Hole Modeling and Detour Scheme for Geographic Routing in Wireless Sensor Networks

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Abstract: **Geographic routing has been considered as an attractive approach in wireless sensor networks, since it routes data packets by using location information rather than global topology information. In geographic routing schemes, packets are usually sent along the boundary of a hole by face routing to detour the hole. As result, all data flows which need to detour the hole are concentrated on the boundary of the hole. This hole detour scheme results in much more energy consumption for nodes at the hole boundary, and the energy exhaustion of hole boundary nodes enlarges the holes. This is referred to as a** ***hole diffusion problem.*** **The perimeter mode may also lead to data collisions on the hole boundary nodes if multiple data flows need to bypass a hole simultaneously. In this paper, we propose a hole modeling and detour scheme for geographic routing in wire-less sensor networks. Our hole modeling and detour scheme can efficiently prevent hole diffusion, avoid the local minimum problem faced by geographic routing protocols, and reduce data collisions on the hole boundary nodes. Simulation results show that the proposed scheme is superior to the other protocols in terms of control overhead, average delivery delay and energy consumption.**

Index Terms: **Geographic forwarding, hole, wireless sensor networks.**

I. INTRODUCTION

Wireless sensor networks (WSNs) have been proposed for observation of events and environments in sensing areas over long periods of time. A large number of sensor devices communicate over short range wireless interfaces to deliver observations over multiple hops to sinks. Sensor nodes are small, simple, and powered by batteries. Since the sensor network consists of a large number of sensor nodes, recharging them is often infeasible. The failure of sensor nodes caused by energy exhaustion or physical destruction may lead to the reduction of sensor areas. In wireless sensor networks, holes can be formed due to void areas (obstacles) in sensor nodes deployment, destruction of sensor nodes, or uneven energy consumption. WSNs are considered for many application scenarios including, temperature measurement, battlefield surveillance, incursion detection, habitat monitoring, traffic monitoring, security applications and so on. The routing paradigms of WSNs can be classified into many-to-one and one-to-one categories. In particular, in application scenario such as average temperature measurement, all nodes in a sensing area need to report the sensed data to a subscribe sink, we term this as many-to-one routing paradigm. In application scenarios such as incursion detection and habitat monitoring, only the sensor nodes which have detected an exciter need to report the sensed data at a time. For instance, a tank in a battlefield may be detected by a few nodes in vicinity. To reduce unnecessary transmission, a node aggregates the sensed data from these nodes and reports the fused data to a subscribe sink (data aggregation and fusion are out of scope of this paper), we term this as one-to-one routing paradigm. This paper focuses on investigating the hole problem in one-to-one routing paradigm.

Geographic routing [1] has been considered as an attractive one-to-one routing protocol since it exploits pure location information instead of global topology information to route data packets, this location based scheme makes it a more efficient, simple and scalable routing protocol in wireless sensor networks. In geographic routing scheme, a source node encapsulates the destination location in each data packet. After received a data packet, a node sends it to the one-hop neighbor which is geographically closest to the destination. This process repeats until the data packet is eventually received by the destination node. However, a hole diffusion problem may arise due to energy exhaustion of the hole boundary nodes. The nodes located on the boundary of holes may suffer from excessive energy consumption since the geographic routing tends to deliver data packets alone the boundary of holes by face routing [1]–[3]. This face routing scheme makes the nodes located on boundary of holes a higher probability to be used for data delivery than other general nodes. All data flows which need to bypass a hole are concentrated on the boundary of the hole. The hole may be enlarged due to excessive energy consumption of the hole boundary nodes. We call this as the hole diffusion problem. Fig. 1 shows a WSN with four ongoing communication sessions. In Fig. 1(a), there is no hole in the network, thus the energy of nodes are evenly consumed. When a small hole exists in the networks as shown in Fig. 1(b), then two communication sessions are concentrated on the boundary of the hole. The hole may be enlarged due to energy exhaustion of hole boundary nodes as shown in Fig. 1(c). In this case, the four communication sessions are concentrated on the boundary of the hole. The thickness of the paths on the boundary of the hole indicates the heaviness of the transmission burden of the hole boundary nodes. By comparing Fig. 1(b) and Fig. 1(c), we can see, the nodes on the boundary of a bigger hole suffer from heavier data transmission and energy consumption than those on the boundary of a small hole. The diffusion speed of a hole is proportional to the size of the hole. Reducing the transmission burden of hole boundary node and preventing hole diffusion are crucial for WSNs. In addition, data collisions may occur in the hole boundary nodes if multiple data flows are bypassing a hole simultaneously as shown in Fig. 1(c). The bigger the hole is, the more serious the

