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# A Hole Avoiding Routing Protocol in Wireless Sensor Networks

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***Abstract*—In wireless sensor networks, an important challenge often faced in geographic greedy forwarding is the *local minimum phenomenon* which is caused by holes. For solving this problem, most hole-avoiding protocols route packets along the perimeter of holes or forbidden regions. Thus, sensor nodes on the perimeter of holes and forbidden regions exhaust their energy faster than others, which enlarge the hole size, called growing hole problem. In this paper, we propose an energy-efficient *hole avoiding routing protocol* (HARP) for *growing hole problem* in multi-hole environments.**

***Index Terms*—local minimum problem; geographic greedy forwarding; wireless sensor networks (WSNs)**

## I. Introduction

Geographic greedy forwarding is a simple, efficient and attractive routing protocol in *wireless sensor networks* (WSNs). It exploits pure local location information instead of global topology information to route data packets. It is assumed that each node knows location information of itself and its one-hop neighbors. When a packet is forwarded to the destination, each intermediate node uses known location information to guess the *expected zone* where the destination exists and calculate a zone where forwarding nodes are able to approach the destination. Therefore, this mechanism can minimize the hops from the source to destination. However, geographic greedy forwarding in WSNs has *local minimum phenomenon* [1], i.e., the forwarding process is blocked at certain nodes near holes.

To solve the *local minimum problem*, i.e., local minimum phenomenon, hole-handling routing protocols are adopted when the packets encounter an obstacle/hole. These protocols can be classified into two categories: passive and active. In the *passive approaches* [2], [3] e.g., GPSR [2], the hole information is usually not maintained by the WSNs. To prevent the packet transmission from blocking, packets are routed along the perimeter of hole according to the predefined rules. Since the passive approaches lack shape information of the holes, packets may route a long detour path to the destination successfully rather than the shortest path. On the other hand, in the *active approaches* [3]–[8], e.g., SLGF [7], sensor nodes nearby the hole automatically detect and maintain the hole information. Thus, the active approaches can prevent the packets from entering a *concave region* where greedy forwarding is impossible and guide packets toward the shortest route.

Whatever passive or active protocols are adopted, packets are routed through a certain fixed area, which results in that sensor nodes on the fixed area are frequently used and exhaust their energy rapidly (see Fig. 1). These sensor nodes are called *hot spots* and the fixed area comprises hot spots are called *hot area*. According to our observation, hot spots' lifetime increases as their corresponding hot area sizes increases. In previous routing protocols, hot areas (i.e., boundary of holes or perimeter of forbidden regions) are quite narrow and small, which accelerates death of hot spots. Consequently, holes are enlarged, called *growing hole problem*.

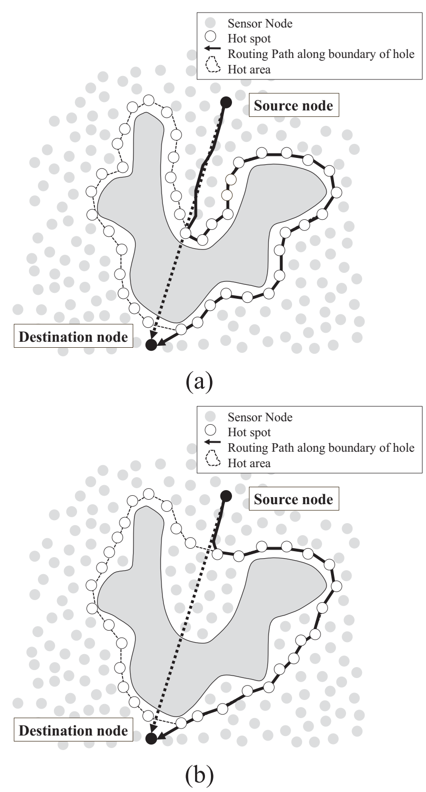


Fig. 1. Hot spots and hot areas. (a) Packets routes through perimeter of holes in passive protocols. (b) Packets routes through perimeter of forbidden regions in active protocols.

