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A Geometric Approach to Model a Detour Success Probability for Geographic Routing Protocols

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Abstract

A void handling technique is an important issue for a geographic routing in wireless sensor networks and ad hoc networks. However, since most of the methods handling the communication voids take heuristic approaches when selecting a next forwarder, the performance of a routing protocol is limited accordingly. In addition, it is difficult to set optimal parameter values in dynamic networking environments. In this paper, we propose an analytic framework to derive the probability that a node detours successfully the void area it faces. Using the geographic information of nodes, we take a geometric approach. For each of one-hop neighbor nodes, the analysis results provide a node facing a void area to calculate the detour success probability using its local information. Therefore, the model could assist the node facing a void area to select the optimal next node that could maximize the detour success probability. Thus, the model is expected to be used to devise an optimal void handling scheme for a geographic routing protocol.

Keywords: *Geometric approach, analytic model, detour success probability*

1. Introduction

Geographic routing schemes haven been proposed for a wireless sensor networks and ad-hoc networks [1]. They use the location information of the nodes deployed in a network to find an appropriate next forwarder. When a node S needs to send a packet, distances from each of S's neighbor nodes to the final destination D of the packet are inspected. Among the neighbor nodes of S that are closer to the final destination than S, the one that minimize a certain cost function becomes the next forwarder. However, a communication void occurs when none of S's neighbor node is closer to D than S. When S faces a void, it attempts to detour the void area by initiating a void handling techniques. The key element of a void handling method is to select a next forwarder among the neighbor nodes that is not closer to D than S [2]. Therefore, to increase the efficiency of a void handling method, a node facing a void should select a node that maximizes the detour success probability as the next forwarder.

A most popular void handling method is to combine the properties of planar graphs and the well-known right hand rule [3]. The basic idea is to remove cross-link to prevent routing loops. However, it is not easy to make a planar subgraph in a distributed manner that guarantees the quality of path discovered by the traversal algorithm is not far from optimal. In addition, the resulting next forwarder does not necessarily guarantee maximum detour success probability. A bio-inspired routing protocol is proposed in [4]. They introduce an activity value that reflects the goodness of current path. When a void occurs at a node S, it selects a next forwarder randomly according to the activity value. Thus, the node that is farthest away from D is likely to be selected. However, it is very difficult to set values of protocol parameters in a way that suits to the operational environments. In GDBF [5], when S detects a

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void, it selects the node that is closest to itself as the next forwarder. However, since [4] and [5] uses only the distance when choosing a next forwarder, they cannot provide any assurance on that a next forwarder could maximize the detour success probability in a given situation. In [6], they divide the non-forwarding area of S into a few sectors. The non-forwarding area is a subset of the transmission region of S where the distance from any point in the area to D is longer than the distance between S and D. Then, S uses the angle and the distance to itself to select the next forwarder such that a node that is far away from S with the smallest angle is likely to be selected. However, they did not present a systematic way to determine the number of sectors. In addition, even though they consider both the distance and the angle, the decision method is heuristic. Thus, the resulting forwarder may not be optimal in terms of the detour success probability.

Therefore, in this paper, we propose an analytic framework to model the detour success probability. In our framework, we only use the position information of nodes. By taking a geometric approach, we derive the detour success probability in a closed form expression. Therefore, it could be easily implemented even in a tiny sensor node that has a very low computational power and memory. Since the analytical results provide definite relation between the position of neighbor node and the detour success probability, it could assist the node facing a void area to select the optimal next forwarder that could maximize the detour success probability. Thus, the model is expected to be used to devise an optimal void handling method for a geographic routing protocol.

2. Detour Success Probability

In this section, we derive an analytical model for the detour success probability. The notations we used are summarized in Table 1. We assume that the transmission radius of all nodes are the same as r.

Table 1. Notations used for the analysis.

Notations	Meaning
r	Transmission radius.
x_I	The x-coordinates of a node I.
y_I	The y-coordinates of a node I.
$d_{X,Y}$	The Euclidean distance between nodes X and Y.
S_{NF}	The set of nodes that resides in the non-forwarding area of S
X_{DS}	The set of nodes residing in the detour success area when S selects X to detour

When a node S encounters a situation where it cannot find a 1-hop neighbor node that is closer to the final destination D of a packet than itself, S tries to detour using its 1-hop neighbors residing in the non-forwarding area of S (S_{NF}). If S detours successfully through a node X $\in$ S_{NF}, at least one of X's neighbor should be closer to D than S. We define the detour success area of X (X_{DS}) as the region where if a neighbor node of X exists in that area, S can detour successfully a void area through X. Therefore, the detour success probability of S via X becomes the probability that at least one of the neighbors of X exists in X_{DS}.

