is relatively simple, but not adaptive to the highly changing network environment.

A typical example of reactive routing is Dynamic Source Routing (DSR) [6], where the route is established only when requested by a source node, which floods a route request throughout the network. When the request reaches the destination, a route reply is returned. Nodes aggressively cache routes, so that intermediate nodes can reply to the request on behalf of the destination node. However, the flooding scheme causes large routing discovery overhead.

Plenty of location-based routing protocols have been proposed in the literature by using greedy forwarding. For example, Greedy Perimeter Stateless Routing (GPSR) [8] makes greedy forwarding decisions using only the location information about a node's immediate neighbors. When a packet reaches a void region, i.e., a hole, it recovers by routing around the perimeter of the void region with the right-hand rule. This perimeter mode forwards the packet using a planar graph traversal. There are different greedy forwarding strategies for a node to select the next hop node among its immediate neighbors. GPSR chooses a neighbor which is the closest to the destination node. This strategy is known as the Most Forward within Radius (MFR) [18]. Another forwarding strategy called compass routing [7] selects the neighbor closest to the straight line between the sender and the destination.

A detailed discussion on location-based routing that use planar graphs traversal to handle holes is shown in [4]. In addition, the BOUNDHOLE algorithm proposed in [3] tries to solve the holes problem in greedy forwarding by building routes around holes. A local rule called TENT is developed for each node in the network to test whether a packet can get stuck at that node. The algorithm finds the boundaries of the holes consisting of all the strong stuck nodes. Thus the routes around the holes can also be discovered in a preprocessing phase and stored locally along the boundaries of holes. However, the TENT rule is very complicated due to the use of Delaunay Triangulation. In the proposed SSR protocol, the hole is defined as the region consisting of adjacent void grids, which can be easily detected by periodical message exchanging among the CHs.

In GRID [9], the locations of the source and the destination are used to confine the search range, and the route requests are broadcast only within the search range. GRID divides the geographic network area into a number of logical square grids. Routing is then performed in a grid-by-grid manner via grid leaders. Actually, it is also a hop-by-hop manner, because the neighboring grid leaders can communicate directly due to the small grids in the protocol. It lengthens the lifetime of routes, since the location of a grid does not change over time. However, the routing may fail when a grid becomes void during the process of packet delivery.

Terminode routing [1,2] uses a combination of location-based routing, i.e., Terminode Remote Routing, TRR, which is applied when the destination is far away; and link state routing, i.e., Terminode Local Routing, TLR, which is applied when the destination node is nearby. TRR uses a greedy forwarding approach to send packets to remote destination along an anchored path, to help route around holes. TLR is used only when a packet has arrived at a node with up to two hops away from the destination. It seems that this scheme is very wasteful, because it incurs so much overhead to maintain local routing tables but only use them when a packet is close to the destination. In our SSR protocol, the *k*-hop vicinity routing information is used during the whole routing process. Moreover, Terminode routing obtains the anchored path by using one of two protocols: FAPD and GMPD, both of which cost very high. In contrast, our SSR protocol obtains the anchor information to maintain route during the process of routing without additional cost.

A hybrid routing protocol is proposed in [14]. Each node updates its current location at nodes

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within its proximity of radius *R* as well as at its location servers chosen over the entire network in a distributed way. A route is discovered based on an Internet-like architecture, i.e. a series of local-region routing is applied until the complete multi-path is found by aggregating the thus-found partial routes and eventually selecting the best one among them. However, the multi-path scheme causes large overhead.

All the above location-based routing protocols assume that each MN is equipped with a GPS. However, this requirement can seriously increase the cost and power consumption of MNs. Our SSR protocol assumes that only those MNs acting as CHs to be equipped with GPS device, thus overcoming the problem. This point is just like a protocol called LABAR [24], which only requires G-nodes to have a GPS device for determining their locations, while other nodes are assumed to know the position of a nearby G-node.