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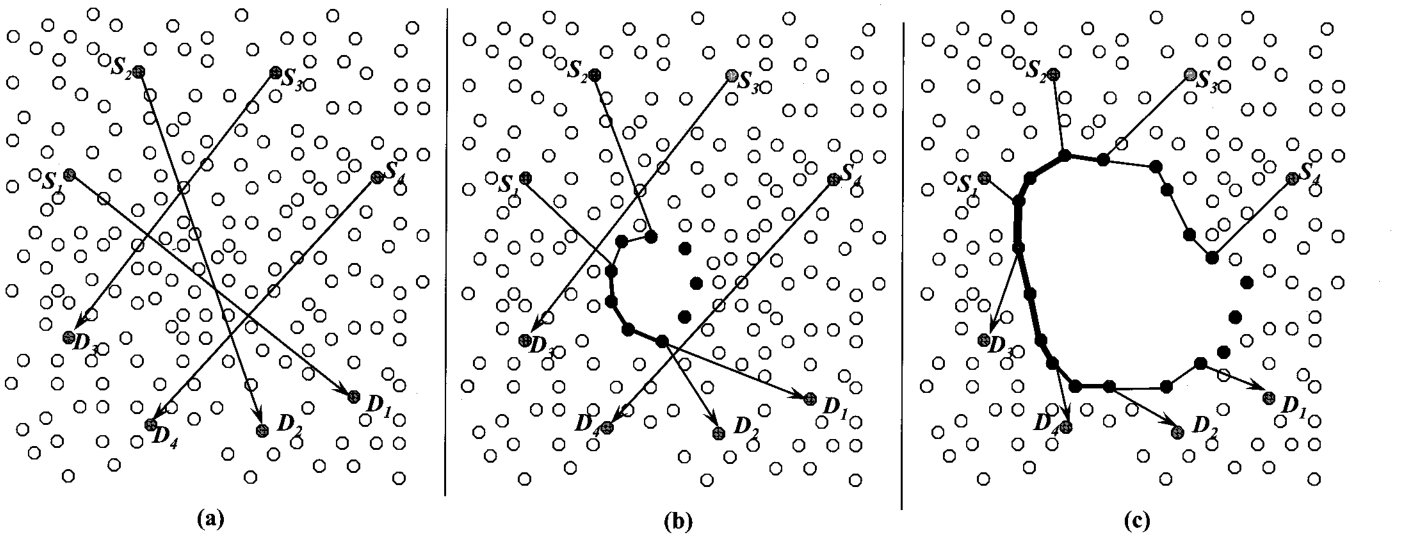


Fig. 1. Multiple communication sessions need to bypass a hole simultaneously.

problem becomes.

In addition, geographic routing suffers from local minimum problem [2]. Specifically, that is a node none of whose neighbors is located closer to destination than itself, e.g., node *I* in Fig. 2. A lot of research has been done to solve this problem. All solutions for the local minimum problem can be classified into two categories: face routing [1]–[3] and back pressure rule [4], [5]. The face routing tends to route data packets along the boundary of holes. The back pressure rule tends to return the data packets to upstream node to find another route to the destination.

Fig. 2 shows a scenario that source node *S* sends a data packet to destination node *D* crossing a hole area by geographic routing. Dotted line ① indicates the data forwarding direction. When the data packet is received by node *I* on the hole boundary, since no 1-hop neighbor of node *I* is closer to destination node *D* than itself (node *I* is called stuck node [2]), in [1], the data packet will be forwarded along the boundary of the hole by perimeter mode as indicated by dotted curve ②. It is obviously that the dotted curve ② is the shortest path from *I* to *D*, but combining the path $\overline{SI}$, the path along $\overline{SI}$ and dotted curve ② may not be the shortest path from *S* to *D*. In addition, if multiple communication sessions need to bypass the hole simultaneously, as shown in Fig. 1(c), the probability is very high that the nodes on the boundary of the hole are shared by several communication sessions by face routing. Thus data collisions may occur in these nodes. Also, the energy of these nodes will be fast exhausted, thus enlarging the hole. This is undesired in sensor networks.

A backpressure rerouting mechanism has been proposed in SPEED [4] for local minimum problem, where a backpressure beacon message is exploited to inform ones in the upstream nodes to find another route to destination in a recursive manner if the current node is a stuck node for the communication session. This mechanism on one hand generates additional overhead on routing rediscovery, on the other hand it also cannot avoid forwarding data packet along the boundary of a hole. So data collisions and excessive energy consumptions of hole boundary nodes also cannot be efficiently avoided.

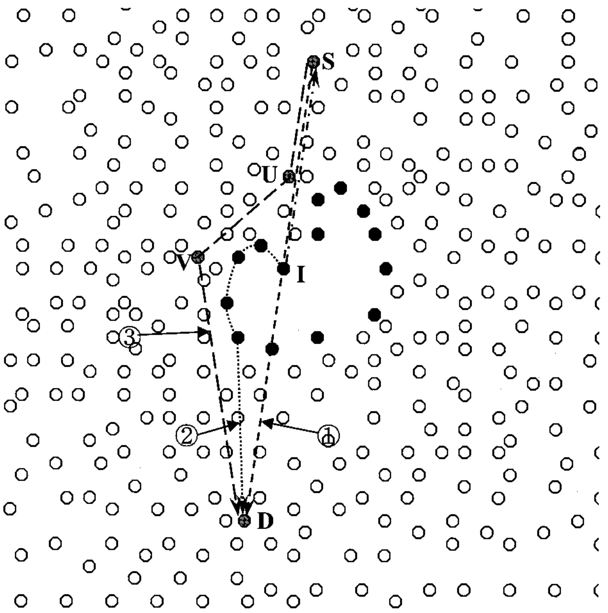


Fig. 2. Scenario of holes problem in sensor network.

In [5], an intermediate node forwarding (INF) mechanism is proposed for the hole problem in sensor networks. As shown in Fig. 2, when stuck node *I* receives a data packet, it sends a negative acknowledgement packet (NAK) to inform source *S* that it cannot forward the data packet to the destination. Source *S* then picks a random intermediate point so that through which to forward packets, the packets can be sent far enough out of the way of holes. This mechanism looks like more efficient than those discussed earlier. However, since the intermediate point is selected by source in random manner, the source can not guarantee that the intermediate point is correctly selected for just one time. To guarantee the success rate, the intermediate point must be selected far away from the hole, thus increasing the length of data delivery path.

All mechanisms discussed above suffer from the fact that route rediscovery occurs after data packet reaching the stuck node. Dotted zigzag line ③ in Fig. 2 shows a more practical path from S to D. We assume that node U is aware of the hole. To bypass the hole, the data packets are redirected to node V by node U before data packets enter the stuck area. This path has some advantages: First, this is a shorter path than previous works [1]–[3] if node U and V are properly selected. Second, since the data packets are redirected before entering the stuck area, so no route rediscovery process is needed, thus reducing the route rediscovery overhead incurred in [4] and [5]. Third, this path is not along the boundary of the hole, the battery consumption of boundary nodes and data collisions can be significantly reduced. The issue is that how to locate the proper U and V so that the path is most efficient.

