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Efficient Broadcasting with Guaranteed Coverage in Mobile Ad Hoc Networks

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***Abstract*—In wireless networks comprised of numerous mobile stations, the *routing* problem of finding paths from a traffic source to a destination through a series of intermediate forwarding nodes is particularly challenging. Some of the current research works cannot fully resolve the void problem, while there exists other schemes that can guarantee the delivery of packets with the excessive consumption of control overhead. The unreachability problem (i.e. the so called void problem) that exists in the greedy routing algorithm in wireless sensor networks. In this paper, a greedy anti void routing (GAR) protocol is proposed to solve the void problem with increased routing efficiency by exploiting the boundary finding technique for the unit disk graph (UDG). The proposed RUT is employed to completely guarantee the delivery of packets from source to destination node under the UDG network. The Boundary Mapping (BM) and Indirect Map Searching (IMS) schemes are proposed as efficient algorithms for the realization of the RUT technique. Comparing with the existing localized routing algorithms the simulation result shows that the proposed GAR based protocols can provide better routing efficiency**

Index Terms- Greedy Routing, Void Problem, Localized Algorithms, Wireless Sensor Networks

1. 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 multihop 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) algorithm [2] is considered a superior scheme with its low routing over-heads. However, the void problem [3], which makes the GF technique unable to find its next closer hop to the destination, will cause the GF algorithm failing to guarantee the delivery of data packets. The network flooding mechanism is adopted within the GRA and PSR schemes while the void problem occurs. There also exist routing protocols that adopt the backtracking method at the occurrence of the network holes (such as GEDIR[4], DFS[5], and SPEED [6]). The routing schemes as proposed by ARP[7] and LFR[8] memorize the routing path after the void problem takes place. Moreover, other routing protocols (such as PAGER, NEAR, DUA, INF, and YAGR) propagate and update the information of the observed void node in order to reduce the probability of encountering the void problem.

Several routing schemes as surveyed in adopt the planar graph derived from the unit disk graph (UDG) as their network topologies. For conducting the above planar graph-based algorithms, the planarization technique is required to transform the underlying network graph into the planar graph. The Gabriel graph (GG) [9] and the relative neighborhood graph (RNG) [10] are the two commonly used localized planarization techniques that abandon some communication links from the UDG for achieving the planar graph. Nevertheless, the usage of the GG and RNG graphs has significant pitfalls due to the removal of critical communication links, leading to longer routing paths to the destination. As shown in Fig. 1, the nodes (N_S,N_D) are considered the transmission pair, while NV represents the node that the void problem occurs.

The representative planar graph-based GPSR scheme cannot forward the packets from N_V to N_A directly since both the GG and the RNG planarization rules abandon the communication link from N_V to N_A. Considering the GG planarization rule for example, the communication link from N_V to N_A is discarded since both N_J and N_K are located within the forbidden region, which is defined as the smallest disk passing through both N_V and N_A. Therefore, based on the right-hand rule, the resulting path by adopting the GPSR protocol can be obtained as (N_S,N_V,N_J ,N_K,N_A,N_B,N_X,N_Y ,N_Z,N_D). The two unnecessary forwarding nodes N_J and N_K are observed, as in Fig. 1.

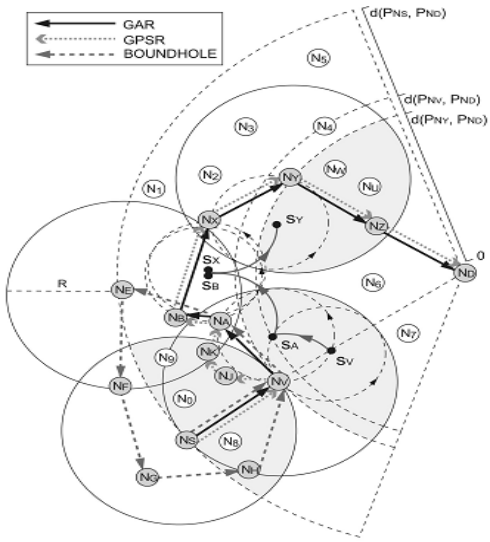

Fig. 1. Routing paths are constructed using the GAR, the GPSR, and the BOUNDHOLE algorithms for the existence of the void problem.

