Telecommun Syst
DOI 10.1007/s11235-009-9227-0

TPGF: geographic routing in wireless multimedia sensor networks

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Abstract In this paper, we propose an efficient Two-Phase geographic Greedy Forwarding (TPGF) routing algorithm for WMSNs. TPGF takes into account both the requirements of real time multimedia transmission and the realistic characteristics of WMSNs. It finds one shortest (near-shortest) path per execution and can be executed repeatedly to find more on-demand shortest (near-shortest) node-disjoint routing paths. TPGF supports three features: (1) hole-bypassing, (2) the shortest path transmission, and (3) multipath transmission, at the same time. TPGF is a pure geographic greedy forwarding routing algorithm, which does not include the face routing, e.g., *right/left hand rules*, and does not use planarization algorithms, e.g., GG or RNG. This point allows more links to be available for TPGF to explore more routing paths, and enables TPGF to be different from many existing geographic routing algorithms. Both theoretical analysis and simulation comparison in this paper indicate that TPGF is highly suitable for multimedia transmission in WMSNs.

Keywords Multimedia sensor networks · Geographic routing · Multipath transmission · Realistic conditions

The work presented in this paper was supported by the Lion project supported by Science Foundation Ireland under grant no. SFI/02/CE1/I131.

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1 Introduction

Efficiently transmitting multimedia streams in wireless multimedia sensor networks (WMSNs) is a significant challenging issue, due to the limited transmission bandwidth and power resource of sensor nodes. Three recent surveys [1–3] on multimedia communication in WMSNs shows that current existing protocols in both multimedia and sensor networks fields are not suitable for multimedia communication in WMSNs, because they do not have enough consideration on the characteristics of multimedia streaming data and natural constrains of sensor networks at the same time. These three surveys also expatiated that there is no solution focusing on addressing the routing problem of multimedia streaming in geographic WMSNs.

Generally, multimedia transmission in WMSNs should consider the following three requirements:

- *Multipath transmission*: Packets of multimedia streaming data generally are large in size and the transmission requirements can be several times higher than the maximum transmission capacity (bandwidth) of sensor nodes. This

Published online: 05 November 2009

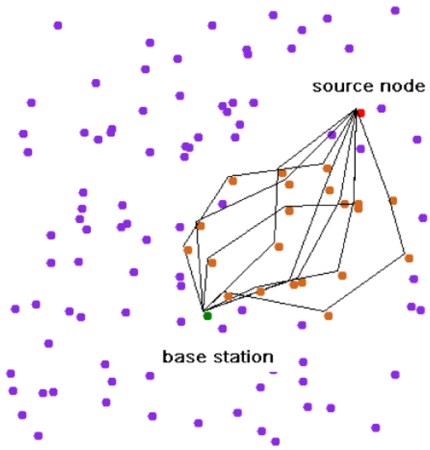


Fig. 1 *Dynamic Hole*. A *Dynamic Hole* can be formed by a group of sensor nodes in the eight existing routing paths because these nodes are overloaded and cannot be used for forming other routing paths

requires that multipath transmission should be used to increase transmission performance in WSNs [4].

- *Hole-bypassing*: *Dynamic holes* may occur if several sensor nodes in a small area overload due to the multimedia transmission, e.g., Fig. 1. Efficiently bypassing these *dynamic holes* is necessary for transmission in WSNs.
- *Shortest path transmission*: Multimedia applications generally have a delay constraint, which requires that the multimedia streaming in WSNs should always use the shortest routing path, which has the minimum end-to-end transmission delay.

Multimedia transmission in WMSNs requires a new routing algorithm that can support all these three requirements at the same time. This paper proposes a new Two-Phase geographic Greedy Forwarding (TPGF) routing algorithm for exploring one or multiple shortest (near-shortest) hole-bypassing transmission paths in WMSNs. The first phase of TPGF is responsible for exploring the possible routing path. The second phase of TPGF is responsible for optimizing the found routing path with the least number of hops. TPGF can be executed repeatedly to find multiple on-demand *node-disjoint* routing paths. TPGF has the following primary features that make it be different from existing geographic routing algorithms [5–8].

- TPGF is a pure geographic greedy forwarding routing algorithm. It does not include the face routing concept, e.g., *right/left hand rules and count/clockwise angles*, which is different from many existing geographic forwarding routing algorithms, e.g., GPSR [5].
- TPGF does not require the computation and preservation of the planar graph in WMSNs. This point allows more links to be available for TPGF to explore more *node-disjoint* routing paths, since using the planarization algorithms actually limits the useable links for exploring possible routing paths.
- TPGF does not have the well-known *Local Minimum Problem* [5], which is defined as "a sensor node finds no next-hop node that is closer to the base station than itself".

Research work in this paper has made both theoretical and practical contributions to understand the geographic routing in WMSNs. The theoretical contributions are:

- It is proved that: there exists a geographic greedy forwarding routing algorithm (TPGF) that can guarantee packet delivery (bypassing holes) in any 2D/3D sensor networks without using the face routing method, when sensor nodes only know about their 1-hop neighbor nodes.
- It is proved that: there exists a geographic greedy forwarding routing algorithm (TPGF) that can find the shortest routing path (or near-shortest routing path when holes exist) for minimizing the end-to-end transmission delay, when the holes information is not identified in advance.