We have proposed similar schemes to solve the hole problem in [6]–[9]. In [6], an ellipse which can cover a hole is constructed, when a node located on the boundary of the ellipse receives a data packet, the node deviates the data packet to an anchor location outside the ellipse, and then the data packet is forwarded towards the original destination. In this scheme, the anchor location is calculated by the node on the boundary of the ellipse. The anchor location is located on the tangent line through the node to the ellipse and dominated a balance parameter α, a large α leads to the anchor location being far from the hole, thus leads to a longer data delivery path, while a small α leads to the anchor location being close to the ellipse, thus, the packets sent from the anchor location to the destination may reencounter the ellipse again. How to define a proper α is a pendent issue. In [7]–[9], a virtual circle which can cover a hole is constructed. When a node one the hole boundary receives a data packet, it informs the source node about the information of the virtual circle, then the source node calculates an anchor location which is the crossing point of two tangent lines through the source and the destination to the virtual circle. The source node sends data packets to the anchor location, and then the packets are forwarded to the original destination by geographic routing. This scheme can solve the preceding hole problems, data packets are sent along a shorter path to the destination. However, a ping-pong problem may arise if there are several holes located between the source and destination, i.e., the packets sent from the source to the anchor location might encounter another hole. The second problem is that it cannot support mobility of the target. If a target, such as a tank, moves to a new location. Another sensor node becomes a source, besides obtaining the destination location, the new source also needs to obtain the information of the hole again. Mobile target increases the burden of source node. Detailed analysis is given in Section IV.

In this paper, we propose a hole geometric modeling and detour scheme to solve the hole problems faced by geographic routing in wireless sensor networks. Firstly, a circle which can exactly cover a hole is geometrically initiated. When a node on the circle (not hole) receives a data packet, the node judges whether the destination is located inside the circle according to the destination location encapsulated in the data packet. If so, the packet is sent to the destination directly or by perimeter mode of GPSR [1], otherwise, the node redirects the data packet to an anchor location. When the node which is geometrically closest to the anchor location receives the data packet, it redirects the data packet to original destination by geographic routing. The anchor location is calculated according to the center location of the circle, the radius of the circle and the destination location.

The main contributions of this paper are summarized as follows:

- Prevent data packets from transmitting along boundary of holes, thus reducing excessive energy consumptions of hole boundary nodes and data collisions in these nodes.
- Solve the local minimum problem by preventing data packet from entering stuck area, thus reducing data packets rerouting overhead.
- The anchor location is communication session specific, different communication sessions have different anchor locations, in other words, no routing path is shared by different communication sessions, thus averaging energy consumption and reducing data collisions.
- Support mobility of source or destination, the hole detour path is auto-changed with mobile source or destination.
- The hole modeling processes are independent of communication sessions. In other words, hole modeling processes repeats only if a hole is enlarged and exceeds the circle.
- The ping-pong routing problem of previous works is avoided.

II. HOLE GEOMETRIC MODELING

We consider topologies where wireless sensor nodes are roughly deployed in a plane, source and destination nodes may have mobility but all other sensor nodes are fixed. Each node is aware of its own location information by GPS or other location services [10]–[13]. Each node can obtain the location of their neighbors by beacon messages [1]. Finally, we assume a packet source can determine the location of packet destinations, and encapsulates the destination location in each packet. Thus, a location registration and lookup service that maps node ID to location [14] is required.

Fig. 3 shows the hole geometric modeling processes. A node can detect whether it is located on the boundary of a hole by the mechanism proposed in [2]. The node which firstly detects a hole sends out a *hole boundary detection* (HBD) packet around the hole by the well-known right hand rule [16] (which states that it is possible to visit every wall in a maze by keeping your right hand on the wall while walking forward). The mission of HBD packet is to trace the location information of all nodes on the boundary of the hole. We suppose that nodes B_0, B_1,$\cdots$,B_n with the coordinates of $(x_0, y_0), (x_1, y_1), \cdots, (x_n, y_n)$ are located on the boundary of the hole. As shown in Fig. 3(a), node B_0 first detects the hole, it initiates a HBD packet marked with its ID and forwards the HBD packet to the neighbor hole boundary node B_1 by the right hand rule. Node B_1 inserts its location information into the received HBD packet and also forwards it to node B_2 by the right hand rule. This process repeats until the HBD packet has traveled around the hole and eventually been received by the initiator node B_0. Node B_0 can obtain the location information of all nodes on the boundary of the hole from the received HBD packet. Then node B_0 can determine two vir-

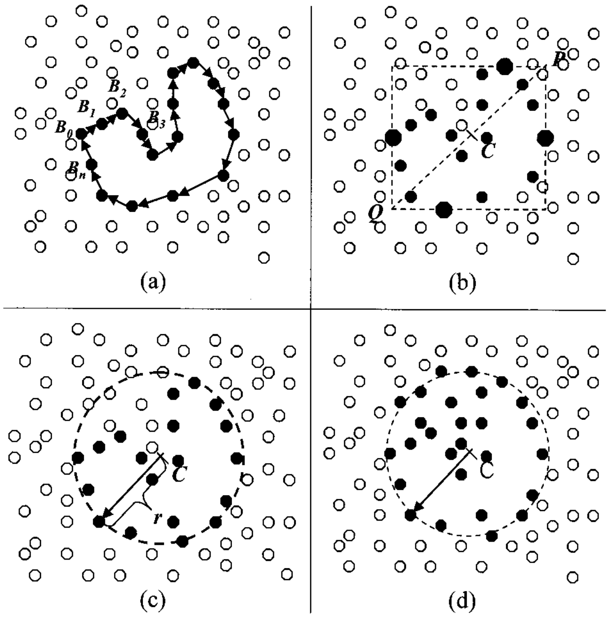


Fig. 3. The holes geometric modeling processes.