In this paper, a greedy anti-void routing (GAR) protocol is proposed to guarantee packet delivery with increased routing efficiency by completely resolving the void problem based on the UDG setting. The GAR protocol is designed to be a combination of both the conventional GF algorithm and he proposed rolling-ball UDG boundary traversal (RUT) scheme. The GF scheme is executed by the

GAR algorithm without the occurrence of the void problem, while the RUT scheme is served as the remedy for resolving the void problem, leading to the assurance for packet delivery. Moreover, the correctness of the proposed GAR protocol is validated via the given proofs. The implementation of the GAR protocol is also explained, including that for the proposed boundary map (BM) and the indirect map searching (IMS) algorithm for the BM construction.

The performance of the proposed GAR protocol and the version with the enhanced mechanisms (denoted as the GAR-E algorithm) is evaluated via simulations under both the UDG network for the ideal case and the non-UDG setting for realistic scenario. The simulation results show that the GAR-based schemes can both guarantee the delivery of data packets and pertain better routing performance under the UDG network.

II. PROBLEM DEFINATION

Considering a set of SNs N ={N_i │$\forall_j$} within a two-dimensional (2D) Euclidean plane, the locations of the set N, which can be acquired by their own positioning systems, are represented by the set P ={P_{Ni} │P_{Ni}= (xN_i,yN_i),$\forall$ i }. It is Considering a set of SNs N ={N_i│$\forall_j$} within a two-dimensional (2D) Euclidean plane, the locations of the set N, which can be acquired by their own positioning systems, are represented by the set P ={P_{Ni}│P_{Ni}= (xN_i ,yN_i),$\forall$ i }. It is assumed that all the SNs are homogeneous and equipped with omnidirectional antennas. The set of closed disks defining the transmission ranges of N is denoted as D ={D(P_{Ni} ,R)│ $\forall$ i },where D(P_{Ni} ,R)={x│‖x-P_{Ni}‖≤ R,$\forall$ x€ IR^2}. It is noted that P_{Ni} is the center of the closed disk with R denoted as the radius of the transmission range for each Ni. Therefore, the network model for the WSNs can be represented by a UDG as G(P,E) with the edge set E ={E_{ij}│E_{ij}=(P_{Ni},P_{Nj}),PNi€ D(PN_j,R),$\forall$ i ≠ j. The edge E_{ij} indicates the unidirectional link from P_{Ni} to P_{Nj} whenever the position P_{Ni} is within the closed disk region D (P_{Nj} ;R). Moreover, the one-hop neighbor table for each Ni is defined as

$$\mathbf{T}_{N_i} = \{[ID_{N_k}, P_{N_k}] \mid P_{N_k} \in \overline{D}(P_{N_i}, R), \forall\, k \neq i\},$$

Where ID_{Nk} represents the designated identification number for N_k. In the GF algorithm, it is assumed that the source node NS is aware of the location of the destination node N_D. If NS wants to transmit packets to N_D, it will choose the next hop node from its N_S which 1) has the shortest Euclidean distance to N_D among all the SNs in TNS and 2) is located closer to N_D compared to the distance between NS and N_D (e.g., N_V , as in Fig. 1). The same procedure will be performed by the intermediate nodes (such as N_V) until ND is reached. However, the GF algorithm 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 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 no neighbor of N_V is closer to the destination as

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

where d(x, y) represents the Euclidean distance between x and y. T_{NV} is the one-hop neighbor table of N_V .