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In this paper, we propose an energy-efficient *hole avoiding routing protocol* (HARP) for mitigating load of hot spots and prolong the network lifetime in multi-hole environments. Comparing with previous works, hot spots in our routing protocol have more remnant energy (see Fig. 2). Besides, more shorter paths which are usually discard in order to dodge holes are chosen in our protocol.

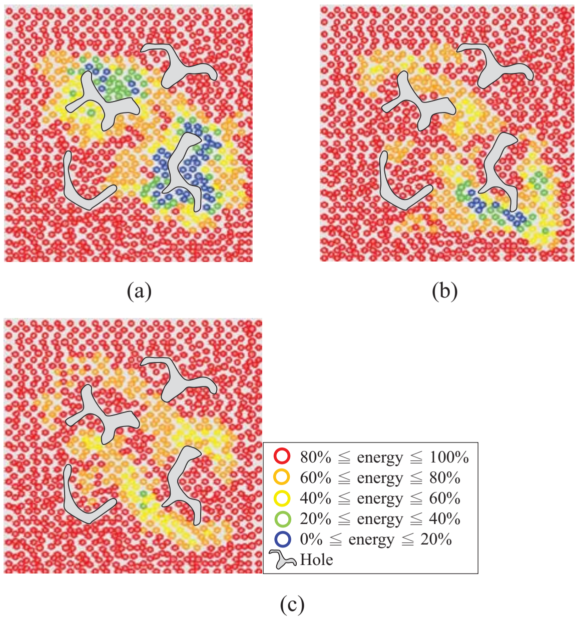


Fig. 2. Remnant energy of three routing protocols. (a) GPSR [2]. (b) SLGF [7]. (c) HARP.

## II. Hole avoiding routing protocol

In this section, we present a distributed *hole avoiding routing protocol* (HARP) to mitigate load of hot spots. We assume that each node knows its own location information and its one-hop neighbors. The location information can be determined by *global positioning system* (GPS) receivers, mobile beacon nodes, or relative coordinate systems. Each node can detect whether it is located on the boundary of a hole by some boundary recognition protocols [9], [10]. We consider an environment which has multi-sources and multi-destinations. Before encountering an expanded hot area, each source node $S$ forwards data packets to its destination node $D$ by geographic greedy forwarding.

### A. Expanded Hot Area

Note that ongoing transmission toward the hole should detour the hole through hot areas. So, a hot spot's loading decreases as the size of its corresponding hot area increases. In this paper, we expand hot areas for mitigating load of hot spots. An *expanded hot area* is the area within $k$-hops of the corresponding hole as shown in Fig. 3. For ease of the following discussion, we define *Boundary Contour 1* to be the set of hole boundary nodes. We also define *Boundary Contour i* ($BC\ i$ for short) to be the set of nodes which is $(i-1)$-hop away from the Boundary Contour 1. The expanded hot area is composed of Boundary Contours $1, 2, ..., k$ (according to our simulation results, $k = 5$ is sufficient).

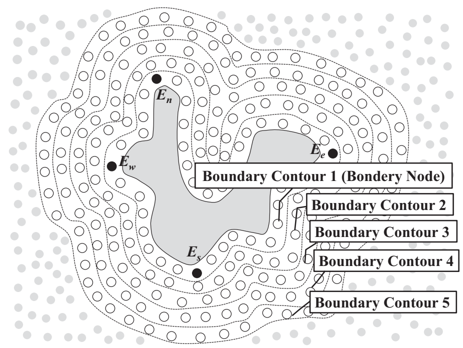


Fig. 3. The expanded hot area when $k = 5$.

### B. Hole Avoiding Routing Protocol (HARP)

In this section, we use expanded hot area to develop a new hole avoiding routing protocol.

*1) Single-Hole Environment:* For ease of the following discussion, we simplify a hole to be a polygon $E_eE_nE_wE_s$, where $E_e$, $E_w$, $E_s$, and $E_n$ denote the extreme east, west, south and north locations on the hole. We also simplify the corresponding hot area to be the union of four bar regions (i.e., four rectangles) and four pie regions, as shown in Fig. 4.

