Greedy Anti-Void Routing Protocol for Wireless Sensor Networks

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***Abstract*— The unreachability problem (i.e. the so-called void problem) which exists in the greedy routing algorithms has been studied for the wireless sensor networks. However, most of the current research work can not fully resolve the problem (i.e. to ensure the delivery of packets) within their formulation. In this letter, the Greedy Anti-void Routing (GAR) protocol is proposed, which solves the void problem by exploiting the boundary finding technique for the Unit Disk Graph (UDG). The proposed Rolling-ball UDG boundary Traversal (RUT) is employed to completely guarantee the delivery of packets from the source to the destination node. The proofs of correctness for the proposed GAR protocol are also given at the end of this letter.**

***Index Terms*— Greedy routing, void problem, unit disk graph, localized algorithm, wireless sensor network.**

I. Introduction

A Wireless Sensor Network (WSN) consists of Sensor Nodes (SNs) with wireless communication capabilities for specific sensing tasks. Due to the limited available resources, efficient design of localized routing protocols [1] becomes a crucial subject within the WSNs. How to guarantee delivery of packets is considered an important issue for the localized routing algorithms. The well-known Greedy Forwarding (GF) protocol [2] is considered a superior scheme with its low routing overheads. However, the void problem [3] that occurs within the GF algorithm will fail to guarantee the delivery of data packets. Several localized routing algorithms as surveyed and proposed in [4] resolve the void problem by using the planar graphs. Nevertheless, the usage of the planar graphs has significant pitfalls due to the removal of critical communication links [5]; while the adoption of the Unit Disk Graph (UDG) for modeling the underlying network is suggested. A representative UDG-based greedy scheme, i.e. the BOUNDHOLE algorithm [6], forwards the packets around the network holes by identifying the locations of the holes. However, the delivery of packets can not be guaranteed in the BOUNDHOLE scheme even if a route exists from the source to the destination node. In this letter, the Greedy Anti-void Routing (GAR) protocol is proposed to completely resolve the void problem based on the UDG setting. The Rolling-ball UDG boundary Traversal (RUT) scheme is utilized within the GAR algorithm with the assurance for packet delivery.

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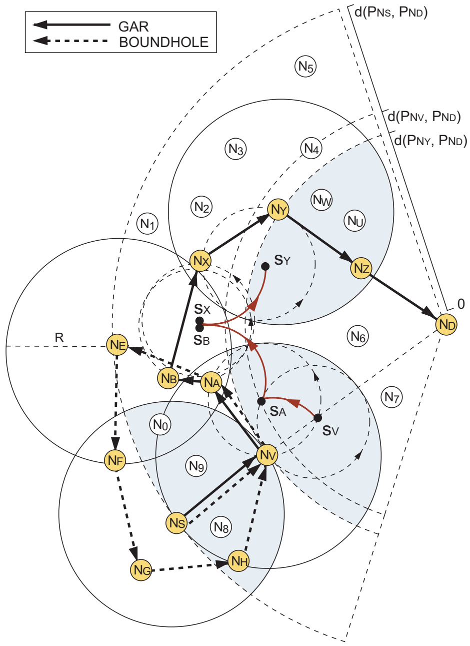

Fig. 1. The example routing paths constructed by using the GAR and the BOUNDHOLE algorithms under the existence of the void problem: (N_S, N_D) is the transmission pair and N_V is the Void Node. Node N_X is within the transmission range of N_B; while it is out of the range of N_A and N_E. The GAR protocol utilizes the RUT scheme (with red solid arcs denoted as the trajectory of the SPs); while the minimal angle criterion is employed by the BOUNDHOLE algorithm. The resulting paths obtained from these two schemes are $\{N_S, N_V, N_A, N_B, N_X, N_Y, N_Z, N_D\}$ using the GAR protocol and $\{N_S, N_V, N_A, N_E, N_F, N_G, N_H, N_V\}$ by adopting the BOUNDHOLE algorithm, which is observed to be undeliverable. The blue-shaded region associated with each SN is utilized to determine if the SN is a Void Node or not.