III. GREEDY ANTI-VOID ROUTING (GAR) PROTOCOL

The objective of the GAR protocol is to resolve the void problem such that the packet delivery from NS to ND can be guaranteed. Before diving into the detail formulation of the proposed GAR algorithm, an introductory example is described in order to facilitate the understanding of the GAR protocol. As shown in Fig. 1, the data packets initiated from the source node N_S to the destination node N_D will arrive in N_V based on the GF algorithm. The void problem occurs as N_V receives the packets, which leads to the adoption of the RUT scheme as the forwarding strategy of the GAR protocol. A circle is formed by centering at s_V with its radius being equal to half of the transmission range R=2. The circle is hinged at NV and starts to conduct counterclockwise rolling until an SN has been encountered by the boundary of the circle, i.e., N_A, as in Fig. 1. Consequently, the data packets in N_V will be forwarded to the encountered node NA. Subsequently, a new equal-sized circle will be formed, which is centered at s_A and hinged at node N_A. The counterclockwise rolling procedure will be proceeded in order to select the next hop node, i.e., N_B in this case. Similarly, same process will be performed by other intermediate nodes (such as N_B and N_X) until the node N_Y is reached, which is considered to have a smaller distance to N_D than that of N_V to N_D. The conventional GF scheme will be resumed at N_Y for delivering data packets to the destination node N_D. As a consequence, the resulting path by adopting the GAR protocol becomes {N_S, NV, NA, N_B, NX, NY, NZ, ND}.

A. Rolling-Ball UDG Boundary Traversal (RUT) Scheme:

The RUT scheme is adopted to solve the boundary finding problem, and the combination of the GF and the RUT scheme (i.e., the GAR protocol) can resolve the void problem, leading to the guaranteed packet delivery. The definition of boundary and the problem statement are described as follows:

Boundary finding problem: Given a UDG G(P,E) and the one-hop neighbor tables T={T_{Ni}│$\forall$ N_i€ 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) Initialization Phase

Rolling Ball: Given N_i€ N, a rolling ball RB_{Ni}(s_i, R/2) is defined by 1) a rolling circle hinged at P_{Ni} with its center point at s_i€ IR^2 and the radius equal to R/2, and 2) there does not exist any N_k€ N located inside the rolling ball as

(RB $_{Ni}$ (s_i,R/2) N} = Ø, where RB Ni ðsi;R=2Þ de- notes the open disk within the rolling ball.

Starting point: The SP of Ni within the RUT scheme the center point si€ IR^2 of RB_{Ni}(si,R/2).

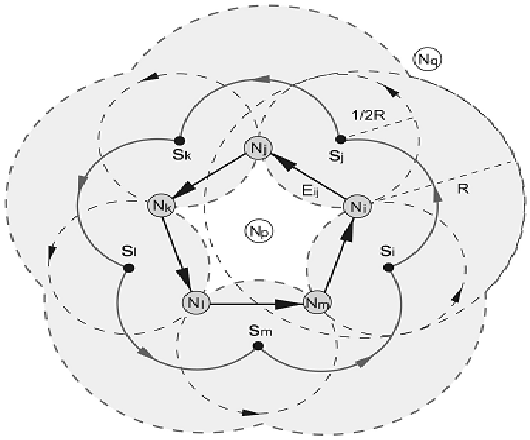

Fig.2.R UT scheme.

Starting point: The SP of N_i within the RUT scheme the center point s_i€ IR^2 of R B_{Ni} (s_i, R/2). In Fig. 2, each node N_i can verify if there exists an SP since the rolling ball RB_{Ni} (s_i, R/2) is bounded by the transmission range of N_i. According to the SPs should be located on the circle centered at P_{Ni} with a radius of R/2. As will be proven 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 an SP, while the void problem occurs within the network.

2) Boundary Traversal Phase

Given si as the SP associated with its RB_{Ni}(s_i,R/2)hinged at N_i, either the counterclockwise or clockwise rolling direction can be utilized. As shown in Fig. 2RB_{Ni} (s_i, R/2) is rolled counterclockwise until the next SN is reached (i.e., $N_j$in Fig. 2). The unidirectional edge E_{ij}=(P_{Ni},P_{Nj}) can therefore be constructed. A new SP and the corresponding rolling ball hinged at N_j(i.e., s_j and RB_{Ni} (s_i, R/2)) will be assigned, and consequently, the same procedure can be conducted continuously.