The shaded region of Figure 1 represents the detour success area of X. Without loss of generality, we assume that S is located to the left of D (*i.e.*, $x_S < x_D$) and X is located to the north of S (*i.e.*, $Y_S < Y_X$). The X_{DS} is the region that is surrounded by the points A, B and C. The point A is the intersection point between the circle which is centered at S and has the radius of r and the circle centered at D with the radius of $d_{S,D}$. The point B is the intersection of the two circles. One is centered at X with radius r, and the other is centered at D and has a radius $d_{S,D}$. The point C is the intersection point between two circles having the same radius r. But one circle is centered at S while the other circle is centered at X.

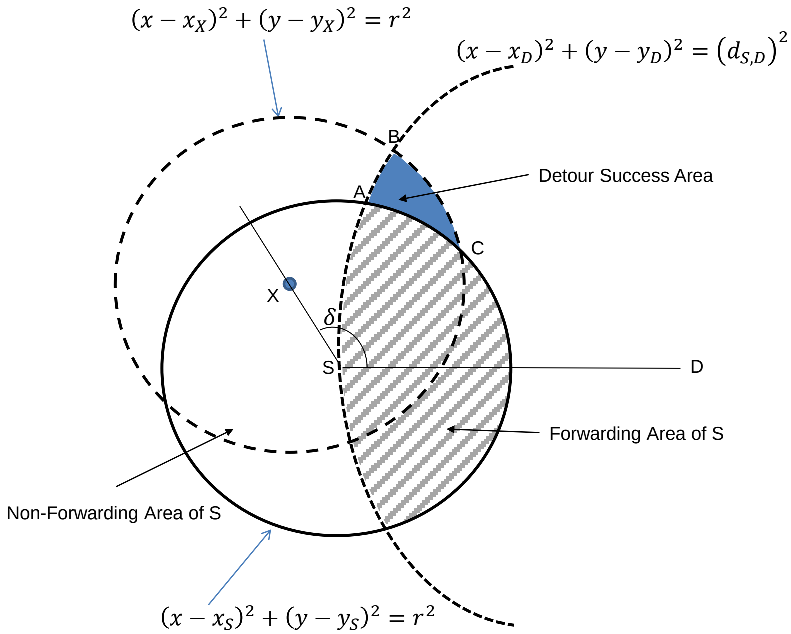


Figure 1. Detour success area when S selects the node X to detour (S: a packet holder facing a void area, D: final destination of a packet, X: a node in the non-forwarding area of S)

The coordinates of the point A can be obtained by solving the following equations

$$(x - x_S)^2 + (y - y_S)^2 = r^2 \quad (1)$$

$$(x - x_D)^2 + (y - y_D)^2 = d_{S,D}^2 \quad (2)$$

From the Eq. (1), $y = y_S \pm \sqrt{r^2 - (x - x_S)^2}$. Since we assume $Y_S < Y_X$, A is located to the north of S. Thus, if we put $y = y_S + \sqrt{r^2 - (x - x_S)^2}$ into Eq. (2), we get

$$2(x_S - x_D)x + 2(y_S - y_D)\sqrt{r^2 - (x - x_S)^2} + K_1 = 0\,, \quad (3)$$

where $K_1 = x_D^2 - x_S^2 + (y_S - y_D)^2 + r^2 - d_{S,D}^2$. If we denote $L_1 = 2(x_S - x_D)$, $M_1 = 2(y_S - y_D)$, Eq. (3) becomes

$$(M_1^2 + L_1^2)x^2 + 2(K_1 L_1 - x_S M_1^2)x + K_1^2 + x_S^2 M_1^2 - r^2 M_1^2 = 0 \quad (4)$$

Since Eq. (4) is the quadratic equation of x, the x-coordinates of A is given as

$$X_A = \frac{-(K_1L_1 - x_S M_1^2) + \sqrt{(K_1L_1 - x_S M_1^2)^2 - (M_1^2 + L_1^2)(K_1^2 + x_S^2 M_1^2 - r^2 M_1^2)}}{M_1^2 + L_1^2} \quad (5)$$

Putting Eq. (5) into Eq. (1), we get the y-coordinates of A as follows.

$$y_A = y_S + \sqrt{r^2 - (x_A - x_S)^2} \quad (6)$$

The coordinates of the point B is the intersection point of the following equations

$$(\mathrm{x} - x_X)^2 + (\mathrm{y} - y_X)^2 = r^2 \quad (7)$$

$$(\mathrm{x} - x_D)^2 + (\mathrm{y} - y_D)^2 = d_{S,D}^2 \quad (8)$$

Following the same procedures, we can get the coordinate of B as follows.