The practical contributions in this paper are as following four aspects:

- *Key novelty*: To the best of our knowledge, TPGF is the first pure geographic greedy forwarding routing algorithm that focuses on supporting multimedia streaming in WMSNs, which supports the following three features at the same time.
- *Supporting multipath transmission*: TPGF can find one routing path per execution and can be executed repeatedly to find more on-demand *node-disjoint* routing paths.
- *Supporting hole-bypassing*: TPGF provides a better solution for hole-bypassing in both 2D and 3D sensor networks than other related research work.
- *Supporting shortest path transmission*: TPGF can find the shortest routing path (or near-shortest routing path when holes exist) for minimizing the end-to-end transmission delay.

We believe that TPGF routing algorithm can make a significant impact on both mobile multimedia and wireless sensor networks (WSNs) research communities.

The rest of this paper is organized as follows: Sect. 2 presents the related work. Section 3 shows the network model and problem statement. Section 4 describes the algorithm and examples. Section 5 discusses the on-demand multipath transmission. Section 6 demonstrates simulation results, and Sect. 7 concludes this paper.

2 Related work

2.1 Related work on hole-bypassing in WSNs

A number of research works on hole-bypassing routing in WSNs have been conducted. These research works can be classified into: (1) Hole-bypassing without knowing the holes information but computing the planar graph in advance [5–8]; (2) Hole-bypassing with identifying the holes or boundary nodes information in advance [13–15].

Hole-bypassing without knowing the holes information but using planarization algorithms in advance: In [5], a greedy forwarding routing algorithm GPSR was proposed. A *Local Minimum Problem* was identified in this paper. Before meeting the *Local Minimum Problem*, in GPSR, a sensor node always chooses the next-hop node that is closer to the base station than itself. When it runs into a *Local Minimum Problem* in GPSR, the face routing (*Right Hand Rule*) is adopted to solve the problem. Several other algorithms in [6–8], e.g., GOAFR, GOAFR+, and GPVFR were proposed subsequently. All these algorithms adopted the face routing to bypass holes. The correctness of these routing algorithms in ideal *Gabriel Graph* (*GG*) [9] and *Relative Neighborhood Graph* (*RNG*) [10] is further proved in [11].

However, in [12], the authors reported that these geographic routing algorithms actually could not guarantee the delivery with arbitrary connectivity under realistic conditions, which include (1) Inaccurate location of sensor nodes, which can cause disconnection in planar graph by removing incorrect links; (2) Irregular radio range coverage, which can cause cross-links in planar graph. This report motivates a clear need for designing a new geographic routing algorithm to guarantee the packet delivery. Furthermore, the correct operation of the face routing requires the WSN to be considered as a planar graph [12]. Using the planarization algorithms, e.g., *GG* or *RNG*, can create a planar graph from a non-planar physical topology by selecting a subset of the links, which actually limits the useable links. However, in WMSNs, the number of usable links is not expected to be reduced since it has strong impact on the exploring result of multiple routing paths. It is clear that geographic face routing should not be an option for hole-bypassing in WMSNs, which further motivates the need for designing a new geographic routing algorithm for hole-bypassing.

Hole-bypassing with identifying the holes or boundary nodes information in advance: In [13, 14], the authors use graph theory to identify hole boundary nodes first, then use the knowledge of these identified boundary nodes to facilitate the hole-bypassing routing. Especially, in [14], every sensor node is requested to identify twice whether it is a first-class node or a second-class node, which will consume a lot of energy. The actual routing algorithm executes after identifying these first-class and second-class nodes. In [15], the authors try to find an optimized hole-bypassing routing path by using hole geometric modeling after knowing the information of holes in advance. In this paper the hole information is obtained by using the algorithm proposed in [13]. All these algorithms can work correctly for identifying *static holes* in WSNs, e.g., Fig. 2. A *static hole* can be formed by a set of dead sensor nodes due to energy exhaustion or damage.

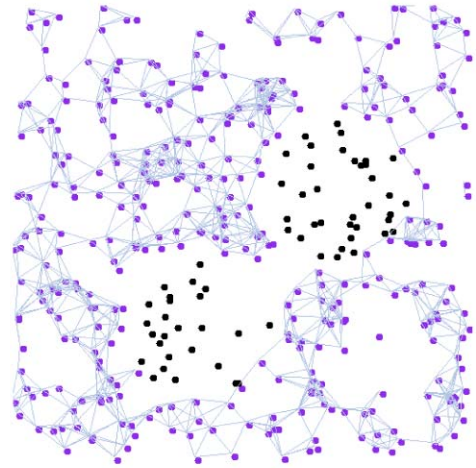


Fig. 2 *Static hole*. A *static hole* can be formed by a set of dead sensor nodes due to running out of energy or damage

However, holes in WMSNs are more likely to be dynamic. Due to the large size of multimedia streaming data packet, transmission in WMSNs will generally use the maximum transmission capacity of each path, which does not allow the sharing of transmission path. Any node that is transmitting multimedia streaming data can hardly be reused for forming another routing path. When additional routing paths are needed for increasing the transmission performance, each new routing path should bypass the *dynamic hole* formed by the nodes of previous routing paths, e.g., in Fig. 1, if the ninth routing path is needed, it should bypass the *dynamic hole* formed by the nodes of the previous eight routing paths. In other words, the routing path nodes can enlarge the holes, because these routing path nodes cannot be reused for forming other routing paths. Using the algorithms proposed in [13, 14] to identify the hole/boundary nodes information in WMSNs after forming each new routing path is inefficient.

2.2 Related work on geographic on-demand disjoint multipath routing in WSNs

Many multipath routing protocols have been studied in the field of wireless ad hoc & sensor networks [16].[1] However, most of the multipath routing protocols focus on energy efficiency, load balance, or fault tolerance in WSNs, and they are the extended versions of DSR [17] and AODV [18].