3) 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 B ={N_i,N_j,N_k,N_l,N_m}.

B. Description of 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 NV as the next hop node by adopting the GF algorithm. However, the void problem prohibits NV to continue utilizing the same GF algorithm for packet forwarding. The RUT scheme is therefore employed by assigning an SP (i.e., s_V) associated with the rolling ball RB_{NV} (s_V ,R/2) hinged at N_V . As illustrated in Fig. 1, s_V can be chosen to locate on the connecting line between N_V and N_D with R/2away from N_V. The GF algorithm is resumed at N_Y , and the next hop node will be selected as N_Z. The route from NS to ND can therefore be constructed for packet delivery. Moreover, if there does not exist a node NY such that d(P_{NY} ;P_{ND})<d(P_{NV} ;P_{ND}) 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 NS and ND.

C. Proof of Correctness

In this section, the correctness of the RUT scheme is proven in order to solve Problem 2, while the GAR protocol is also proven for resolving the void problem (i.e., Problem 1) in order to guarantee packet delivery.

Lemma 1. All the SPs within the RUT scheme form the border of a shape that results from overlapping the closed disks D(P_{Ni},R/2) for all N_i€ N, and vice versa.

Proof: Based on Definitions 2 and 3, the set of SPs can be obtained as S=R1 ∧R2 ={s_i││s_i-P_{Ni}││ =R/2,∃ N_i€ N,si€ IR^2 }∧{s_j││s_j-P_{Nj}││ ≥R/2,∀N_j€ N s_j€ IR^2} by adopting the 1) and 2) rules within Definition 2. On the other hand, the border of the resulting shape from the overlapped closed disks D{P_{Ni} ,R/2} for all Ni € N can be denoted as Ω=Q1- Q2 =$U_{Ni€N}$ C(P_{Ni} ,R/2)- NU $_{Ni€N}$D(P_{Ni} ,R/2) where C(PNi,R/2)and D(P_{Ni}, R/2)represent the circle and the open disk centered at P_{Ni} with a radius of R/2, respectively. It is obvious to notice that R1 = Q1 and R2 = Q 2, which result in S=Ω .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 D(P_{Ni},R/2) for all Ni € N. Moreover, the border of a closed filled 2D geometry is a simple closed curve. 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 simple closed curve by rotating the rolling balls RB_{Ni}(si,R/2) hinged at P_{Ni} for all N_i €N. The closed curve can be divided into arc segments S(s_i,s_j),where $s_i$is the starting SP associated with N_i, and s_j is the anchor point while rotating the RB_{Ni} (s_i,R/2) hinged at P_{Ni}. The arc segments S (s_i; s_j) can be mapped into the unidirectional edges for all N_i , N_j€ U where U N. Due to the one -to -one mapping between S(S_i, S_j) and E_{ij} a simple unidirectional ring is constructed by E_{ij} for all N_i, N_j€ U.*Theorem 2***.**The void problem (Problem 1) in UDGs 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 an SP (s_V) with the rolling ball RB_{NV} (s_V,R/2) hinged at N_V . The RUT scheme within the GAR protocol will conduct boundary (i.e., the set B) traversal under the condition that $d(P_{Ni},P_{ND}) \geq d(P_{NV}, P_{ND})$ for all $N_i €B$. Boundary within the underlying network is completely traveled based on Theorem 1, it indicates that the SNs inside the boundary (e.g., N_V)are 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 node N_Y such that $d(P_{NY},P_{ND}) < d(P_{NV}, P_{ND})$ (as shown in Fig. 1), the GF algorithm 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.