tual point P and Q (as shown in Fig. 3(b)) in the network plane with the coordinates:

$$P\{x_p = \max\{x_0, x_1, \cdots, x_n\}, y_p = \max\{y_0, y_1, \cdots, y_n\}\}$$
$$Q\{x_q = \min\{x_0, x_1, \cdots, x_n\}, y_q = \min\{y_0, y_1, \cdots, y_n\}\}. \tag{1}$$

Suppose C is the center point of line $\overline{PQ}$. The coordinate of C can be obtained as:

$$C\{x_c = (x_p + x_q)/2, y_c = (y_p + y_q)/2\}. \tag{2}$$

Then node B_0 calculates a circle:

$$(x - x_c)^2 + (y - y_c)^2 = r^2 \tag{3}$$

with C as the center and r as the radius as shown in Fig. 3(c), where r is the longest distance between C and all hole boundary nodes $B_0, B_1, \cdots, B_n$, i.e., $r = \max\{\overline{B_0C}, \overline{B_1C}, \cdots, \overline{B_nC}\}$. Here we can see that this circle can cover the hole exactly. Then node B_0 initiates a *circle distribution* (CD) packet, which includes the circle center location and the radius r, and geocasts the CD packet to all nodes inside the circle. Then all nodes inside the circle are aware of the center location and the radius of the circle as shown in Fig. 3(d).

III. DATA DELIVERY UNDER HOLE GEOMETRIC MODELING

Section II has described how to model a hole with a circle which can exactly cover the hole. The mission of the nodes on the circle is to redirect the received data packet to an anchor location if the destination is outside of the circle. This section presents the data delivery process under the proposed hole geometric modeling.

To facilitate discussion, in Fig. 4, only the hole geometric modeling circles and the data delivery paths are presented, all sensor nodes are ignored. Source node S initiates data packets and forwards them to destination node D by geographic routing. Each data packet header includes an *anchor location* field and a *flag* field which is used to indicate whether the packet is *destined to destination mode* or *redirect to anchor mode*. All data packets are initially set to *destined to destination mode* and their *anchor location* field is set to *void* by source. Source also includes the location of the destination in each data packet. The destination location field is only set by source, and left unchanged as the packet is forwarded through the network.

A node can know whether it is located on the circle by checking whether it has received a CD packet as described in Section II. In Fig. 4(a), source node S sends a data packet to destination D along line $\overline{SD}$ by geographic routing. When a node located on the boundary of the circle receives the data packet, it checks whether the destination is located inside the circle. If so, the node sends the packet to the destination by GPSR with no redirection, i.e., if the data packet encounters the hole, the data transmission switches to perimeter mode [1]. Otherwise it sets the data packet to *redirect to anchor mode*, and sets the *anchor location* field to the value calculated according to its own location, the destination location and the circle center location, and the radius of the circle, and then forwards the data packet to anchor location by geographic routing. When the node closest to the anchor location receives the data packet, it resets the packet to *destined to destination mode* and resets the anchor location field to void, then forwards the data packet to original destination by geographic routing.

The issue is how to calculate the anchor location. We propose that the anchor location is the crossing point of the tangent line through tangent point U to the circle and the tangent line through the destination to the circle. As shown in Fig. 4(a), V is the anchor location of U for the packet destined to destination D. Line $\overline{UV}$ is the tangent line to the circle through tangent point U. Assuming that the coordinate of node U is (x_u,y_u) and the coordinate of the center of the circle is (x_c,y_c), the slope of line $\overline{UC}$ is $(y_u - y_c)/(x_u - x_c)$, then the slope of tangent line $\overline{UV}$ can be obtained as $-(x_u - x_c)/(y_u - y_c)$, the function of line $\overline{UV}$ can be obtained as:

$$\frac{y - y_u}{x - x_u} = -\frac{x_u - x_c}{y_u - y_c}. \tag{4}$$

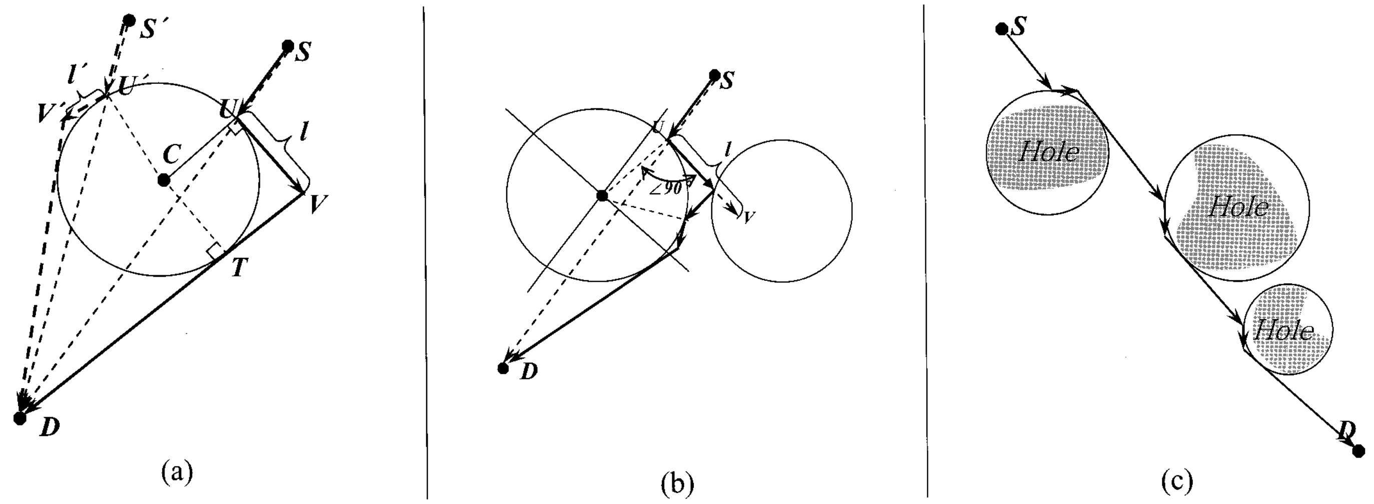
Assuming the coordinate of tangent point T is (x_t, y_t) and the coordinate of the destination is (x_d, y_d), according to right-angled triangle theory and circle theory, we make the following two equations to obtain the tangent line function:

$$[(x_t - x_c)^2 + (y_t - y_c)^2] + [(x_t - x_d)^2 + (y_t - y_d)^2]$$
$$= (x_d - x_c)^2 + (y_d - y_c)^2, \tag{5}$$
$$(x_t - x_c)^2 + (y_t - y_c)^2 = r^2 \tag{6}$$

where (x_d, y_d) is the coordinate of the destination D, (x_c, y_c) is the coordinate of the center of the circle, r is the radius of the circle. By (5) and (6), node U can obtain (x_t, y_t) which is the coordinate of tangent point T. Then the function of line $\overline{DT}$ can be obtained as:

$$\frac{y - y_d}{y_t - y_d} = \frac{x - x_d}{x_t - x_d}. \tag{7}$$

In tangent line function (4) and (7), (x_u, y_u) is the coordinate of node U, the circle center coordinate (x_c, y_c) can be obtained



(a) (b) (c)

Fig. 4. Data delivery scenarios of holes geometric modeling.

from the CD message as described in Section II, and the destination coordinate (x_d, y_d) can be obtained from the received data packet. The coordinate (x_t, y_t) of the tangent point *T* can be calculated by (5) and (6). So the coordinate of anchor location *V* can be calculated by tangent line function (4) and (7) as (x_v, y_v).

We summarize the data delivery process as follows: Source node *S* sends data packets to the destination by geographic routing. Each data packet contains the destination location. When a node *U* which is located on the boundary of a hole modeling circle receives the data packets, it first checks whether the destination is located inside the circle. If so, the node sends the packets to the destination by GPSR with no redirection, i.e., if the data packets encounters the hole, the data transmission switches to perimeter mode [1]. Otherwise the node calculates an anchor location according to its own location, the destination, and the information of the circle, e.g., center location and radius, and then redirects the data packets to the anchor location. When the node which is geographically closest to the anchor location receives the data packets, it redirects the data packets to the original destination by geographic routing. By this way, the data packets can detour the hole.

The above discussion is based on the situation that the node *U* in Fig. 4(a) is exactly located on the perimeter of the modeling circle. In a practical network environment, it is possible that a node inside the circle receives a packet from an outside node which is not aware of the information of the circle. In other words, node *U* is located inside but closed to the perimeter of the circle. In this case, since node *U* is aware of the information of the circle, and the destination location *D* can be obtained from the received data packet. Thus node *U* can calculate the crossing point location of line $\overline{UD}$ and the perimeter of the circle. This crossing point location is used for calculation of anchor location as described above.

IV. CONTRIBUTIONS

The hole modeling circle construction scheme proposed in this paper is similar to that in previous works [7]–[9]. However, this paper develops it as follows: First, after construction the hole modeling circle, the circle information is flooded to all nodes within the circle. While in previous works, the circle information is only sent to all nodes on the boundary of the hole. In other words, in this paper, all nodes within the modeling circle are aware of the information of the circle, while in the previous works, only the hole boundary nodes are aware of that. For data delivery, in previous works as shown in Fig. 5, since only the hole boundary node are aware of the information of the circle, data packets are first sent to node *V* on the boundary of the hole. Then node *V* informs the source node about the circle information, and the source node calculates the anchor location and forwards data packets to the anchor location. Several problems arise in the cases that: First, if the source is far away from the hole, transmissions between the source and the hole generate more overhead. Second, if there is another hole located on the path of $\overline{SV}$ or $\overline{VD}$ as shown in Fig. 5, data packets from *S* to *V* encounter the hole and will be redirected to another anchor location, thus may lead to ping-pong routing problem. Third, if the target has mobility, e.g., a tank moves from *S* to other location, another node becomes a new source, and the new source has no information of the hole. In this case, besides obtaining the location of the destination, the source node has to obtain the information of the hole and calculate the anchor location again. This will generate significant overhead, thus the previous work does not support mobile source well.

In current work, the location of *U* and *V* are dynamically changed if the source or destination is moving. Source node is not required to know any information of holes in the network. We suppose that source node moves to S' as shown in Fig. 4(a), and the anchor location is automatically changed to V'. Only the sensor nodes inside the circle are aware of the hole, all other nodes as well as the source node are unaware of the hole. The proposed scheme does not increase burden to the source node thus supports mobile source well.

Fig. 4(c) shows that the proposed scheme is applicable when several holes existing between source and destination. If the data packet from the first anchor location to destination encounters another hole, the data packet is redirected to another anchor lo-

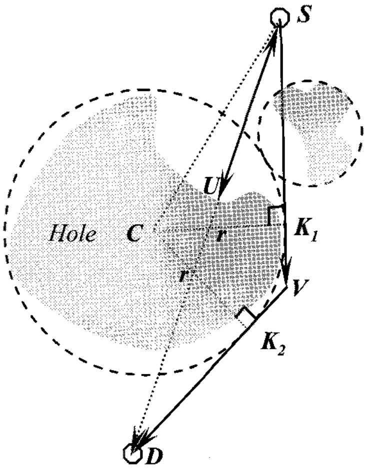


Fig. 5. Ping-pong routing problem of previous works.

cation again. This process repeats until the data packet reaches original destination. The ping-pong routing problem does not arise in the current routing scheme in case of multiple holes existing in the network.