II. Network Model and Problem Statement

Consider a set of SNs $\mathbf{N} = \{N_i \,|\, \forall i\}$ within a two-dimensional Euclidean plane, the locations of the set $\mathbf{N}$, which can be acquired by their own positioning systems, are represented by the set $\mathbf{P} = \{P_{N_i} \,|\, P_{N_i} = (x_{N_i}, y_{N_i}), \forall i\}$. It is assumed that all the SNs are homogeneous and equipped with omni-directional antennas. The set of closed disks defining the transmission ranges of $\mathbf{N}$ is denoted as $\overline{\mathbf{D}} = \{\overline{D}(P_{N_i}, R) \,|\, \forall i\}$, where $\overline{D}(P_{N_i}, R) = \{\boldsymbol{x} \,|\, \|\boldsymbol{x} - P_{N_i}\| \le R, \forall \boldsymbol{x} \in \mathbb{R}^2\}$. It is noted that P_{N_i} is the center of the closed disk with R denoted as the radius of the transmission range for each N_i. Therefore, the network model for the WSNs can be represented by a UDG as $G(\mathbf{P}, \mathbf{E})$ with the edge set $\mathbf{E} = \{E_{ij} \,|\, E_{ij} = (P_{N_i}, P_{N_j}), P_{N_i} \in \overline{D}(P_{N_j}, R), \forall\, i \neq j\}$. The edge E_{ij} indicates the unidirectional link from P_{N_i} to P_{N_j} whenever the position P_{N_i} is within the closed disk region $\overline{D}(P_{N_j}, R)$. Moreover, the one-hop neighbor table for each N_i is considered available via the neighbor information acquisition [7] as $\mathbf{T}_{N_i} = \{P_{N_k} \mid P_{N_k} \in \overline{D}(P_{N_i}, R), \forall\, k \neq i\}$.

In the Greedy Forwarding (GF) algorithm, it is assumed that the source node N_S is aware of the location of the destination node N_D. If N_S wants to transmit packets to N_D, it will choose the next hopping node from its $\mathbf{T}_{N_S}$ which (i) has the shortest Euclidean distance to N_D among all the SNs in $\mathbf{T}_{N_S}$ and (ii) is located closer to N_D compared to the distance between N_S and N_D (e.g. node N_V as in Fig. 1). The same procedure will be performed by the intermediate nodes (such as N_V) until N_D is reached. However, the GF will be inclined to fail due to the occurrences of voids even though some routing paths exist from N_S to N_D. The void problem is defined as follows.

Problem 1 (Void Problem). *The Greedy Forwarding (GF) algorithm is exploited for packet delivery from N_S to N_D. The void problem occurs while there exists a Void Node (N_V) in the network such that*

$$\{P_{N_k} \mid d(P_{N_k}, P_{N_D}) < d(P_{N_V}, P_{N_D}), \forall\, P_{N_k} \in \mathbf{T}_{N_V}\} = \emptyset, \quad (1)$$

where $d(x, y)$ represents the Euclidean distance between x and y. $\mathbf{T}_{N_V}$ is the neighbor table of N_V.

III. The Proposed Greedy Anti-Void Routing (GAR) Protocol

A. The Rolling-ball UDG boundary Traversal (RUT) Scheme

The RUT scheme is adopted to solve the boundary finding problem. The definition of boundary and the problem statement are described as follows.

Definition 1 (Boundary). *If there exists a set $\mathbf{B} \subseteq \mathbf{N}$ such that (i) the nodes in $\mathbf{B}$ form a simple unidirectional ring and (ii) the nodes located on and inside the ring are disconnected with those outside of the ring, $\mathbf{B}$ is denoted as the Boundary Set and the unidirectional ring is called a Boundary.*

Problem 2 (Boundary Finding Problem). *Given a UDG $G(\mathbf{P}, \mathbf{E})$ and the one-hop neighbor tables $\mathbf{T} = \{\mathbf{T}_{N_i} \mid \forall\, N_i \in \mathbf{N}\}$, how can a Boundary be obtained by exploiting the distributed computing techniques?*

There are three phases within the RUT scheme, including the initialization, the boundary traversal, and the termination phases.