IV. REALIZATION of GAR PROTOCOL

The implementation of the proposed GAR protocol is explained in this section. The format of the one-hop neighbor table T_{Ni} , as defined in (1), is realized for the implementation purpose. T_{Ni} is considered a major information source the localized routing protocols, which can be obtained via the neighbor information acquisition [29]. It is noticed that the one-hop neighbor for packet transmission.

A. Implementation of GF Scheme

The GF scheme is considered a straightforward algorithm that only requires the implement ation of the one-hop neighbor table T_{Ni}. The next hop node can be found by the linear search of T_{Ni}if the void problem does not occur;

B. Implementation of RUT Scheme

1) Concept of Boundary Map

A new parameter called BM (denoted as M_{Ni} for each N_i) is introduced in this section. Moreover, the BM M_{Ni} is mainly derived from the one-hop neighbor table T_{Ni} via the IMS method, as shown in Algorithm 1. Instead of diving into the IMS algorithm, the functionality of M_{Ni} is first explained. The purpose of the BM M_{Ni} is to provide a set of direct mappings between the input SNs and their corresponding output SNs with respect to Ni. Based on Theorem 1, the two adjacent communication links formed by the input node, the node N_i, and the corresponding output node within the RUT scheme consist part of the network boundary. Therefore, the direct mappings between the input SNs and their corresponding output SNs with respect to N_i lead to the so called BM. An example is shown in Fig. 3 to illustrate the functionality of M_{Ni}. Based on Definition 2, the rolling balls hinged at N_i can be constructed by rotating the dashed circle counterclockwise from N_1 to N_2. The SPs associated with the rolling balls (from Definition 3) result in the arc segment $S^{SP}_{Ni}(P^L_1 ;P^R_2)$ between the endpoints P^L_1 and P^R_2 ,i.e., the dashed arc segment, as in Fig. 3. Similarly, the arc segment $S^{SP}_{Ni}(P^L_2 ;P^R_3)$ can be constructed by rotating the rolling balls (hinged at N_i) counterclockwise from N_2 to N_3.

Algorithm 1: *Indirect Map Searching Algorithm*

```
Data: R, P_{N_i}, T_{N_i}
Result: M_{N_i}, L_{N_i}
begin
    M_{N_i} ← null
    L_{N_i} ← null
    if T_{N_i} ≠ ∅ then
        foreach (id_{N_j}, P_{N_j}) ∈ T_{N_i} do
            compute S^{SP}_{N_i∘N_j}(P_A, P_B) by R, P_{N_i}, and P_{N_j}
            Ψ(P_A) ←
            [id_{N_j}, RIGHT, angle(P_A, P_{N_i}), FALSE, Ψ(P_B)]
            Ψ(P_B) ←
            [id_{N_j}, LEFT, angle(P_B, P_{N_i}), FALSE, Ψ(P_A)]
            wrap and insert Ψ(P_A) and Ψ(P_B) into L_{N_i}
        end
        sort(L_{N_i})
        foreach ℓ_A ∈ L_{N_i} and ℓ_A.flag() = RIGHT do
            ℓ_B ← ℓ_A.counterpart()
            foreach ℓ_C ∈ L_{N_i} located between [ℓ_A, ℓ_B] do
                set Color for ℓ_C
            end
        end
        foreach ℓ_B ∈ L_{N_i} and ℓ_B.flag() = LEFT do
            if ℓ_B.color() = FALSE then
                ℓ_C ← ℓ_B.next()
                while ℓ_C.flag() = LEFT do
                    ℓ_C ← ℓ_C.next()
                end
                get the SNs N_B and N_C from ℓ_B and ℓ_C
                create the direct mapping from N_B to N_C
                insert the mapping N_B → N_C into M_{N_i}
            end
        end
    end
end
```