III. NETWORK MODEL

In the design of SSR, we assume that the large scale MANET is divided into a number of smaller square regions of equal size, each of which is called a *grid*. This assumption is also used in some existing work [9]. Clustering technique is commonly used in MANETs in order to limit the amount of routing information maintained at individual MNs. Our motivations to partition the MANET into grids is for easy formation of clusters. Each grid approximately covers the area of a cluster in the network.

We assume a heterogeneous network, where the MNs have different computation and communication capabilities, with *super MNs* having stronger capabilities than the *normal MNs*. The super MNs are equipped with a GPS device and two-level radios: the *long radio* with long transmission range and the *short radio* with short transmission range; while the normal MNs only have short radios, without a GPS device. We argue that this assumption is reasonable in practice, e.g., in a battlefield, a mobile device equipped on a tank can have stronger capability than the one equipped for a foot soldier. The multi-level radios are also applied in other protocols in the literature, such as the landmark routing [23]. It is shown that the scheme significantly improves the performance of non-hierarchical schemes, and it is robust to failures.

The proposed network model has two tiers, as shown in Fig.1. For clarity, only the *CH Tier* (*CHT*) is drawn with grids. The *MN Tier* (*MNT*) consists of all the MNs in the network. To elect a CH among the super MNs in a grid, we use two criteria similar to those used in the stable CAMP algorithm proposed in our previous work [21]. The first criterion requires that the MN is closest to the grid center, and the second requires that the MN stays alive for the longest time among the MNs in the grid. The elected CH then broadcasts a request to recruit cluster members. When the message is received, the MNs that reside in or around the grid sends an ACK to the corresponding CH. Thus, the clusters are formed. We assume a uniform distribution of super MNs in the whole network area, so that it seldom occurs that some MNs exist in a grid but no super MNs exist in the grid. When this case does occur, those normal MNs located in the grid will accept the request and become cluster members of other neighboring grid CHs.

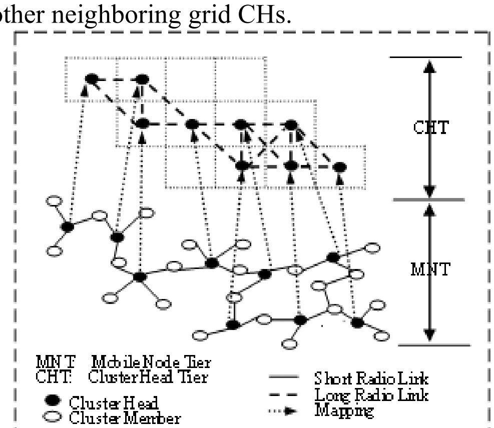

Fig.1 The network model

The CH Tier consists of CHs in the network as the backbone nodes. The CHs are responsible for communicating between clusters, and for managing their member nodes. A CH can communicate with its eight neighboring CHs directly by using the long radio (see Fig.2). The short radio is used for the communications between the CH and its member nodes, or among

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the member nodes within the cluster.

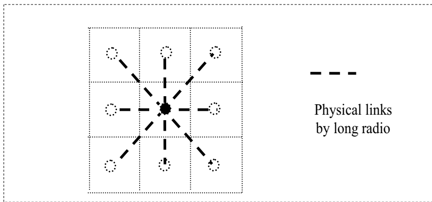

Fig.2 The direct communications by long radios

All the MNs have knowledge about some system information, including total number of MNs N, network width W, network length L, side length of a grid d, the coordinate of network origin point (x_o, y_o). With these parameters, we have the total number of grids as $\frac{WL}{d^2}$.

Two identifiers are defined. MNID is the global identifier of an MN, which is given at the system start-up time, and GID is the identifier of a grid, which is labeled by Definition 1 given below. Definition 2 defines the logical location of an MN. Each normal MN acquires the logical location from its CH. The SSR protocol uses logical locations to make routing decisions. An MN's logical location changes less frequently than its geographic location, so the use of logical location makes the route more stable.