Only a few research works adopt the geographic information to facilitate the on-demand disjoint multipath routing in Ad Hoc networks and WSNs, e.g., [19, 20]. In [19], the authors proposed a Geography based Ad Hoc On demand Dis-

[1] Multipath routing in wireless ad hoc & sensor networks, http://snac.eas.asu.edu/snac/multipath/multipath.html, the latest access on March 13, 2008.

joint Multipath (GAODM) routing protocol in Ad Hoc networks. This GAODM uses the push-relabel algorithm [21] to convert the Ad Hoc network as a flow network. The focus of this research work is how to use the push-relabel algorithm to find multiple node/edge disjoint paths based on the flow assignment. The routing algorithm is similar to the first phase of TPGF, which actually can bypass holes. But, the authors didn't mention this point in the whole paper. Furthermore, the routing paths found by GAODM are far from the optimal paths in terms of the end-to-end transmission delay. In [20], the authors proposed a node-Disjoint Parallel Multipath Routing algorithm (DPMR). This DPMR actually uses the algorithm proposed in [13] to identify the hole boundary first, then divides the identified hole into two regions (*clockwise region* and *unclockwise region*). When the *Local Minimum Problem* [5] is met, the node always chooses a next hop only from either *clockwise region* or *unclockwise region*. Although, this research work breakes through the using of facing routing and planarization algorithms in geographic routing, it still has a key problem: it relies on the algorithm proposed in [13], and the restriction of using only either *clockwise region* or *unclockwise region* actually limits the usable sensor nodes, consequently, limits the number of routing paths. The found routing paths in [20] are also far from the optimal paths in terms of the end-to-end transmission delay. Thus, these approaches in [19, 20] are not suitable, since finding multiple routing paths with the shortest length and satisfying the end-to-end transmission delay are extremely important for transmitting multimedia streaming data in WMSNs.

Therefore, to propose the first geographic routing algorithm in WMSNs for: (1) supporting hole-bypassing without using the face routing or identifying the hole/boundary nodes information in advance, (2) supporting the shortest path transmission, (3) supporting multipath transmission, is the key focus of this paper.

3 Network model and problem statement

In this paper, we consider a geographic wireless multimedia sensor network. The locations of sensor nodes and the base station are fixed and can be obtained by using GPS. Each sensor node has its transmission radius *TR* and *M* 1-hop neighbor sensor nodes. Each sensor node is aware of its geographic location and its 1-hop neighbor nodes' geographic locations. We assume that only source nodes know the location of the base station and other sensor nodes can only know the location of base station by receiving the packet from source nodes. This assumption is the same with that used in [5–8].

The considered WMSN can be represented as a graph $G(V, E)$, where $V = \{v_1, \dots, v_n\}$ is a finite set of sensor nodes (vertexes) and $E = \{e_1, \dots, e_n\}$ is a finite set of links (edges). A finite set of nodes (vertexes) $V_{source} = \{v_{S1}, \dots, v_{Sn}\}$ are source nodes. The base station can be randomly deployed in the WSN. Each sensor node can have three different states: (1) *active and available*, (2) *active but unavailable*, and (3) *dead*. Each link can have two different states: (1) *available* and (2) *unavailable*. A subset $V_{Static\_Hole} = \{v_{SH1}, \dots, v_{SHn}\}$ of V are in the state of *dead*. The nth routing path $P_{n\text{th}}$ from a source node to the base station can be represented by a subset of the V as $P_{n\text{th}} = \{v_{Pn1}, \dots, v_{Pnm}\}$, which results in that a subset $V_{Dynamic\_Hole} = \{v_{DH1}, \dots, v_{DHn}\} = P_{1\text{th}} + \cdots + P_{n\text{th}}$ of V are in the state of *active but unavailable* and a subset $E_{Hole} = \{e_{H1}, \dots, e_{Hn}\}$ of E are in the state of *unavailable*. The available sensor nodes and available links can be represented as $V_{available} = V - V_{Dynamic\_Hole} - V_{Static\_Hole}$ and $E_{available} = E - E_{Hole}$.

The first sub-problem of this paper is to find the subset $P_{n\text{th}} = \{v_{Pn1}, \dots, v_{Pnm}\}$ inside the graph $G_{available}(V_{available}, E_{available})$ from one of the source nodes to the base station, which means to find a successful path while bypassing holes.

The second sub-problem of this paper is to find the subset $P_{n\text{th}\_optimized} = \{v_{OPn1}, \dots, v_{OPnm}\}(P_{n\text{th}\_optimized} \subseteq P_{n\text{th}})$ to optimize the found routing path $P_{n\text{th}}$ with the least number of nodes $N_{optimized}$ in $P_{n\text{th}\_optimized}$.

We propose a new Two-Phase geographic Greedy Forwarding (TPGF) routing algorithm to solve these two sub-problems in the following section.

4 Algorithm and examples

Motivated by the two sub-problems, TPGF consists of two phases: (1) *Geographic forwarding*; (2) *Path optimization*.