In Fig. 4(b), the anchor location V is located in another circle. In this case, when the node on the circle receives the data packet from U, it resets the packet to *destined to destination mode* and set anchor location to *void*, and forwards the packet to original destination by geographic routing mechanism. When the data packet reencounters the circle, it was redirected to another anchor location by the process described earlier.

In some sense, we can regard a hole modeling circle as a shield. The data packets are redirected to anchor location by the node on the circle. This scheme can not only prevent data packets from entering the stuck area of a hole, thus reducing route rediscovery overhead; but also avoid the data packets being delivered along the boundary of the hole, thus reducing the energy consumption of the hole boundary nodes.

We have analyzed that the perimeter mode in [1] leads the data packets to be transmitted along the boundary of the hole, and this strategy significantly consumes the energy of the nodes on the boundary of a hole and leads to data collisions in these nodes. In our algorithm, we model a hole with a circle. A data packet is redirected to an anchor location outside of the circle when it reaches the circle. This strategy has two advantages: First, the circle prevents data packets from entering the stuck area of the hole. Second, data delivery paths are not superposed if the data packets are sent from different sources or to different destinations, thus balances energy consumption and reduces data collisions.

V. PERFORMANCE EVALUATIONS

In this section, we evaluate the performance of hole modeling and detour scheme by simulations. We first describe the performance evaluation metrics and simulation environments, then evaluate the performance with given environments and parameters. Finally, we show the comparisons between our scheme, GPSR [1] and SPEED [4] protocols.

A. Simulation Environments and Metrics

We implemented the simulation in Network Simulator Qualnet 3.8 and selected IEEE 802.15.4 as the MAC protocol. The transmission range of sensor nodes is 10 m. The size of the sensor network is set to 200×200 m^2 where 10,000 nodes are randomly distributed. The average distance between nodes is 2 m. We manually make a hole with a shape like a cashew nut in the center of the network. Each simulation lasts for 1000 sec.

We use four metrics to evaluate the performance of hole geometric modeling. The packet delivery ratio is defined as the ratio of the number of successfully delivered data packets to the number of data packets generated by the source. This metric reflects the data delivery efficiency. The average delivery delay is defined as the average time delay between the moment a source transmits a packet and the moment a destination receives the packet. The control overhead is the number of control packets generated during simulation time. The average energy consumption is defined as the ratio of the total energy consumption to the number of nodes which have participated in data forwarding. This metric reflects how the routing load is balanced.

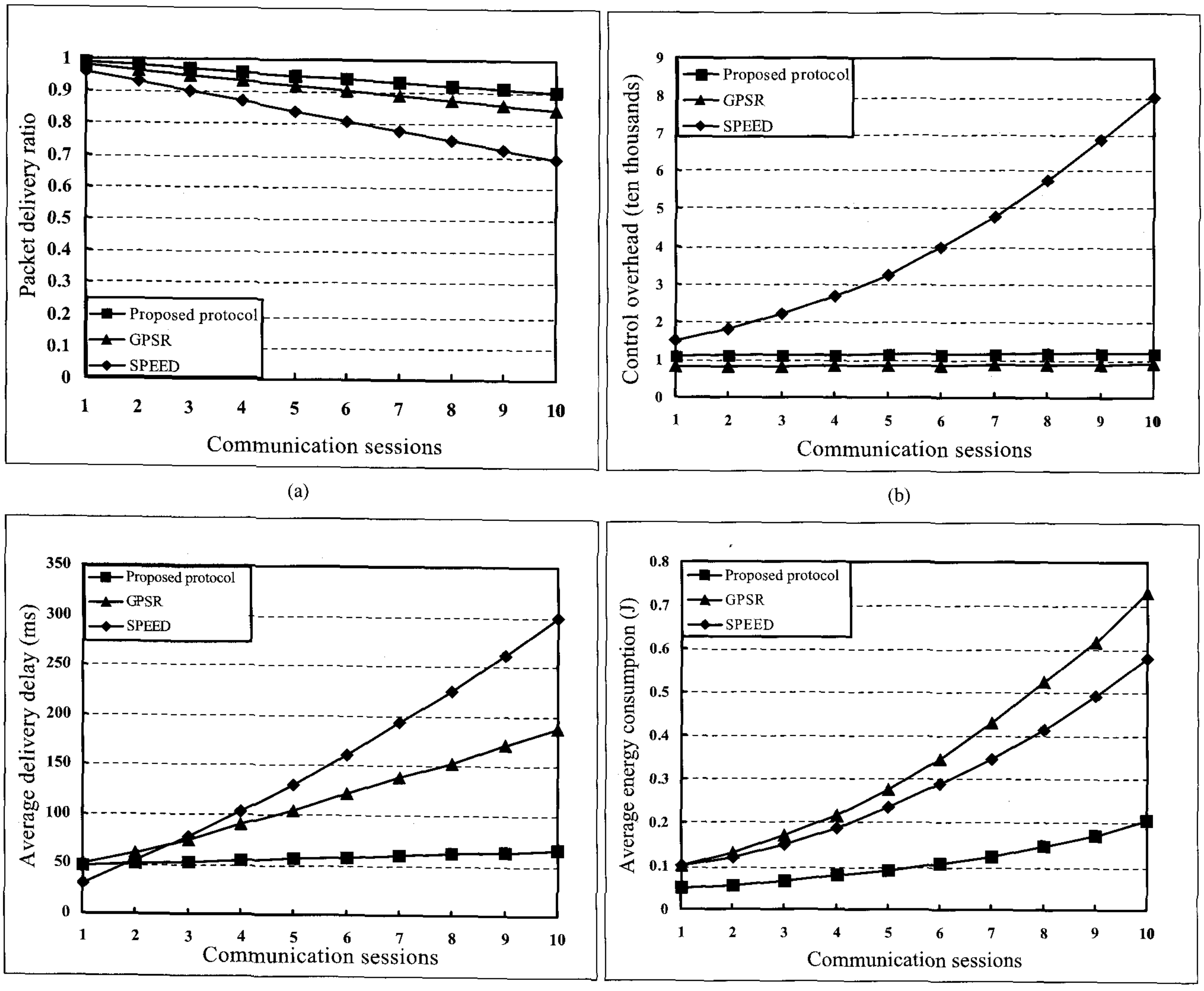
B. Simulation Results

B.1 Effects of the Number of Communication Sessions

We manually set a hole with the size of about 40 m in the center of the networks and vary the number of communication from 1 to 10. All communication sessions intend to traverse the hole.