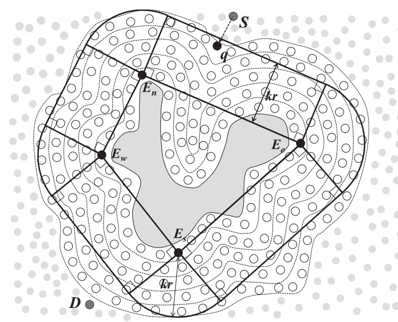


Fig. 4. Simplification of the hole and the corresponding expanded hot area.

Fig. 5 shows a simplified expanded hot area. In the simplified expanded hot area, the blue path (i.e., $P^*$) is an optimistically shortest path from the source $S$ to the destination $D$. Obviously, $P^*$ should pass through some vertices in $\{E_e, E_n, E_w, E_s\}$ and includes some segments in $\{E_eE_n, E_nE_w, E_wE_s, E_sE_e\}$. If all packets are transmitted along such $P^*$s, vertices located in these four line segments $E_eE_n, E_nE_w, E_wE_s$, and $E_sE_e$, become hot spots. For the purpose of load balancing and reducing path length, in our protocol, the detour through the expanded hot area is $i$-hop shift from the optimistically shortest path $P^*$, i.e., a $P^*$-like path at other BCs. For example, the red path in Fig. 5. The detail is described below. In the red path in Fig. 5, the packet is transmitted to a entry point $q$, which is the first point in the simplified expanded hot area that is achieved by geographically greedy forwarding. Then, the packet is forwarded to destination $D$ according the following steps.

**Step 1:** Randomly choose one $BC$, say $BC$ 3.

**Step 2:** Determine the travelling start point $u$. First, determine the boundary of the bar/pie region which $q$ is located in and $P^*$ passes through, i.e., line segment $E_n p$. Then $u$ is the intersection of $BC$ 3 and $E_n p$.

**Step 3:** The packet is forwarded to travelling start point $u$ by greedy forwarding.

**Step 4:** The packet is forwarded along $BC$ 3 from travelling start point $u$ to travelling stop point $x$, where $x$ is at the boundary of the bar/pie region where $P^*$ lastly passes through.

**Step 5:** The packet is forwarded from $x$ to $D$ by greedy forwarding.

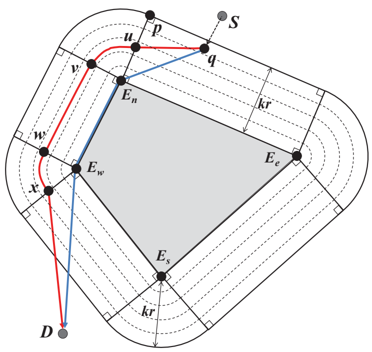

Fig. 5. Simplified expanded hot area and our simplified path. The red path denotes our path in the simplified expanded hot area. The blue path denotes an optimistically shortest path (i.e., $P^*$) from $S$ to $D$.

For ease of the following discussion, the path determined by step 1 to step 5 above (e.g., the red path in Fig. 5) is called the *simplified path*. Note that our path has small *stretch factor*.

$$\text{stretch factor} = \frac{\text{(our path length)}}{\text{(the length of the shortest path)}} \approx \frac{\text{(the simplified path)}}{\text{(the path length of } P^*\text{)}}, \quad (1)$$

Our simplified path in a bar region (i.e., our simplified path $\cap$ a bar region) is shorter than or equal to that of $P^*$ (e.g., blue path in Fig. 5). Note that the total length of arcs of the four pie regions is $2\pi(kr)$, where $r$ is sensors' communication