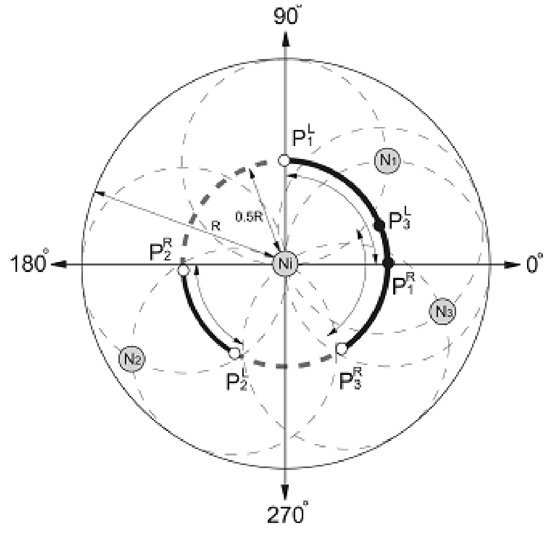

Fig. 3. Shows the SP and non SP arc segments with respect to Niand the resulting BM.

*Definition 4 (SP and non-SP arc segments).*Given an $SNN_i € N$ and a pair of points (P_A, P_B) on the circle (centered at P_{Ni} with a radius of R/2), an SP arc segment $S^{SP}_{Ni}(P_A,P_B)$ ofN_i is defined by the arc from P_A to P_B counterclockwise where all points on this arc segment are SPs. Likewise, a non-SP arc segment $S^{SP}_{Ni}(P_A,P_B)$ of N_i is defined by the endpoint excluding arc from P_A to P_B counter clockwise, where all points on this arc segment are not SPs.

*Definition 5 (converged SP and non-SP arc segments).*Given an SP arc segment $S^{SP}_{Ni}(P_A,P_B)$, it is regarded as a converged SP arc segment if there does not exist any SP arc segment $S^{SP}_{Ni}(P_J,P_K)$ such that $S^{SP}_{Ni}(P_A,P_B)$ $S^{SP}_{Ni}(P_J,P_K)$.Similarly, a non-SP arc segment $S^{SP}_{Ni}(P_A,P_B)$ is considered as a converged non-SParc segment if there exists no other non-SP arc segment $S^{SP}_{Ni}(P_J ,P_K)$ such that $S^{SP}_{Ni}(P_A,P_B)$ $S^{SP}_{Ni}(P_J ;P_K)$.

It is noticed that the converged arc segments are defined to represent the combined arc segments, e.g., the converged non-SP arc segment $S^{SP}_{Ni}(P^R_3 ,P^L_1)$ is formed by overlapping the non-SP segments $S^{SP}_{Ni}(P^R_3 ,P^L_3)$ and $S^{SP}_{Ni}(P^R_1 ,P^L_1)$,as shown in Fig. 3. As will be proven in Theorem 3, all incoming packets to N_i that are acquired from its neighbor node N_1 (which induces the rightmost endpoint P^L_1 of the converged SP arc segment $S^{SP}_{Ni}(P^L_1 ;P^R_2)$will be forwarded to its neighbor node N_2 (which results in the leftmost endpointP^R_2 of the same converged SP arc segment) under the counterclockwise rolling direction. There exist two converged SP arc segments $S^{SP}_{Ni}(P^L_1 ;P^R_2)$ and $S^{SP}_{Ni}(P^L_2 ;P^R_3)$, where $S^{SP}_{Ni}(P^L_1 ;P^R_2)$ is constructed by the input SN N_1 and the corresponding output SN N_2 and $S^{SP}_{Ni}(P^L_2 ,P^R_3)$ is established by the input N_2 and the output N_3. As a result, the BM with respect to N_i can be obtained as $M_{Ni}=\{(N_1\rightarrow N_2),(N_2\rightarrow N_3)\}$. Therefore, all packets from N_1 will be forwarded to N_2, while those fromN_2 will be relayed to N_3 according to the BM.