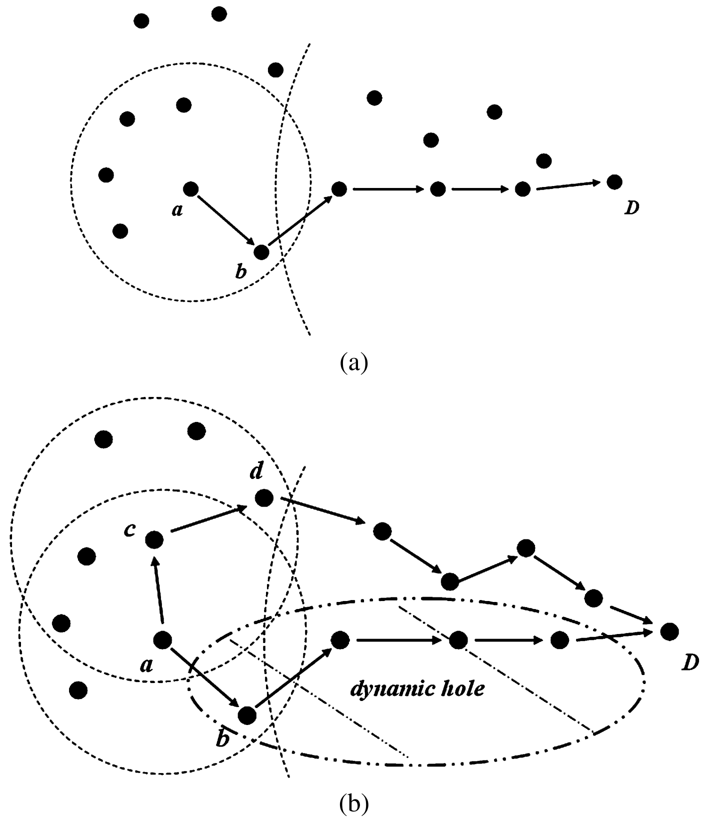
Definition 1 (Node-disjoint routing path) A *node-disjoint* routing path is defined as a routing path that consists of a set of sensor nodes, and excluding the source node and the base station, none of these sensor nodes can be reused for forming another routing path.

In TPGF, all the found routing paths are *node-disjoint* routing paths. The feature of *node-disjoint* should be used because generally transmitting multimedia streaming data in WMSNs will use the maximum transmission capacity of each path, which does not allow the sharing of any node in the used transmission path.

4.1 Geographic forwarding

This first phase is responsible for solving the first sub-problem: exploring a delivery guaranteed routing path while bypassing holes in WMSNs. The *geographic forwarding*

Fig. 3 (**a**) Greedy forwarding example 1: *b* is *a*'s closest neighbor to *D*, and *b* is closer than *a* to *D*. (**b**) Greedy forwarding example 2: *b* is transmitting data and is not available. The routing path nodes from *b* to *D* form one *dynamic hole*. *c* is *a*'s closest neighbor to *D* now, and *c* is further than *a* to *D*. *d* is *c*'s closest neighbor to *D*, and *d* is closer to *D* than both *a* and *c*



consists of two methods: *greedy forwarding* and *step back & mark*. The latter is used in the situation when *greedy forwarding* cannot find the next-hop node.

4.1.1 Greedy forwarding

The principle for *greedy forwarding* in this paper is: *a forwarding node always chooses the next-hop node that is closest to the based station among all its neighbor nodes, the next-hop node can be further to the base station than itself.* This *greedy forwarding* principle is different from the *greedy forwarding* principle used in [5–8]: a forwarding node always chooses the 1-hop neighbor node that is closer to the base station than itself. Two examples of this new principle are shown in Figs. 3(a) and (b). Especially, in Fig. 3(b), if following the *greedy forwarding* principle of [5–8], there is a *Local Minimum Problem* on the node *a*, since it has no 1-hop neighbor node that is closer to the base station than itself. However, this *Local Minimum Problem* does not exist in this new principle, which means the TPGF does not need to change to the face routing. The forwarding decision is purely based on the comparison among the geographic distance of each neighbor node to the base station.

4.1.2 Step back & mark

Definition 2 (Block node and block situation) For any sensor node, during the exploration of a routing path, if it has no next-hop node that is available for transmission except its previous-hop node, this node is defined as a block node, and this kind of situation is defined as a block situation.

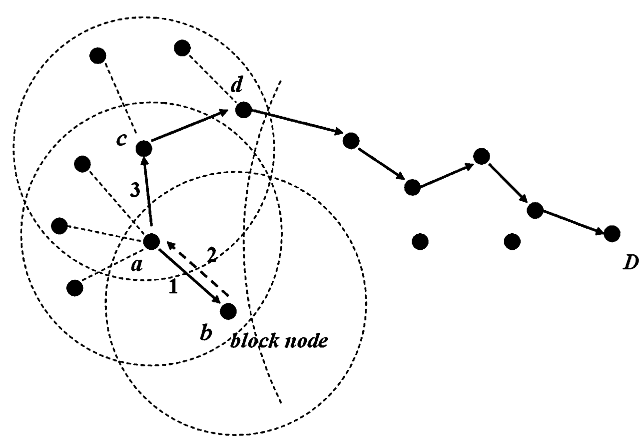


Fig. 4 *Block node and block situation*: *b* is a *block node* since it has no 1-hop neighbor that is available to be the next-hop node except node *a*, which is the previous-hop node of *b*. This kind of situation is a *block situation*

There is a worst situation (*block situation*) for this new *greedy forwarding* principle, e.g., Fig. 4. To handle the *block situation*, we propose the *step back & mark* approach: *When a sensor node finds that it is a block node, it will step back to its previous-hop node and mark itself as a block node.*

The previous-hop node will attempt to find another available neighbor node as the next-hop node. Marking the *block node* is to forbid the loop. The *step back & mark* will be repeatedly executed until a sensor node successfully finds a next-hop node that allows the path exploration to change to the *greedy forwarding*.