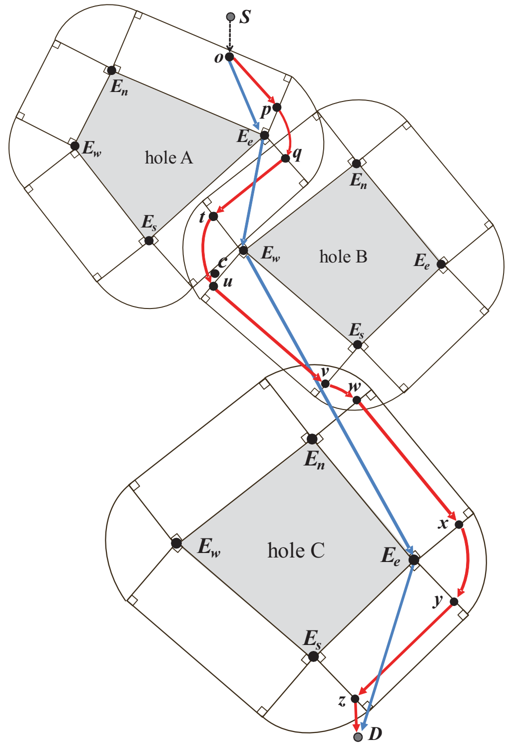

Fig. 6. The red path denotes our simplified path and the blue path is $P^*$.

range. Hence, our simplified path in a pie region has length $2\pi(kr)/4/2 = \pi kr/4$ on average (because there are four pie regions and the expected value of our simplified path in a pie region is half of the length of its arcs). So the stretch factor is approximately equal to $1 + 2(\pi kr/4)$/(the length of $P^*$), which is usually small.

*2) Multi-Hole Environment:* In multi-hole environments, shorter paths along narrow corridors between holes are chosen in our protocol. For ease of the subsequent discussion, we have the following definitions. Given a vertex $b$ which is located in the intersection of two or more holes' expanded hot areas. Define a *avoiding hole* of $b$ to be a hole which line segment $bD$ passes through and $b$ is located in its expanded hot area. And define the *first-avoiding hole* of $b$ to be an avoiding hole which is closest to vertex $b$. Intuitively, when the packet is forwarded to a vertex $b$, $b$ should pay its attention to detour its avoiding holes. And $b$ does not need to detour holes which are not avoiding. For example, in Fig. 6, vertex $q$ is in the intersection of hole $A$'s expanded hot area and hole $B$'s expanded hot area, and has one avoiding hole, i.e., hole $B$. Note that hole $A$ is not $q$'s avoiding hole, because line segment $qD$ does not pass through hole $A$. When $b$ has more than one avoiding holes, $b$ takes care the closest one first, called b's *first-avoiding hole*. Clearly, hole $B$ is vertex $q$'s first-avoiding hole.

Now, we define the *current-focus hole* to be the hole which the forwarder should take care immediately. When a packet forwarder is located in exactly one expanded hot area (i.e., vertices $p$, $u$, $x$, $y$, $z$ in Fig. 6), the forwarder's current-focus hole is the corresponding hole of the expanded hot area which it is located in. For example, the current-focus hole of $p$ is hole $A$. When the forwarder $f$ is in more than one expanded hot areas and one of them is the expanded hot area of $f$'s first-avoiding hole (e.g., vertices $q$, $v$, and $w$ in Fig. 6), the current-focus hole of $f$ is $f$'s first-avoiding hole. For example, in Fig. 6, vertex $q$ is in the expanded areas of hole $A$ and hole $B$. Since hole $B$ is vertex $q$'s first-avoiding hole, $q$'s current-focus hole is hole $B$. When the forwarder $f$ is in more than one expanded hot areas and none of them is the expanded hot area of $f$'s first avoiding hole (e.g., vertex $t$ in Fig. 6), $f$'s current-focus hole is the current-focus hole of a vertex $c$ which satisfies all the following three conditions.

(1) $c$ is on line segment $fD$;

(2) $c$ is in exactly one expanded hot area; and

(3) line segment $fc$ is the shortest among all points satisfying both (1) and (2).

For example, in Fig. 6, vertex $t$ is in the expanded hot areas of hole $A$ and hole $B$. Since $t$ has no avoiding hole, $t$'s current-focus hole is hole $B$ (because the current-focus hole of the vertex $c$ which satisfies conditions (1), (2), and (3) is hole $B$).