Definition 1: Given the coordinate of a grid center (x, y), the GID can be labeled by two integers corresponding to X-axis and Y-axis respectively:

$$\left\lfloor \frac{(x-x_o)}{d} \right\rfloor, \left\lfloor \frac{(y-y_o)}{d} \right\rfloor \tag{3.1}$$

Definition 2: The *logical location* of each MN is identified as the center of the grid where its cluster head resides.

We assume that the source node knows the location of the destination node via some location service, such as home region-based location service [20], or multiple home regions based location service [22]. We call a grid where no MNs reside *void grid*. Several adjacent void grids form a *hole*.

IV. THE SSR PROTOCOL

There are two different approaches for location-based routing protocols to handle the hole-induced local optimum problem: the reactive approach, such as various kinds of recovery strategies discussed in Section II, and the proactive approach, which proactively maintain the holes information to avoid the local optimum problem, such as the SSR protocol proposed here. It uses an avoidance-based strategy to avoid meeting the hole by using information about the hole, which is collected in advance during the process of maintaining the k-hop vicinity routing tables. Furthermore, by maintaining the routing tables, the protocol can reduce the mobility-induced location errors.

A. Routing tables

Each CH maintains two kinds of routing tables: the intra-cluster routing table and the k-hop vicinity routing table. A CH transfers the two routing tables to a candidate CH before it moves out of the grid where it currently resides. k is a system parameter, which is an important factor of achieving the tradeoff between the routing delay and routing overhead. For simplicity, in this section, we use $k = 3$ for describing our examples.

We first define the terms used in the SSR protocol.

- *The k-hop vicinity* of a CH is the region consisting of those grids whose cluster heads can be reached by the CH in at most k hops with long radio transmissions.
- *The kth-hop vicinages* of a CH are those CHs that can be reached by the CH in k hops. If there are no holes, the maximum number of the kth-hop vicinages of each CH is $8 \times k$. For the example shown in Fig.3, M has 19 3th-hop vicinages which are the CHs resided in the numbered grids.
- *The k-hop reachability information* of a CH consists of the GIDs of the CH's kth-hop vicinages.
- An MN is defined as *being progressive towards the destination* if it has some kth-hop vicinage which is closer to the destination than itself when the destination is out of its k-hop vicinity.

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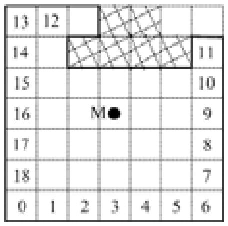

Fig.3 The *k*th-hop vicinages of a CH

Next, we describe how the routing tables are maintained.

Intra-cluster routing table maintenance: Within a cluster, each cluster member periodically broadcasts a message to the CH with its MNID and current time stamp. Other cluster members that have forwarded the message encapsulate its own MNID into the message. Thus, when the CH received all those messages, it can calculate the routes to all the members, and then broadcasts the intra-cluster routing table and logical location to all the cluster members. If the CH does not receive a cluster member's information for a certain period of time, it assumes that the MN has roamed away or broken down, and then deletes the MN's information from the routing table.

k-hop vicinity routing table maintenance: It has two parts. Firstly, it is to maintain the routing information. Each CH periodically broadcasts a message with its MNID, geographic and logical location, and current time stamp to its *k*-hop vicinity by using the long radios. This is achieved by setting the message's Time-To-Live (TTL) to be *k*. then, all the CHs get the routing information of those CHs in its *k*-hop vicinity.

Secondly, it is to maintain the vicinage's *k*-hop reachability information. Based on the current *k*-hop vicinity routing information, each CH knows the information about its *k*th-hop vicinages. Thus, after exchanging the routing information in the first round *k*-hop broadcasting, each CH broadcasts a message containing the collected information about both routing and *k*-hop reachability. Therefore, the *k*-hop routing table contains both the information about the routes to vicinages and the information about the vicinages' *k*-hop reachability. That is, a CH has the detailed information about the routes in its *k*-hop vicinity, and the summarized information about reachability in its 2*k*-hop vicinity.