$$X_B = \frac{-(K_2L_2 - x_X M_2^2) + \sqrt{(K_2L_2 - x_X M_2^2)^2 - (M_2^2 + L_2^2)(K_2^2 + x_X^2 M_2^2 - r^2 M_2^2)}}{M_2^2 + L_2^2} \quad (10)$$

$$y_B = y_X + \sqrt{r^2 - (x_B - x_X)^2}\ , \quad (11)$$

where $K_2 = x_D^2 - x_X^2 + (y_X - y_D)^2 + r^2 - d_{S,D}^2$, $L_2 = 2(x_X - x_D)$,

and $M_2 = 2(y_X - y_D)$.

We can also calculate the xy-coordinate of C using the same procedures.

$$X_C = \frac{-(K_3L_3 - x_S M_3^2) + \sqrt{(K_3L_3 - x_S M_3^2)^2 - (M_3^2 + L_3^2)(K_3^2 + x_S^2 M_3^2 - r^2 M_3^2)}}{M_3^2 + L_3^2} \quad (12)$$

$$y_C = y_S + \sqrt{r^2 - (x_C - x_S)^2}\ , \quad (13)$$

where$K_3 = x_X^2 - x_S^2 + (y_S - y_X)^2$, $L_3 = 2(x_S - x_X)$, and $M_3 = 2(y_S - y_X)$.

To derive the area of X_{DS}, we define the following variables.

·R_1 : the area of the triangle covered by BAC.

·R_2 : the fan shaped area covered by BXC – the area of the triangle covered by BXC.

·R_3 : the area covered by the straight line AB and an circular arc AB.

·R_4 : the area covered by the straight line AC and an circular arc AC.

If we denote $P_1 = (d_{A,B} + d_{A,C} + d_{B,C})/2$, from the Heron's formula [7], R_1 is calculated as

$$R_1 = \sqrt{P_1(P_1 - d_{A,B})(P_1 - d_{A,C})(P_1 - d_{B,C})} \quad (14)$$

To calculate R_2 , we denote ∠BXC = α . Then, $\alpha = \cos^{-1}(\frac{d_{B,X}^2 + d_{C,X}^2 - d_{B,C}^2}{2d_{B,X}d_{C,X}})$. Therefore, the fan shaped are covered by BXC becomes $\alpha r^2/2$. Using the Heron's formula, we can get the area of the triangle covered by BXC as

$\sqrt{P_2(P_2 - d_{B,X})(P_2 - d_{C,X})(P_2 - d_{B,C})}$, where $P_2 = (d_{B,X} + d_{C,X} + d_{B,C})/2$.

Therefore,

$$R_2 = \frac{r^2}{2}\alpha - \sqrt{P_2(P_2 - d_{B,X})(P_2 - d_{C,X})(P_2 - d_{B,C})} \quad (15)$$

R_3 is derived in a similar way. If we let $\angle ADB = \beta$, $\beta = \cos^{-1}(\frac{d_{A,D}^2 + d_{B,D}^2 - d_{A,B}^2}{2d_{A,D}d_{B,D}})$. Therefore, the sector covered by ADB becomes $\beta d_{S,D}^2/2$.

If we denote $P_3 = (d_{A,D} + d_{B,D} + d_{A,B})/2$, R_3 can be obtained as

$$R_3 = \frac{d_{S,D}^2}{2}\beta - \sqrt{P_3(P_3 - d_{A,D})(P_3 - d_{B,D})(P_3 - d_{A,B})} \qquad (16)$$

To derive R_4 , we denote $\angle ASC = \theta$ and $P_4 = (d_{A,S} + d_{C,S} + d_{A,C})/2$. Then the fan shaped area covered by ASC becomes $\theta r^2/2$, where $\theta = \cos^{-1}(\frac{d_{A,S}^2 + d_{C,S}^2 - d_{A,C}^2}{2d_{A,S}d_{C,S}})$, and the area of the triangle covered by ASC is $\sqrt{P_4(P_4 - d_{A,S})(P_4 - d_{C,S})(P_4 - d_{A,C})}$. Therefore,

$$R_4 = \frac{r^2}{2}\theta - \sqrt{P_4(P_4 - d_{A,S})(P_4 - d_{C,S})(P_4 - d_{A,C})} \qquad (17)$$