Fig. 6(a) shows the packet delivery ratio with different number of communication sessions. When there is only one communication session (one source and one destination), three protocols almost achieve the same packet delivery ratio. This is because almost no collision occurs during simulation time. Only a few data packets are lost due to signal attenuation and interference. With the number of communication session increasing, multiple communication sessions need to bypass the hole simultaneously. GPSR and SPEED forward data packets along the hole boundary by the perimeter mode. In other words, all communication sessions are concentrated on the hole boundary nodes. The data collisions occurred in the hole boundary nodes are increased with the number of communication sessions, thus lead to increasing packet loss ratio. In our hole modeling scheme, for each communication session, the data packets are redirected to an anchor location once they encounter the modeling circle of the hole (not the boundary of the hole), the anchor location is different with different sources or destinations, so the routing path of different communications cross but do not overlap with each other. Thus, the probability of data collisions does not significantly increase with the number of communication sessions. So we can see the packet delivery ratio of the hole geometric modeling does not significantly decrease with the number of communication sessions.

Fig. 6(b) shows control overhead of three protocols. For GPSR, the data packet delivery is purely based on location information. All nodes need to update location information to neighbor nodes by beacon messages. This location update scheme has no relation with the number of communication sessions. So there is nearly no change in control overhead with the number of



(a) (b)

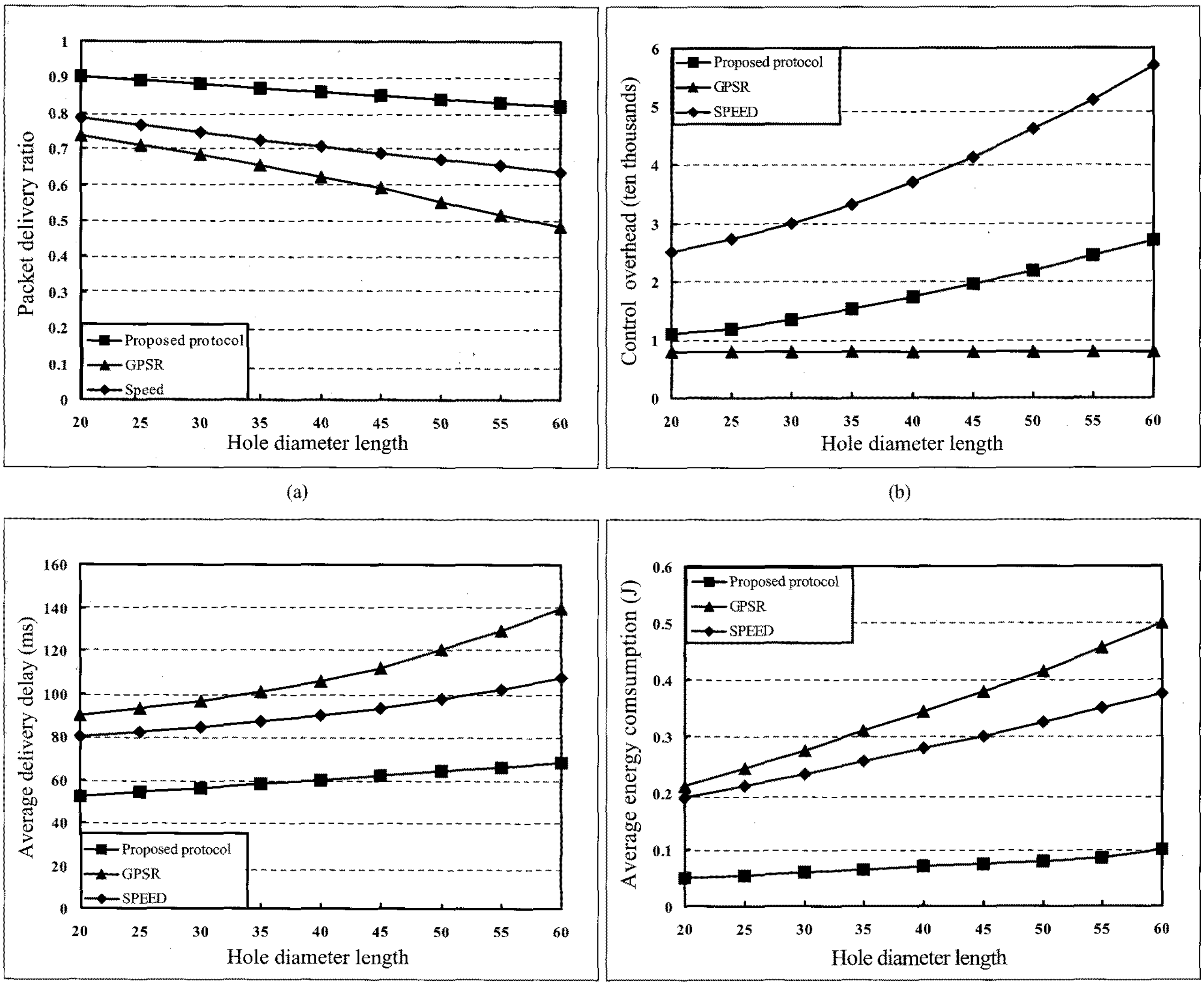
(c) (d)

Fig. 6. Simulation results with different number of communication sessions: (a) Packet delivery ratio, (b) control overhead, (c) average delivery ratio, and (d) energy consumption.

communication sessions. Comparing with GPSR, our algorithm includes an additional circle construction process. But this circle construction process also has no relation with the number of communication sessions since all nodes are assumed to be fixed in this paper. In fact, the overhead incurred by circle construction is closely related to the number and size of holes in sensor networks. SPEED focuses on finding a high speed data deliver path to forward data packet, so additional overhead was generated to find high speed path. This high speed path discovery process closely relates to the number of communication sessions. In addition, because of the data collisions in the nodes aground holes, the SPEED protocol needs to find other high speed paths to deliver data packets, and this route rediscovery process is proportionately increased with the number of communication sessions. So the control overhead of SPEED significantly increases than the other two protocols with the number of communication sessions.