4.1.3 Theoretical analysis

Theorem 1 *For a given source node, using the combination of greedy forwarding and step back & mark can guarantee that it can explore every connected sensor node, which can be reached in any number of hops.*

Proof The *greedy forwarding* and *step back & mark* actually convert the WSN to a Distance based Search Tree (DST), e.g., Fig. 5(a). The search of all connected nodes is guaranteed. Here, the Dis means the distance between each node to the base station. □

Corollary 1 *There exists a geographic greedy forwarding routing algorithm that can guarantee packet delivery (bypassing holes) in any 2D/3D WSNs without using the face routing method, when sensor nodes only know their 1-hop neighbor nodes.*

Proof According to Theorem 1, this corollary is proved. □

Routing algorithms in GPSR [5] and GPVFR [8] actually convert the WSN to a Distance and Angle based Search Tree (DAST), e.g., Fig. 5(b).

When converting the DST_TPGF, all the neighbor nodes are added into the search tree no matter whether they are further or closer to the base station than that of the source node. When converting the DAST_GPSR, only the sensor node that has a shorter distance to the base station than that of the source node can be added into the search tree, which means the number of nodes in the DAST_GPSR [5] is less than the number of nodes in the DST_TPGF. When converting the DAST_GPVFR in [8], a further constraint (an elliptical bound) is added to DAST_GPSR for the face routing model, which means the number of nodes in the DAST_GPVFR is less than the number of nodes in the DAST_GPSR. Thus, these three search trees have the following relationship on the number of nodes: DST_TPGF $\geq$ DAST_GPSR $\geq$ DAST_GPVFR. Based on this relationship, it is easily to know that in the worst case using TPGF to search the base station requires the exploration of the whole tree, which means the searching performance of TPGF in DST_TPGF is not faster than that of both GPSR in DAST_GPSR and GPVFR in DAST_GPVFR.

However, this is the situation in the theoretical ideal condition. Under realistic conditions, TPGF actually has the better exploration performance than that of GPSR and GPVFR in the worst case. According to [12], in realistic conditions, GPSR and GPVFR can get into a permanent loop. The major reason is: using planarization algorithms based on inaccurate node location information will cause cross-links, and consequently, cause permanent loop by face routing. This permanent loop causes that GPSR and GPVFR cannot guarantee the packet delivery. However, TPGF always can since it does not adopt the face routing method, which means TPGF actually has the better exploration performance than that of GPSR and GPVFR.

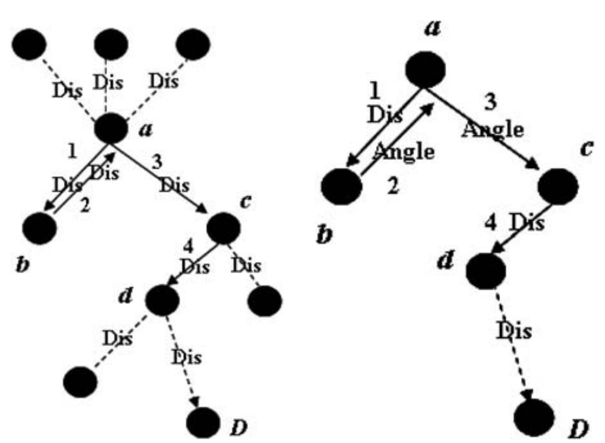


Fig. 5 (**a**) DST: the Distance (Dis) based Search Tree of Fig. 4. (**b**) DAST: the Distance (Dis) and Angle based Search Tree of Fig. 4

4.1.4 Conclusion on geographic forwarding of TPGF

The *geographic forwarding* phase in TPGF provides a different method to bypass holes other than using the face routing method. It guarantees to find the deliverable routing path. The exploration performance of this *geographic forwarding* is not as good as previous research work [5–8] in ideal network, but it actually has the better performance when cross-links exist in the network under realistic conditions.

4.2 Path optimization

This second phase is responsible for solving the second sub-problem: optimizing the found routing path with the least number of nodes. The *path optimization* include one method: *label based optimization*.

4.2.1 Path circle

Definition 3 (Path Circle) For any given routing path in a WSN, if two or more than two sensor nodes in the path are neighbor nodes of another sensor node in the path, we consider that there is a path circle inside the routing path, e.g., Figs. 6(a) and (b).