1) The Initialization Phase: No algorithm can be executed without the algorithm-specific trigger event. The trigger event within the RUT scheme is called the Starting Point (SP). The RUT technique can be initialized from any SP, which is defined as follows.

Definition 2 (Rolling Ball). *Given $N_i \in \mathbf{N}$, a Rolling Ball $RB_{N_i}(\boldsymbol{s}_i, R/2)$ is defined by (i) a rolling circle hinged at P_{N_i} with its center point at $\boldsymbol{s}_i \in \mathbb{R}^2$ and the radius equal to $R/2$; and (ii) there does not exist any N_i located inside the rolling ball as $\{RB^{\sim}_{N_i}(\boldsymbol{s}_i, R/2) \cap \mathbf{N}\} = \emptyset$, where $RB^{\sim}_{N_i}(\boldsymbol{s}_i, R/2)$ denotes the open disk within the rolling ball.*

Definition 3 (Starting Point). *The Starting Point of N_i within the RUT scheme is defined as the center point $\boldsymbol{s}_i \in \mathbb{R}^2$ of $RB_{N_i}(\boldsymbol{s}_i, R/2)$.*

As shown in Fig. 2, each node N_i can verify if there exists a SP since the rolling ball $RB_{N_i}(\boldsymbol{s}_i, R/2)$ is bounded by the

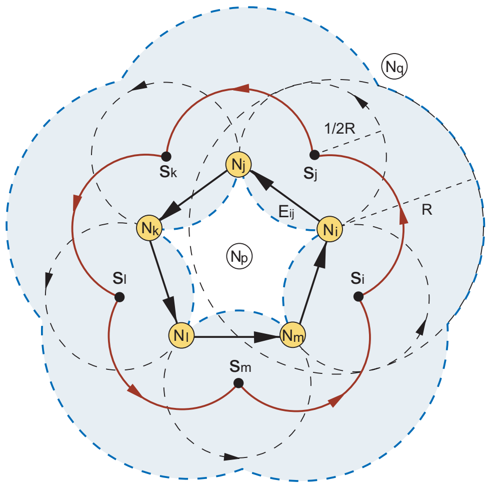

Fig. 2. The Rolling-ball UDG boundary Traversal (RUT) scheme: Given $\mathbf{s}_i$ and N_i, the RUT scheme rotates the rolling ball $RB_{N_i}(\mathbf{s}_i, R/2)$ counter-clockwise and constructs the simple closed curve (i.e. the flower-like red solid curve). The Boundary Set $\mathbf{B} = \{N_i, N_j, N_k, N_l, N_m\}$ is established as a simple unidirectional ring by using the RUT scheme.

transmission range of N_i. According to Definition 3, the SPs should be located on the circle centered at P_{N_i} with a radius of $R/2$. As will be proved in Lemmas 1 and 2, all the SPs will result in the red solid flower-shaped arcs as in Fig. 2. It is noticed that there should always exist a SP while the void problem occurs within the network, which will be explained in subsection B. At this initial phase, the location $\boldsymbol{s}_i$ can be selected as the SP for the RUT scheme.

2) The Boundary Traversal Phase: Given $\boldsymbol{s}_i$ as the SP associated with its $RB_{N_i}(\mathbf{s}_i, R/2)$ hinged at N_i, either the counter-clockwise or clockwise rolling direction can be utilized. As shown in Fig. 2, $RB_{N_i}(\boldsymbol{s}_i, R/2)$ is rolled counter-clockwise until the next SN is reached (i.e. N_j in Fig. 2). The unidirectional edge $E_{ij} = (P_{N_i}, P_{N_j})$ can therefore be constructed. A new SP and the corresponding rolling ball hinged at N_j (i.e. $\boldsymbol{s}_j$ and $RB_{N_j}(\mathbf{s}_j, R/2)$) will be assigned, and consequently the same procedure can be conducted continuously.