B. Route discovery

In SSR, when delivering a packet to the destination, a forwarding CH selects the next CH among its *k*th-hop vicinages such that the selected CH is progressive to the destination and is closest to the destination. It then forwards the packets on the sub-path to the next CH as specified in the *k*-hop vicinity routing table. The center of the grid where the next CH resides is called an *anchor*. The next CH is called an *anchor CH*. The sub-path is called a *segment*. The whole route from the source to the destination consists of a sequence of segments.

By maintaining the *k*-hop vicinity routing table, the SSR protocol can naturally bypass such small holes in CH's *k*-hop vicinity. Thus it only needs to focus on how to avoid relatively large holes. This is achieved by using the destination reachability information. The routing protocol is described as follows.

When source node *S* needs to send packets to a destination node *D*, *S* first obtains the logical location of *D* by querying the location service, and then includes it into the header of the packets. If *S* is a cluster member, it first sends the packets to its CH.

The source CH checks whether an entry of the destination CH exists within its *k*-hop vicinity routing table. If exists, it uses local routing. The source CH finds a route from itself to the destination CH in its *k*-hop vicinity routing table and then forwards the packets using the route. When the destination CH receives the packets, it forwards the packets to *D* based on its intra-cluster routing table.

If there is no entry for the destination CH in its *k*-hop vicinity routing table, it uses remote routing. The source CH determines whether it is progressive towards the destination. If yes, it computes the distance to *D* from those *k*th-hop vicinages that are also progressive to the destination, and selects the closest one to set it as an anchor CH (called *M*). Then, the source CH forwards the packets along the segment to *M* as specified in its *k*-hop vicinity routing table. The step is continued by intermediate CHs until an anchor CH finds that the destination CH is

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within its k-hop vicinity. Then, local routing is used to forward the packet to the destination D.

```
The SSR protocol.

For the source node S:
If (S needs to send a packet to D) Then
        Obtains the logical location of D;
If (S is a cluster member) Then
        Sends the packet to its CH;

For the CHs:
If (D is within the k-hop vicinity of source CH) Then
        Performs local routing.
Else {
    If (source CH is not progressive towards D) Then
         Do
              Computes the distance to D among
            the kth-hop vicinages that are adjacent
            to hole and along the same direction;
              Selects a next anchor CH with the
            shortest distance;
         Until (an intermediate anchor CH is
              progressive towards D);
    Do
         Computes the distance to D among the
       kth-hop vicinages that are progressive
       towards D;
         Selects a next anchor CH with the
       shortest distance;
    Until (an intermediate anchor CH finds that D is
         within its k-hop vicinity);
    Performs local routing.
}
The packet reaches D.
```

Fig.4 The Proposed SSR protocol

If the source CH is not progressive towards the destination, it means that the source CH is adjacent to a relatively large hole, and routing encounters a hole unavoidably. The only way to handle this rarely occurred situation is to route around the hole's boundary. Then, the source CH computes the distances to D from kth-hop vicinages adjacent to the hole, and selects the next anchor CH with the shortest distance. A CH knows whether its vicinage is adjacent to the hole during maintaining the k-hop vicinity routing table. Routing is continued around the hole along the same direction in order to eliminate loops, until an intermediate anchor CH finds that it is progressive towards the destination. Then, the normal routing process resumes.

The determination of routing along the same direction is determined by using Formula 4.1 given below. Given the coordinate of the current anchor (X, Y), the coordinate of its previous anchor is (X_f, Y_f), and the coordinate of the next anchor is (X_n, Y_n). If Formula 4.1 is satisfied, they follow the same direction.

$$(X_n - X)(X - X_f) \geq 0 \,\&\&\, (Y_n - Y)(Y - Y_f) \geq 0 \qquad (4.1)$$

The pseudo code of SSR protocol is shown in Fig.4.