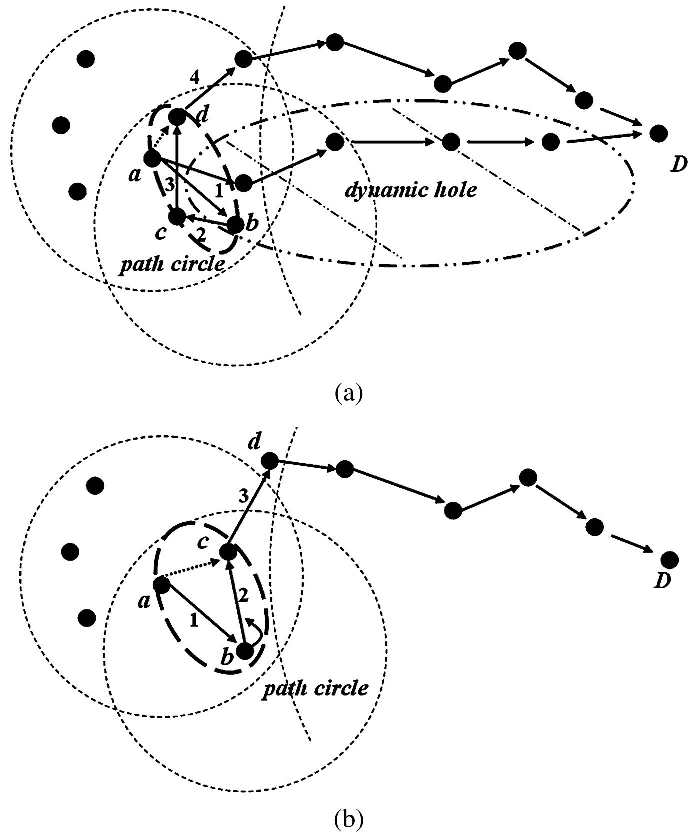


Fig. 6 (**a**) *Path circle*: b, c, and d are nodes in the path, and all of them are neighbor nodes of a. The *path circle* is formed by nodes a, b, c, and d. Actually, a can directly transmit packets to d as the dotted line. (**b**) The *path circle* is formed by nodes a, b, and c. The *path circle* is caused by the face routing. Actually, a can directly transmit packets to c as the dotted line

A routing path found by *geographic forwarding* phase in TPGF can have *path circle*s, which actually can be eliminated for reducing the number of nodes in the routing path. *Path circle* also appears in the routing path of [5–8] due to the using of face routing, e.g., Fig. 6(b). It is clear that the routing paths found by TPGF and other algorithms can be optimized to have the least number of routing nodes by eliminating all *path circles*.

4.2.2 Label based optimization

To eliminate the *path circle*s in the routing path, we propose the *label based optimization*, which needs to add an additional function in the *geographic forwarding* phase: *whenever a source node starts to explore a new routing path, each chosen node is assigned a label that includes a path number and a degressive node number*, e.g., Fig. 7(a). In TPGF, whenever a routing path reaches the base station, an acknowledgement is requested to send back to the source node. During the reverse travelling in the found routing path, the *label based optimization* is performed to eliminate the *path circle*s. The principle of the *label based optimization* is: *Any node in a path only relays the acknowledgement to its one-hop neighbor node that has the same path number and the largest node number. A release command is sent to all other nodes in the path that are not used for transmission*, e.g., Fig. 7(b). These released nodes can be reused for exploring other additional paths.

4.2.3 Conclusion on path optimization of TPGF

For any given routing path found by the first phase of TPGF or other algorithms in [5–8] with face routing, using the *label based optimization* to eliminate the path circles can sometimes minimize the number of nodes in the path. The *path optimization* phase in TPGF provides *label based optimization* method to optimize the routing path found by using the TPGF. The method is not used in previous research work [5–8], and it demonstrates an important contribution of TPGF.

4.3 TPGF Algorithm

The flowchart of TPGF routing algorithm is shown in Fig. 8. The inputs of TPGF are: (1) location of the current forwarding node; (2) location of the base station; (3) locations of 1-hop neighbor nodes. The outputs of TPGF are: (1) location of the next-hop node; (2) or successful acknowledgement; (3) or unsuccessful acknowledgement. It is worth noting that the inputs of TPGF are exactly the same as the inputs of the algorithms in [5–8].

The detailed description of TPGF routing algorithm is as follows:

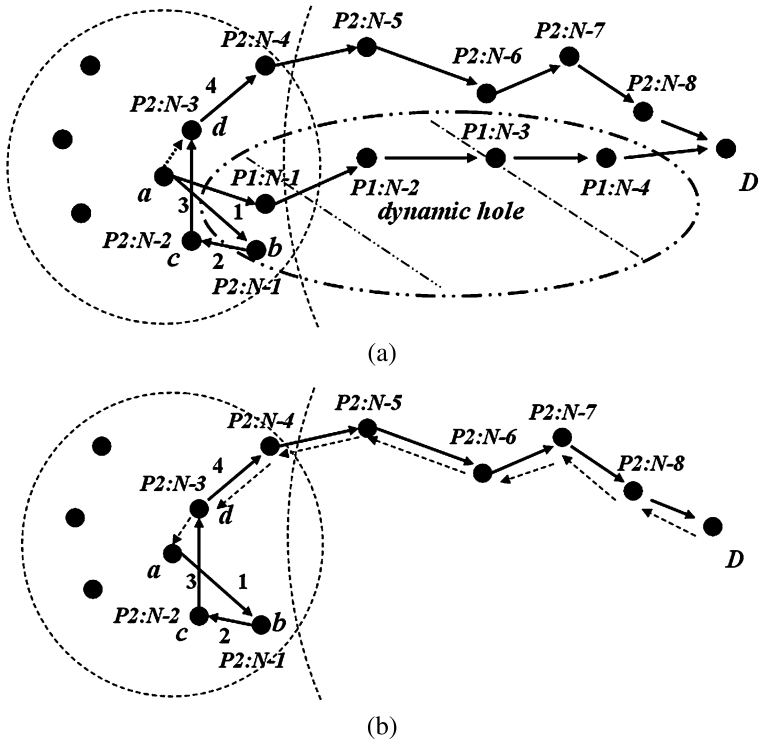


Fig. 7 (**a**) Each node in the routing paths is assigned a label that includes a path number and a degressive node number. (**b**) The dash line shows the reverse travelling in the found path. *b* and *c* are not used for transmission, and will be released. The *path circle* is eliminated, since *d* directly sends the acknowledgement to *a*