From Eq.(14)~(17), the detour success area of X is derived as

$$X_{DS} = R_1 + R_2 + R_3 - R_4 \qquad (18)$$

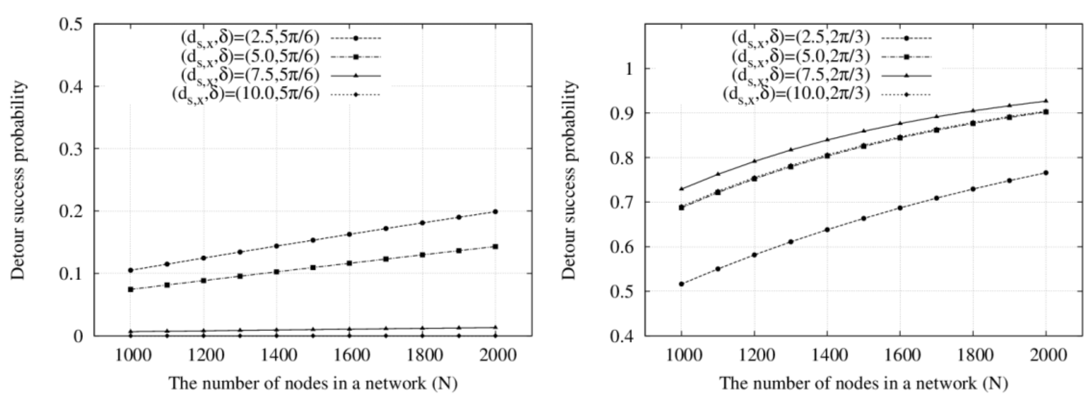
If S detours successfully through X, there should be at least one node in X_{DS}. If the area covered by a network is R_{TA} and N sensor nodes are uniformly distributed over R_{TA} , the probability that a node is located within X_{DS} becomes $p_X = X_{DS} / R_{TA}$. Therefore, the probability that S detours successfully through X becomes

$$p_X^d = 1 - (1 - p_X)^N \qquad (19)$$

We assume that the set of nodes that resides in the non-forwarding area of S, $S_{NF} = \{n_1, \cdots, n_{|S_{NF}|}\}$ is sorted in an descending order according to Eq. (19). Then, the probability that S can detour is derived as

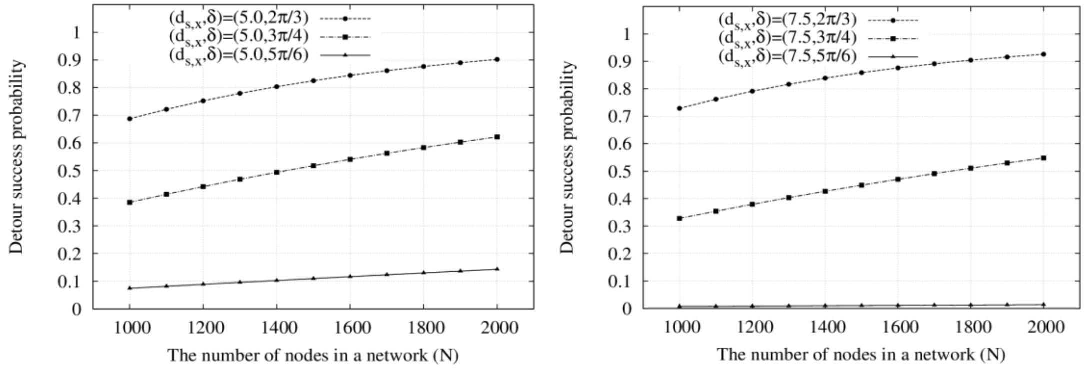
$$\mathrm{p} = 1 - \prod_{i=1}^{|S_{NF}|}(1 - p_{n_i}^d) \qquad (20)$$

3. Numerical Results and Discussions



(a) $\delta = 5\pi/6$ (b) $\delta = 2\pi/3$

Figure 2. Detour success probability when by δ is the same



(a) $d_{S,X} = 5$m (b) $d_{S,X} = 7.5$m

Figure 3. Detour success probability when by $d_{S,X}$ is the same

In this section, we numerically shows p_X^d by varying the positions of X. We locate D at (100,100) and S at (50,100), respectively. The transmission radius of nodes (r) is set to be 10m. We denote by δ as the angle between the two lines. One line goes through S and D, and the other penetrates S and X (see figure 1). We deploy N nodes in a 200x200 region. In this network environment, we vary N, δ, and $d_{S,X}$ to examine the effects of these parameters to the detour success probability.