In multi-hole environments, routing path outside expanded hot areas is based on geographically greedy forwarding, while routing path inside expanded hot areas are determined by the aid of forwarder's current-focus hole and the five steps (step 1 to step 5 in Section II.B). More precisely, when the forwarder satisfies one of the two conditions,

(C1) forwarder is at the entry of a expanded hot area from a non-expanded hot area, or

(C2) forwarder is at the boundary of a pie/bar region of a expanded hot area,

the forwarder determines its current-focus hole. For example, in Fig. 6, the packet which is aimed to sent from $S$ to $D$ is firstly geographically greedy forwarded from $S$ to entry vertex $o$. Since vertex $o$ is at the entry of an expanded hot area, vertex $o$ determines its current-focus hole, i.e., hole $A$. Then a path in hole $A$'s expanded hot area from vertex $o$ is determined by step 1 to step 3 (in Section II.B), i.e., the red path from vertex $o$ to vertex $p$. Note that vertex $p$ is at the boundary of a bar region, vertex $p$ determines its current-focus hole, i.e., hole $A$. Then the path from vertex $p$ is traveling along the BC which is in hole $A$'s expanded hot area and has point $p$, i.e., the red path from vertex $p$ to vertex $q$, until a boundary of pie/bar region is encountered. Vertex $q$ is at the boundary of a bar region, vertex $q$ determines its current-focus hole, i.e., hole $B$. Then the path from vertex $q$ is along the BC which is in hole $B$'s expanded hot area and has point $q$, i.e., the red path from vertex $q$ to vertex $t$. Note that the red path from $p$ to $q$ is along a BC in hole $A$'s expanded hot area, while the red path from $q$ to $t$ is along a BC in hole $B$'s expanded hot area. Suppose that $q$ is in $BC$ 2 of the expanded area of hole $B$. Then the path from $q$ to $t$ is along $BC$ 2 in hole $B$'s expanded hot area. Similarly, the red path from $t$ to $z$, where $z$ is the travelling stop point (described in Section II.B step 4), could be determined. The red path from $z$ to $D$ is determined by geographically greedy forwarding.

Similarly, our simplified path in a bar region is shorter than or equal to $P^*$ in the same region and our simplified path in a pie region has length $\pi kr/4$ on average. So the stretch factor is approximately equal to $1 + \lambda(\pi kr/4)/(\text{the length of } P^*)$, where $\lambda$ is the number of pie regions our simplified path passes.

## III. Simulation

In this section, we implement our HARP using ns-2 and compare the performance of our protocol, GPSR [2] and SLGF [7]. Performance measures considered the average routing hops and network lifetime. The number of nodes varies from 900 to 1400 in increments of 100. Initial total energy of each node is $0.07J$. Energy consumption in transmitting and receiving packets are $0.35W$ and $0.38W$, respectively. The communication range of each node is $10m$. The monitored area is a $200 \times 200m^2$ rectangle area with four holes see (Fig. 7).

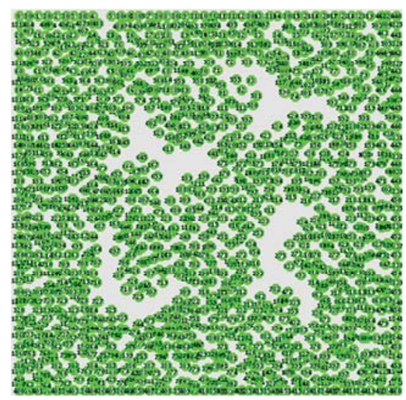

Fig. 7. The monitored area is a $200 \times 200$ $m^2$ rectangle area with four holes.

### A. Path length

Fig. 8 shows that HARP has shorter average path length (hops) than that of SLGF and GPSR.

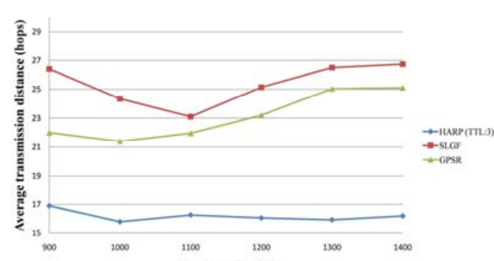


Fig. 8. The monitored area is a $200 \times 200$ $m^2$ rectangle area with four holes.