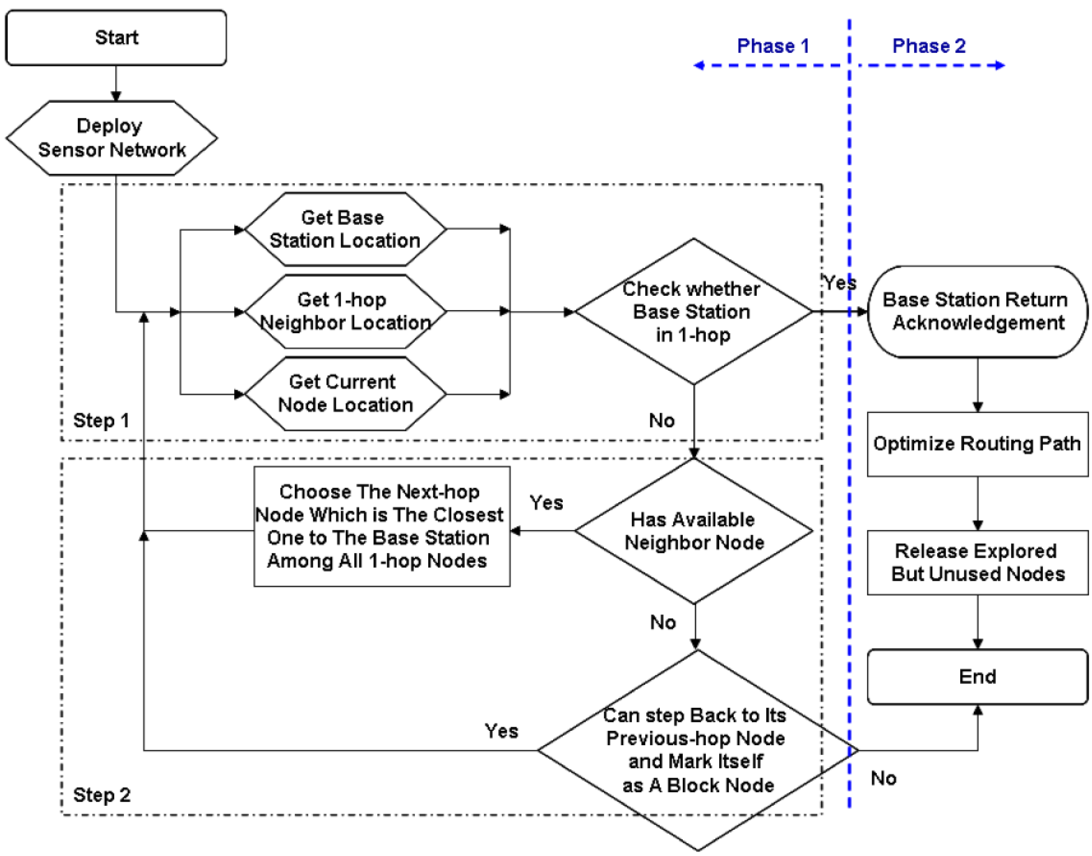


Fig. 8 The flowchart of TPGF routing algorithm

Phase 1 (Geographic forwarding)

Step 1: The source node checks whether it has usable one-hop neighbor node. If no, the source node produces an unsuccessful acknowledgement and stops transmitting. If yes, then the source node checks whether the base station is in its one-hop neighbor nodes. If yes, then it builds up routing path. If no, then the source node tries to find the next-hop node that is the closest one to the base station among all its neighbor nodes that have not been labeled (occupied). A degressive number-based label is given to the chosen sensor node along with a path number.

Step 2: The chosen sensor node checks whether the base station is in its one-hop nodes. If yes, then it builds up routing path. If no, then the chosen sensor node always tries to find the next-hop node that is the closest one to the base station among its all neighbor nodes that have not been labeled (occupied). A degressive number-based label is given to the found next-hop node along with a path number. When this sensor node finds that it has no neighbor node which is available for the next-hop transmission, which means the *block situation* is met, it will step back to its previous-hop node and mark itself as a *block node*. The previous-hop node will attempt to find another available neighbor node as the next-hop node. The *step back & mark* will be repeatedly executed until a sensor node successfully finds a next-hop node which has a routing path to the base station.

Phase 2 (Path optimization)

Step 3: Once the routing path is built up. A successful acknowledgement is sent back from the base station to the source node. Any sensor node that belongs to this path only relays packets to its one-hop neighbor node which is labeled in Step 2 with the same path number and the largest node number. A release command is sent to all other one-hop neighbor nodes which are labeled in Step 2 but are not used for transmission. After receiving the successful acknowledgement, the source node then starts to send out multimedia streaming data to the successful path with the pre-assigned path number.

When the WSN is converted to a DST, the time complexity of TPGF is $O(n)$ where n is the number of nodes in the WSN.

5 On-demand multipath transmission

5.1 Multipath exploration

The needed number of paths is based on the transmission requirement of multimedia source nodes. According to Definition 1, the way of finding multiple paths in TPGF is: *repeatedly using the TPGF in the same WMSN with the guarantee that any node will not be used twice*, which is the same with that of [20] by repeatedly using the DPMR algorithm.

5.2 Comparing with geographic routing algorithms

Using the planarization algorithms, e.g., GG or RNG, can create a planar graph from a non-planar physical topology by selecting a subset of the links, which actually limits the useable links [5–10], e.g., Figs. 9(a) and (b).

Repeatedly using TPGF without using planarization algorithms in advance can find more routing paths than that of repeatedly using the algorithms in [5–8], e.g., GPSR or GPVFR, with using the planarization algorithms in advance.