After the route is constructed, the destination CH replies a success message to the source node containing the information about the anchors. By forwarding the message, each anchor CH records the information about its three neighboring anchors, namely, *PREVIOUS anchor*, *NEXT anchor*, and *NEXT to NEXT anchor*, for maintaining the route. Fig.5 shows an example where a hole exists on the way of the path which can be avoided in SSR. Fig.6 shows an example where a hole exists at the beginning of the path which can not be avoided.

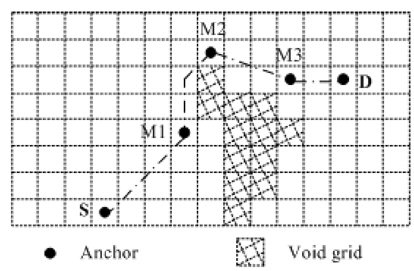

Fig.5 Routing with holes on the way

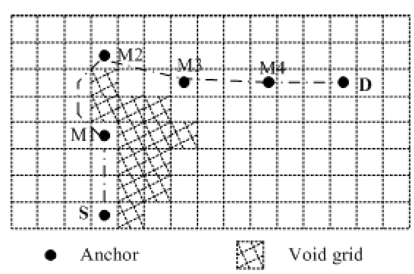

Fig.6 Routing with holes at the beginning

C. Route maintenance

The route constructed by the proposed SSR protocol is very stable. Because a route is determined by a series of anchors, the segment between two anchors is maintained by the k-hop

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vicinity routing table. These anchors are valid almost all the time, except in three rare cases below. Corresponding route maintenances of three cases are discussed as follows.

Moving of the source node: When a source node S roams to a new cluster, S sends the information about its neighboring anchors to its new CH. The new CH checks whether the former grid of S is still within its k-hop vicinity. If so, the CH sets the former grid center as its NEXT anchor; otherwise, the CH finds a new anchor in its k-hop vicinity that is closest to the former grid, and sets the new anchor as its NEXT anchor and the former grid center as its NEXT-to-NEXT anchor. If the new CH finds that the next anchor of the former cluster is within its k-hop vicinity, it sets this anchor as its NEXT anchor. That is, the route has been truncated.

Void anchor grid: If an anchor CH has not received the CH information of its NEXT anchor CH for a certain time, it assumes that the anchor grid is void. Then it finds a new NEXT-anchor in its k-hop vicinity which is nearest to its NEXT-to-NEXT anchor.

Moving of the destination node: When a destination node D roams to a new cluster, the new CH sends a message containing D's new location to the CH (named M) of D's previous cluster. Then, M checks whether D is still within its k-hop vicinity. If so, M sets the new grid center as its NEXT anchor; otherwise, M finds an anchor in its k-hop vicinity which is closest to D, and sets this anchor as its NEXT anchor and the grid center of D as its NEXT-to-NEXT anchor. Then M sends a message containing the NEXT anchor information to its PREVIOUS anchor CH. If M's PREVIOUS anchor CH finds that D is within its k-hop vicinity, it sets this anchor as its NEXT anchor directly.

V. Comparative Analysis

This section analyzes the performance of the proposed SSR protocol, in comparison with GPSR [8]. GPSR is currently the most advanced recovery strategy to handle holes-induced local optimum problem in location-based routing protocols, while SSR tries to avoid the occurrence of a local optimum so as to eliminate extra delay caused by the recovery strategy. To facilitate the analysis, we first give three definitions below.

Definition 3: The *node density* γ is defined as the average number of nodes residing in a unit area of one square meters. Then, we have:

$$\gamma = \frac{N}{WL} \tag{5.1}$$

Definition 4: The *communication complexity* is defined as the average number of hops traveled by a packet from the source to the destination.

Definition 5: The *control complexity* is defined as the total number of control messages required by the routing protocol.

Property 1: The SSR protocol has higher reliability than that of GPSR.