In Figure 2, we depict p_X^d for various $d_{S,X}$ and N while fixing δ to investigate the effects of the distance between S and X. The probability that at least one node exists in the detour success area increases as the number of nodes in a network increases. Therefore, p_X^d increases with the number of nodes in a network. In Figure 2-(a), p_X^d becomes smaller with $d_{S,X}$, In this case, δ is $5\pi/6$ which is close to 180°. Hence, the size of the detour success area decreases as $d_{S,X}$ increases. On the contrary, if δ increases from $5\pi/6$ to $2\pi/3$, p_X^d does not show a consistent pattern with $d_{S,X}$ (see Figure 2-(b)). For all the cases, p_X^d is the smallest when $d_{S,X}$ is 2.5m while it is the largest when $d_{S,X}$ is 7.5m. The results suggest that the node whose distance from S is the smallest is not necessarily the optimal detour node.

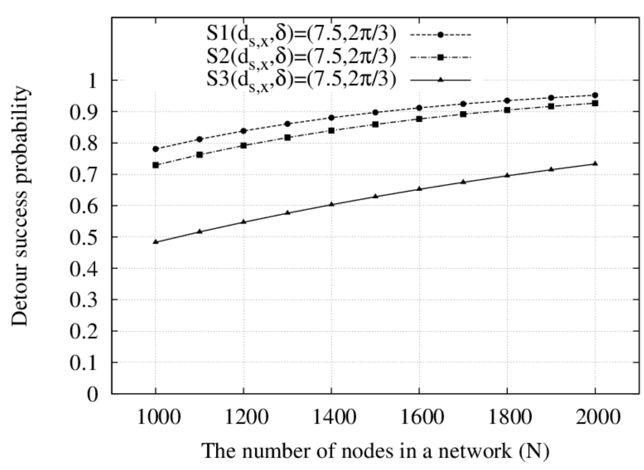


Figure 4. Detour success probability according to the location of S relative to D

In Figure 3, we depict p_X^d for various δ by fixing $d_{S,X}$. If the distance from X to S is fixed, the detour success area of the node increases δ becomes smaller (*i.e.*, X is located closer to the forwarding area of S). Therefore, p_X^d increases as δ decreases. Since p_X^d depends on the size of the detour success area, these results show that the optimal node that maximize p_X^d is neither the farthest from S nor the closest to S. Hence, heuristic methods fail to find an optimal node. These results suggest that the angle and the distance must be considered when S estimates the detour success probability. Therefore, our model could be used to design more optimal next forwarder selection method to detour a void area.

To investigate the effect of the distance between a source node facing a void and D, we choose two additional source nodes that face a void. Considering the coordinates of D and the cell radius of r = 10m, one node denoted by S1 is located at (10,100) and the other node denoted by S3 is located at (80,100). For presentation purpose, the source node S located at (50,100) is renamed as S2. In Figure 4, for each of the source node, we show the detour success probabilities when each of the source node chooses the optimal detour node for itself (i.e. maximum p_X^d). As a source node is farther away from D, the size of the detour success area increases. Therefore, the maximum p_X^d of a source node increases as the distance between the source node and D increases. This implies that our model could be used to derive an efficient node deployment strategy. For example, in Figure 4, S1 needs 1600 nodes in the network to provide the maximum detour success probability of 0.91. Under the same condition, the maximum p_X^d of S2 is 0.87. If we want to guarantee the success probability of 0.9 for S2, the number of nodes in the network should be increased from 1500 to 1800. It means that the nodes should be more densely populated in the area closer to D.

4. Conclusions and Future Works

In this paper, we present an analytical framework to derive a detour success probability. Since we take a geometric approach, a node facing a void area needs only geographical locations of its 1-hop neighbor nodes to calculate the probability. We provide the closed form expression that relates the position of a node and the detour success probability. Therefore, a node facing a void area could easily find an optimal next forwarder in terms of maximizing the detour success probability. Since our results show the influences of both the angle and the distance on the detour success probability, it is expected to be used in designing a more efficient void handling techniques for a geographical routing protocol. In this research direction, the assumption of the model that nodes are uniformly distributed in a network needs further verification. In a wireless sensor network, nodes may not be evenly distributed all over the network. However, it is probable that the node density in a small area is almost the same. Therefore, we expect that a node facing a void could assume that the node densities of its 1-hop neighbors are almost the same. Since our model is to be used to find the most probable node that leads to successful detour, the node could find a neighboring node that maximizes p_X^d with this assumption. The other research direction based on our model is to derive an efficient node deployment strategy. Since our model assumes that the cell radius of each node is the same, the effect of the amorphous cells due to fading effects in wireless communication environments needs further investigation.

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