2) Construction of Boundary Map

Definition 6 (neighbor-related non-SP arc segment). Anon-SP arc segment $S^{SP}_{Ni}(P_A,P_B)$ of Ni is given. If there exists N_j€ N as a neighbor node of N_i such that an arc segment of $C(P_{Ni},R/2)$ that lies inside the closed disk $D(P_{Nj},R/2)$ is identical to $S^{SP}_{Ni}(P_A,P_B)$, this segment $S^{SP}_{Ni}(P_A,P_B)$ is called a neighbor-related non-SP arc segment $S^{SP}_{NioNj}(P_A,P_B)$,distinguished by N_j.Two properties that are related to the SP and non-SP arc segments are described as follows:

*Property 1***.** The circle $C(P_{Ni},R/2)$ centered at P_{Ni} with a radius of R/2 is entirely composed by all the converged SP and non-SP arc segments of Ni.

Proof. Based on Definitions 2 and 3, it can be observed that each point on the circle $C(P_{Ni},R/2)$ must either be an SPor a non-SP. A number of adjacent SPs on $C(P_{Ni},R/2)$will establish an SP arc segment with respect to N_i; while there must exist the largest number of adjacent SPs such that the underlying SP arc segment is a converged SP arc segments with respect to N_i. Therefore, all the adjacent SPs on $C(P_{Ni},R/2)$ will result in converged SP arc segments with respect to N_i. Similarly, all the adjacent on-SPs on $C(P_{Ni},R/2)$ must be aggregated into converged non-SP arc segments with respect to Ni. On the other hand, the circle $C(P_{Ni},R/2)$ is entirely composed by the SPs and non-SPs corresponding to Ni. Consequently, all the converged SP and non-SP arc segments of Ni will construct the entire circle $C(P_{Ni};R/2)$.

Property 2. The union of all the neighbor-related non-SP arc segments with respect to Ni is equivalent to the union of all the converged non-SP arc segments with respect to Ni.

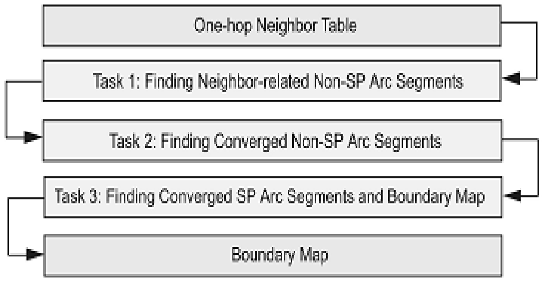

Fig. 4. The process flow of the IMS algorithm

*Proof***.** This property will be proven by contradiction as follows: It is assumed that the union of all the neighbor related non-SP arc segments corresponding to N_i is not equivalent to the union of all the converged non-SP arc segments with respect to N_i. Based on Definitions 4 and 5,and Property 1, it is stated that all the converged non-SP arc segments with respect to N_i result in the union of all the non-SPs on $C(P_{Ni},R/2)$. Therefore, there must exist anon-SP PJ located on $C(P_{Ni},R/2)$ such that it does not relate to any neighbor-related non-SP arc segments with respect to Ni, i.e., there does not exist any Nk 2 TNithatlies inside the rolling ball RBN_i(PJ ,R/2). However, based on Definitions 2 and 3, there should exist at least a node N_k within the rolling ball $RBN_i(P_J ,R/2)$ since P_J is a non-SP on $C(P_N,R/2)$.Table 1 summarizes the notations in the IMS algorithm, and the pseudo code of the IMS method, as shown in Algorithm 1, is explained as follows: Based on that in Fig. 4,the first task within the IMS algorithm is to identify each neighbor-related non-SP arc segment $S^{SP}_{Ni}N_j(P_A;P_B)$ with respect to N_i that is distinguished by its neighbor N_j. Intuitively, it is feasible to utilize the two endpoints P_A and P_B to represent S^{SP}_{Ni} $N_j(P_A;P_B)$, where each endpoint Pfor 2€ {A,B} can be characterized by an endpoint entry defined as $\Psi_{N_i}(P_\zeta) = [Id, Flag, Angle, Color, Counterpart]$.