3) The Termination Phase: The termination condition for the RUT scheme happens while the first unidirectional edge is revisited. As shown in Fig 2, the RUT scheme will be terminated if the edge E_{ij} is visited again after the edges E_{ij}, E_{jk}, E_{kl}, E_{lm}, and E_{mi} are traversed. The boundary set initiated from N_i can therefore be obtained as $\mathbf{B} = \{N_i, N_j, N_k, N_l, N_m\}$.

B. The Proposed GAR Protocol

As shown in Fig. 1, the packets are intended to be delivered from N_S to N_D. N_S will select N_V as the next hopping node by adopting the GF protocol. However, the void problem prohibits N_V to continue utilizing the same GF algorithm for packet forwarding. The RUT scheme is therefore employed by assigning a SP (i.e. $\boldsymbol{s}_V$) associated with the rolling ball $RB_{N_V}(\boldsymbol{s}_V, R/2)$ hinged at N_V. As illustrated in Fig. 1, $\boldsymbol{s}_V$ can be chosen to locate on the connecting line between N_V and N_D with $R/2$ away from N_V. It is noticed that there always exists a SP for the void node (N_V) since there is not supposed to have any SN located within the blue-shaded region (as in

Fig. 1), which is large enough to satisfy the requirements as in Definitions 2 and 3. The RUT scheme is utilized until N_Y is reached (after traversing N_A, N_B, and N_X). Since $d(P_{N_Y}, P_{N_D}) < d(P_{N_V}, P_{N_D})$, the GF algorithm is resumed at N_Y and the next hopping node will be selected as N_Z. The route from N_S to N_D can therefore be constructed for packet delivery. Moreover, if there does not exist a N_Y such that $d(P_{N_Y}, P_{N_D}) < d(P_{N_V}, P_{N_D})$ within the boundary traversal phase, the RUT scheme will be terminated after revisiting the edge E_{VA}. The result indicates that there does not exist a routing path between N_S and N_D.

IV. Proof of Correctness

Fact 1. *A simple closed curve is formed by traversing a point on the border of a closed filled two-dimensional geometry.*

Lemma 1. *All the SPs within the RUT scheme form the border of the resulting shape by overlapping the closed disks* $\overline{D}(P_{N_i}, R/2)$ *for all* $N_i \in \mathbf{N}$*, and vice versa.*

Proof: Based on Definitions 2 and 3, the set of SPs can be obtained as $\mathbf{S} = \mathbf{R_1} \cap \mathbf{R_2} = \{\boldsymbol{s}_i \mid \|\boldsymbol{s}_i - P_{N_i}\| = R/2, \exists N_i \in \mathbf{N}, \boldsymbol{s}_i \in \mathbb{R}^2\} \cap \{\boldsymbol{s}_j \mid \|\boldsymbol{s}_j - P_{N_j}\| \geq R/2, \forall N_j \in \mathbf{N}, \boldsymbol{s}_j \in \mathbb{R}^2\}$ by adopting the (i) and (ii) rules within Definition 2. On the other hand, the border of the resulting shape from the overlapped closed disks $\overline{D}(P_{N_i}, R/2)$ for all $N_i \in \mathbf{N}$ can be denoted as $\boldsymbol{\Omega} = \mathbf{Q_1} - \mathbf{Q_2} = \bigcup_{N_i \in \mathbf{N}} C(P_{N_i}, R/2) - \bigcup_{N_i \in \mathbf{N}} D(P_{N_i}, R/2)$, where $C(P_{N_i}, R/2)$ and $D(P_{N_i}, R/2)$ represent the circle and the open disk centered at P_{N_i} with a radius of $R/2$ respectively. It is obvious to notice that $\mathbf{R_1} = \mathbf{Q_1}$ and $\mathbf{R_2} = \mathbf{Q_2'}$, which result in $\mathbf{S} = \boldsymbol{\Omega}$. It completes the proof. □