In a multi-hole environment, SLGF needs more hops to detour unsafe forbidden regions. As a result, average path length of SLGF is longer than that of HARP and GPSR. In 900-node to 1100-node environments, as the node density become larger, the detour path of SLGF is closer to the real border of forbidden area, which implies a shorter detour path. In 1200-node to 1400-node environments, average path length of SLGF increases. An example is shown in Fig. 9. The $S$ finds some new safe neighbors (i.e., neighbors not in forbidden area), node a, which are closer the destination than original safe neighbors. Therefore the data packet is forwarded to node $a$. At node $a$, $D$ is located in third quadrant of a and no safe neighbors are in third quadrant of $a$. It must employ right-hand rule to search next hop. Consequently, it results ineffective path to increase average transmission distance of SLGF.

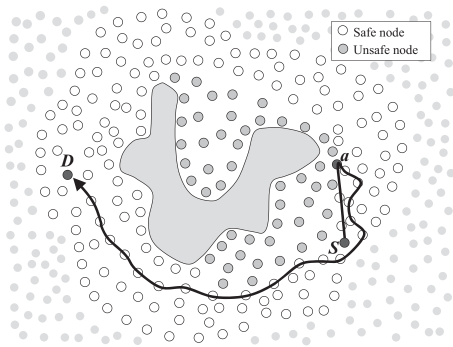


Fig. 9. The increase of node density affects a routing path of SLGF.

In GPSR, average path length of GPSR increases as node density increases. It is because nodes find new neighbors which are closer to the destination than original neighbors and forward data packets to these new neighbors. However, the new routing path could route deeply into concave of holes, which causes longer path length.

### B. Network lifetime

Fig. 10 shows the average network lifetime of HARP, SLGF, and GPSR. Hot spots of SLGF are located on perimeter of forbidden region and hot spots of GPSR are located on perimeter of holes. In the scenario of Fig. 7, SLGF has larger hot areas than GPSR has. So the average network lifetime of SLGF is better than GPSR. Similarly, HARP has larger hot areas than GPSR and SLGF have. Therefore the average network lifetime of HARP is better than SLGF by approximately 1.7 times and GPSR by approximately 2 to 3 times.

In 1200-node environment, the network lifetime of SLGF suddenly decrease because generation of new ineffective paths makes many nodes be used meaninglessly and squanders energy of nodes, see Fig 9. In GPSR, average network lifetime of GPSR decreases with the increase of node density. It is because the increase of node density causes more routing paths walk along boundary of holes and makes energy of hot spots exhausts quickly.

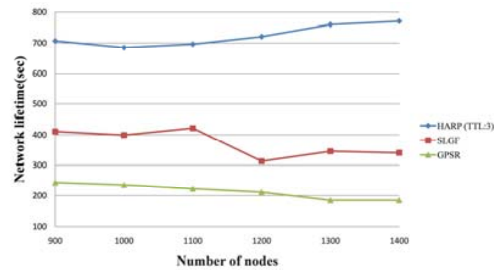


Fig. 10. The average network lifetime of HARP, SLGF, and GPSR.

## IV. Conclusion

In wireless sensor networks, existing research works for by-passing holes tend to route data packets along the perimeter of holes or forbidden regions, which results in that sensor nodes in boundary of holes or perimeter of forbidden regions have excessive loading and exhaust their energy rapidly. Hence, holes are enlarged, called growing hole problem.

In this paper, we proposed an energy efficient hole avoiding routing protocol. We establish expanded hot areas which comprise multi-layer boundary contours to mitigate load of boundary nodes and prolong the network lifetime. The experimental result shows that our protocol achieves better performance in network lifetime.

In multi-hole environment, we adopt shorter paths along narrow corridors between holes. As a result, our protocol outperforms other protocol in term of route hops in multi-hole environment.

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