TATBL I
NOTATION FOR IMS ALGORITHM

Notation	Description
R	Maximum Communication Distance
P_{N_i}	Position of N_i
$\mathbf{T}_{N_i}$	One-hop Neighbor Table of N_i
$\mathbf{M}_{N_i}$	Boundary Map of N_i
$\mathbf{L}_{N_i}$	Circular Doubly-linked List of N_i
(id_{N_j}, P_{N_j})	ID and Position of a Neighbor N_j
$S^{\overline{SP}}_{N_i \circ N_j}(P_A, P_B)$	Neighbor-related Non-SP Arc Segment
$\Psi(P_A), \Psi(P_B)$	Endpoint Entries of $S^{\overline{SP}}_{N_i \circ N_j}(P_A, P_B)$
ℓ_A, ℓ_B, ℓ_C	List Items of $\mathbf{L}_{N_i}$

The parameter Id is utilized as the identification number of the corresponding neighbor SN for this entry. Flag represents the endpoint type of this entry, which is denoted as either RIGHT or LEFT (e.g., the Flag field of the right endpoint P_A is denoted as RIGHT, while that of the left endpoint P_B is indicated as LEFT). The Angle field is adopted to represent the polar angle with respect to Ni by rotating counterclockwise from the x-axis. The Color field is employed to indicate whether the endpoint Pis a non-SPor not (i.e., Color = TRUE denotes that Pis a non-SP). The Counterpart field provides the linkage to the counterpart endpoint entry that possesses the opposite Flag value (e.g.,the counterpart of$\Psi N_i(P_A)$isΨNi(PB), and vice versa).Therefore, the neighbor-related non-SP arc segment S^{SP}_{Ni} N_j(PA;PB) can be denoted by a pair of the endpoint entries as $\Psi_{Ni}(P_A),\Psi_{Ni}(P_B)$

C. Proof of Correctness

Theorem 3. Given a converged SP arc segment $S^{SP}_{Ni}(P_S,P_T)$with respect to N_i, where 1) the rightmost endpoint P_S is an SP for both N_i and its neighbor N_S, and 2) the leftmost endpoint P_T is an SP for both N_i and its neighbor N_T ,respectively. All incoming packets to Ni that are acquired from its neighbor node NS will be forwarded to $N_{T.}$

Proof. Based on Definitions 4 and 5, a converged SP arc segment $S^{Sp}_{Ni}(P_S,P_T)$ is an arc segment composed by some of the SPs with respect to Ni. According to Lemma 2, a simple closed curve is constructed by the trajectory of the SPs. In order to form the closed curve, there must exist other converged SP arc segments contributed by other SNs that are connected to the endpoints P_S and P_T . In other words, the endpoints P_S and P_T must also be owned by one of N_i's neighbor, respectively. On the contrary, the other points on this converged SP arc segment $S^{SP}_{Ni}(P_S,P_T)$ should only be contributed by N_i based on Definitions 2 and 3. Moreover, it is intuitive to observe (from Definition 3) that the distances between the SNs related to the same endpoints (i.e., either P_S or P_T) must be located in their transmission ranges. By adopting the RUT scheme (as stated in Theorems 1 and 2) starting from N_S, the rolling ball will be traversed counterclockwise via N_i to N_T .This corresponds to the situation that all the packets coming from N_S to N_i will be forwarded to N_T .It completes the proof.

V. CONCLUSION

In this paper, a UDG-based GAR protocol is proposed to resolve the void problem incurred by the conventional GF algorithm. The RUT scheme is adopted within the GAR protocol to solve the boundary finding problem, which results in guaranteed delivery of data packets under the UDG networks. The BM and the IMS are also proposed to conquer the computational problem of the rolling mechanism in the RUT scheme, forming the direct mappings between the input/output nodes. The correctness of the RUT scheme and the GAR algorithm is properly proven. The performance of the GAR protocols is evaluated and compared with existing localized routing algorithms via simulations. The simulation study shows that the proposed GAR algorithms can guarantee the delivery of data packets under the UDG network.

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