Lemma 2. *A simple closed curve is formed by the trajectory of the SPs.*

Proof: Based on Lemma 1, the trajectory of the SPs forms the border of the overlapped closed disks $\overline{D}(P_{N_i}, R/2)$ for all $N_i \in \mathbf{N}$. Moreover, the border of a closed filled two-dimensional geometry is a simple closed curve according to Fact 1. Therefore, a simple closed curve is constructed by the trajectory of the SPs, e.g. the solid flower-shaped closed curve as in Fig 2. It completes the proof. □

Theorem 1. *The Boundary Finding Problem (Problem 2) is resolved by the RUT scheme.*

Proof: Based on Lemma 2, the RUT scheme can draw a simple closed curve by rotating the rolling balls $RB_{N_i}(\boldsymbol{s}_i, R/2)$ hinged at P_{N_i} for all $N_i \in \mathbf{N}$. The closed curve can be divided into segments $S(\boldsymbol{s}_i, \boldsymbol{s}_j)$, where $\boldsymbol{s}_i$ is the starting SP associated with N_i; and $\boldsymbol{s}_j$ is the anchor point while rotating the $RB_{N_i}(\boldsymbol{s}_i, R/2)$ hinged at P_{N_i}. The segments $S(\boldsymbol{s}_i, \boldsymbol{s}_j)$ can be mapped into the unidirectional edges $E_{ij} = (P_{N_i}, P_{N_j})$ for all $N_i, N_j \in \mathbf{U}$, where $\mathbf{U} \subseteq \mathbf{N}$. Due to the one-to-one mapping between $S(\boldsymbol{s}_i, \boldsymbol{s}_j)$ and E_{ij}, a simple unidirectional ring is constructed by E_{ij} for all $N_i, N_j \in \mathbf{U}$.

According to the RUT scheme, there does not exist any $N_i \in \mathbf{N}$ within the area traversed by the rolling balls, i.e. inside the light blue region as in Fig. 2. For all $N_p \in \mathbf{N}$ located inside the simple unidirectional ring, the smallest distance from N_p to N_q, which is located outside of the ring, is greater than the SN's transmission range R. Therefore, there does not exist any $N_p \in \mathbf{N}$ inside the simple unidirectional ring that can communicate with $N_q \in \mathbf{N}$ located outside of the ring. Based on Definition 1, the set $\mathbf{U}$ is identical to the Boundary Set, i.e. $\mathbf{U} = \mathbf{B}$. It completes the proof. □

Theorem 2. *The Void Problem (Problem 1) is solved by the GAR protocol with guaranteed packet delivery.*

Proof: With the existence of the void problem occurred at the Void Node N_V, the RUT scheme is utilized by initiating a SP $(\boldsymbol{s}_V)$ with the rolling ball $RB_{N_V}(\boldsymbol{s}_V, R/2)$ hinged at N_V. The RUT scheme within the GAR protocol will conduct Boundary (i.e. the set $\mathbf{B}$) traversal under the condition that $d(P_{N_i}, P_{N_D}) \geq d(P_{N_V}, P_{N_D})$ for all $N_i \in \mathbf{B}$. If the Boundary within the underlying network is completely traveled based on Theorem 1, it indicates that the SNs inside the Boundary (e.g. N_V) is not capable of communicating with those located outside of the Boundary (e.g. N_D). The result shows that there does not exist a route from the Void Node (N_V) to the destination node (N_D), i.e. the existence of network partition. On the other hand, if there exists a N_Y such that $d(P_{N_Y}, P_{N_D}) < d(P_{N_V}, P_{N_D})$ (as shown in Fig. 1), the GF scheme will be adopted within the GAR protocol to conduct data delivery toward the destination node N_D. Therefore, the GAR protocol solves the void problem with guaranteed packet delivery, which completes the proof. □

V. Conclusion

In this letter, the Greedy Anti-Void Routing (GAR) protocol is proposed to completely resolve the void problem incurred by the conventional Greedy Forwarding (GF) algorithm. The Rolling-ball UDG boundary Traversal (RUT) scheme is adopted within the GAR protocol to solve the boundary finding problem, which results in the guarantee of packet delivery. Finally, the correctness of the RUT and the GAR algorithms are properly proved.

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