Fig. 6(c) shows the average delivery delay with the number of communication sessions. When there is only one communication session, the average delivery delay of SPEED is lower than other two protocols since SPEED focuses on finding high speed paths for data delivery. However, when the number of communication sessions exceeds 2, the average delivery delay of SPEED significantly increases than other protocols. This is because the collisions occurring in the hole boundary nodes. Data collisions lead to low throughput of sensor nodes, thus SPEED pays more time for finding a higher speed routing path. In our hole geometric modeling scheme, the data packets are redirected to anchor location once they encounter a circle. The anchor location is determined by source location, destination, and the location and radius of hole modeling circle. The data collision probability in hole geometric modeling scheme is lower than other two protocols since the routing path of different communication sessions cross but do not overlap with each other. So the average delivery delay of our protocol does not increase significantly with the number of communication sessions.

Fig. 6(d) shows the average energy consumption with different number of communication sessions. GPSR and SPEED utilize perimeter mode to route data packet when the data packet encounter a hole, in other words, as long as a hole is located



(a) (b)

(c) (d)

Fig. 7. Simulation results with different hole size: (a) Packet delivery ratio, (b) control overhead, (c) average delivery ratio, and (d) energy consumption.

between a source and a destination, the data packets are sent along the boundary of the hole. Thus the energy consumption of the nodes on the boundary of holes is quite higher in SPEED and GPSR (each hole boundary node might be share multiple communications). In our proposed scheme, the data packets are redirected to anchor location when the data packets encounter the modeling circle. This way, we prevent data packet from being forwarded along the boundary of holes. We have explained that different communication sessions have different anchor locations, the routing path of different communication sessions cross but do not overlap with each other, thus comparing with GPSR and SPEED, and there are more nodes in the vicinity of the hole participating in data forwarding. Therefore, the average energy consumption of the proposed scheme is lower than that of GPSR and SPEED.

B.2 Effects of the Hole Size

In this section we vary the diameter (the longest distance between to any two hole boundary nodes) of the hole from 20 to 60 m to evaluate the effect of the hole size. Five communication sessions bypass the hole simultaneously.

Fig. 7(a) shows the packet delivery ratio with different hole sizes. The packet delivery ratio is mostly affected by data collisions. Both GPSR and SPEED send data packets along the hole boundary by the perimeter mode. In other words, all communication sessions of GPSR and SPEED are concentrated at the hole boundary. We can regard the hole boundary as collision area. The bigger the hole is, the wider the collision area becomes. This leads to increasing of data collisions with the size of the hole. We can regard the hole boundary as collision area. The bigger the hole is, the bigger the collision area becomes. So the packet delivery ratio of GPSR and SPEED is significantly decreased with the hole size. In the proposed protocol, the data packets are redirected to anchor locations once they encounter the hole modeling circle. Different communication sessions have different anchor location since the routing path of different communication sessions cross but do not overlap with each other. So the data delivery ratio of the proposed protocol decreased a little with the hole size.

Fig. 7(b) shows the control overhead of three protocols with the hole size. For GPSR, There is nearly no change in control overhead with the number of communication sessions, because the delivery of GPSR is purely based on location information. Comparing with GPSR, our algorithm includes an additional circle construction process. The circle construction process is increased with the hole size. For SPEED, the bigger the hole is, the bigger collision area becomes, so to find a high speed data delivery path, SPEED pays additional overhead on routing rediscovery. So the control overhead of SPEED is significantly increased than the other two protocols with the hole size.

Fig. 7(c) shows the average delivery delay with the hole size. The average delivery of our protocol is lower than the other two protocols because the average delivery is closely related to the collision area which increases with the hole size.

Fig. 7(d) shows the average energy consumption of nodes on boundary of holes. GPSR and SPEED utilize perimeter mode to route data packet when the data packet encounter a hole. In other words, the bigger the hole is, the more number of hole boundary nodes are shared by several communications as shown in Fig. 1(c), thus leads to higher average energy consumption. In the proposed scheme, the data packets are redirected to anchor location when the data packet encounters the hole modeling circle. This way, it prevents the data packet to go along the boundary of holes. Since the routing path of different communications cross but do not overlap with each other, the bigger the hole is, the farther the anchor locations are located, and the more number of nodes participates in data forwarding. So the average energy consumption of the proposed scheme is lower than that of GPSR and SPEED.

VI. CONCLUSIONS

In this paper we proposed a hole geometric modeling mechanism which models a hole by a circle to solve the holes problems faced by geographic routing in wireless sensor network. The node on the boundary of circle redirects the received data packets to anchor location, by this way to bypass the holes area. This mechanism has the advantages that: On one hand, prevent data packets from entering the area uncovered by a hole, thus reduce route rediscovery overhead; on the other hand, reduce energy consumption and data collision of the nodes on boundaries of holes.

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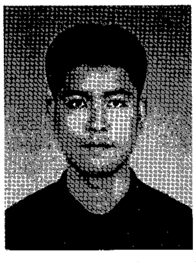

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