Proof: In SSR, the route consists of several segments. Each segment between two adjacent anchors is maintained periodically by the k-hop vicinity routing tables. Even in the case that an old segment is broken down, a new segment can be easily found to replace it. Hence, the route is very reliable. Due to the void grid, the anchor may be invalid. SSR has easily solved the problem in the route maintenance procedure. Therefore, each route established by SSR has long lifetime. However, in GPSR, the constructed route fails as long as a link is broken down. So the SSR protocol has higher reliability than that of GPSR. □

Property 2: The SSR protocol achieves a higher degree of tolerance of location inaccuracy than that in GPSR.

Proof: A big drawback of GPSR is that location information of the destination needs to be known with an accuracy of a one-hop transmission range; otherwise, the packets cannot be delivered successfully. While the usage of k-hop vicinity routing tables in SSR not only simplifies the routing decision and avoids holes, but also provides higher degree of tolerance of location inaccuracy with a k-hop long radio transmission range. □

Property 3: The communication complexity of SSR is $O\left(\frac{\sqrt{N}}{d}\right)$, which is better than that of $O\left(\sqrt{N}\right)$ for GPSR.

Proof: As the network grows larger, the number of hops between each pair of source and

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destination may also increase. If γ is constant, the average path length is expected to increase with the spatial diameter of the network, or equivalently the square root of the area of the network. Since the total number of MNs N is in proportion to the network area WL, the communication complexity in GPSR is $O(\sqrt{N})$. But in SSR, routing is mainly at the CHs, and the maximal number of the CHs equals to the number of grids $\frac{WL}{d^2}$ Therefore, the communication complexity is $O\left(\frac{\sqrt{WL}}{d}\right)$, which can be simplified to $O\left(\frac{\sqrt{N}}{d}\right)$. □

Property 4: Let C be the number of CHs in the network. The control complexity of the proposed protocol is $O(N+k^2C)$. It is a little higher than $O(N)$ of GPSR.

Proof: The control complexity of SSR is consumed by maintaining two kinds of routing tables.

The maintenance of intra-cluster routing tables: Each cluster member periodically broadcasts a message to its CH and the CH sends a message containing the logical location to the cluster members. If these messages only involve one hop transmissions, then N messages are needed. In addition, suppose the probability of the re-election of CHs in a period of time is α, which is very small in this short time. The number of messages from a new CH to notify its cluster members is $C \times \alpha$. Hence, the total number of messages is:

$$N + C \times \alpha \approx N \tag{5.2}$$

The maintenance of k-hop vicinity routing tables: Each CH broadcasts a message in its k-hop vicinity. At most 8(1+2+...+(k-1))=4k(k-1) vicinages need to forward the message except the void grids. So at most 4k(k-1)+1 messages are needed for each CH at this phase. Thus the total number of messages is:

$$(4k(k-1)+1)C = (2k-1)^2 C \tag{5.3}$$

Therefore, by adding formulae 5.2 and 5.3 together, the total number of messages is:

$$N + (2k-1)^2 C \tag{5.4}$$

Thus, the control complexity can be simplified as:

$$O(N + k^2 C) \tag{5.5}$$

In GPSR, in order to make each node's location known by all its neighbors, each node needs to periodically broadcast a beacon to all its neighbors with its own ID and the location. Thus, N messages are needed. So the control complexity is $O(N)$.

In SSR, k and C are relatively small compared with N, thus the control complexity of SSR is a little higher that that of GPSR. □

VI. Conclusions

We proposed a hierarchical network structure where the network area is divided into grids, each of which is indeed a cluster in the network. Network nodes are classified as super MNs and normal MNs with different capabilities. In each grid, a CH is elected among the super MNs. The proposed SSR protocol is a hybrid of location-based routing and topology-based routing. The main idea is to maintain k-hop vicinity routing table for each CH and, when routing a packet, it uses proactive topology-based routing to select a segment in a CH's k-hop vicinity and uses location-based routing to select an anchor between neighboring k-hop vicinities. Since k is an important system parameter in the proposed protocol, as one of our future work, we will further investigate the design of this parameter regarding different situations of networks and MNs.

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