Repeatedly using TPGF also can find more routing paths than that of using DPMR [20]. For example in Fig. 10, in DPMR, when a is the source node and it meets the *Local Minimum Problem*, a always chooses a next hop only from either *clockwise region* or *unclockwise region*. But in TPGF, the algorithm does not care the angle information, any 1-hop neighbor node is the candidate for exploration. The restriction of using only either *clockwise region* or *unclockwise region* in DPMR actually limits the usable sensor nodes, consequently, limits the number of routing paths.

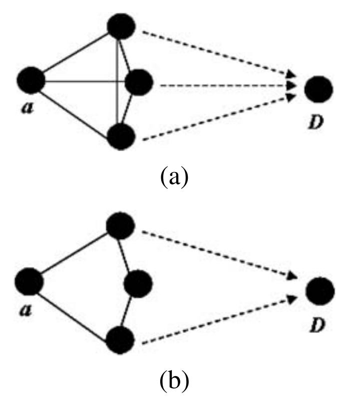


Fig. 9 (**a**) Before using planarization algorithms, a has three usable links. (**b**) After using planarization algorithms, a has two usable links

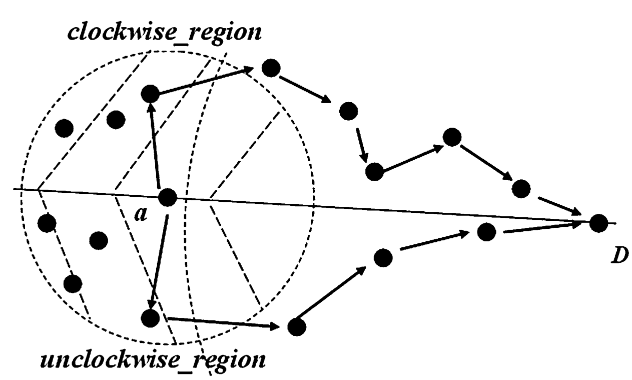


Fig. 10 Using the DPMR, the found number of routing paths can be only 1. But, using the TPGF, the found number of routing paths can be 2

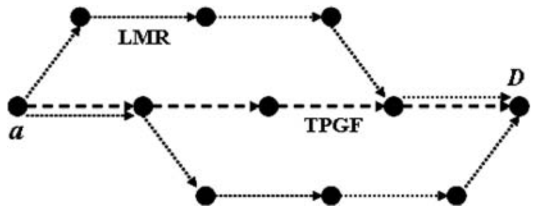


Fig. 11 Using the TPGF, the found number of routing paths can be only 1. But, using the LMR, the found number of routing paths can be 2

5.3 The factors of affecting the number of paths

The number of routing paths is restricted by three factors as following presented.

- For any given source node S with M number of 1-hop neighbor nodes, it can have maximum M number of node-disjoint routing paths.
- The maximum number of node-disjoint routing paths is restricted by the 1-hop neighbor nodes of the base station.
- For any given source node, the maximum number of possible node-disjoint routing paths is affected by the routing algorithms. For example, in Fig. 11, if TPGF is used, the number of routing paths can be only one (dashed path) with a short end-to-end transmission delay. However, if the label-based multipath routing (LMR) [22] is used, the number of routing paths can be two (dotted path) with a relative longer end-to-end transmission delay.

TPGF and LMR actually demonstrate a confliction between two different design principles: (1) always explore the shortest routing path in each round; (2) explore more redundant routing paths with longer end-to-end transmission delay. TPGF uses “always explore the shortest routing path in each round” as the criteria and then explores the possible number of multiple paths. The primary motivation is that the shortest transmission path generally has the shortest end-to-end transmission delay, which may satisfy the delay constraint of multimedia streaming data. If the data cannot be transmitted to the base station within the delay constraint, it is useless. In short, the number of routing paths found by using the TPGF is not larger than that of LMR. However, the end-to-end transmission delay of the found routing paths by using the TPGF is not longer than that of LMR.

5.4 Conclusion on multipath transmission of TPGF

Repeatedly using TPGF can explore more routing paths than that of repeatedly using the protocols in [5–8], e.g., GPSR, GOAFR, GOAFR+, and GPVFR. The number of routing paths found by using the TPGF is not larger than that of some other non-geographical routing algorithms, e.g. LMR. But, TPGF is more suitable for transmitting multimedia data in WMSNs, because it always try to satisfy the delay constraint of multimedia streaming data.

6 Simulation and evaluation

The goals of this simulation section include:

- Prove that TPGF can find more number of routing paths than that of GPSR
- Prove that TPGF can have shorter average end-to-end transmission delay than that of GPSR
- Demonstrate the working of TPGF

The reason for choosing GPSR for comparison rather than other geographic routing algorithms, e.g., GOAFR and GPVFR, or DPMR is that: GPSR only uses the planarization algorithms to eliminate the links, and it does not have any further restriction on the face routing. This point allows that repeatedly using GPSR can find more node-disjoint routing paths than that of repeatedly using GOAFR or GPVFR. The DPMR actually uses the algorithm proposed in [13] to identify the hole boundary first, which is not in the same category of TPGF that bypasses holes without identifying holes in advance.

6.1 Performance comparison with GPSR

In the simulation, to clearly compare the features of both TPGF and GPSR algorithms, we simplify the end-to-end transmission delay as following defined, which is also widely used in other research work, e.g., [23].

Definition 4 (End-to-end transmission delay) Given a source node and a base station, when using any geographic routing algorithm, k hops are needed for connecting the source node to the base station. The average delay of each hop is $D_{hop} + D_{otherfactors}$, the end-to-end transmission delay D_{e2e} is defined as:

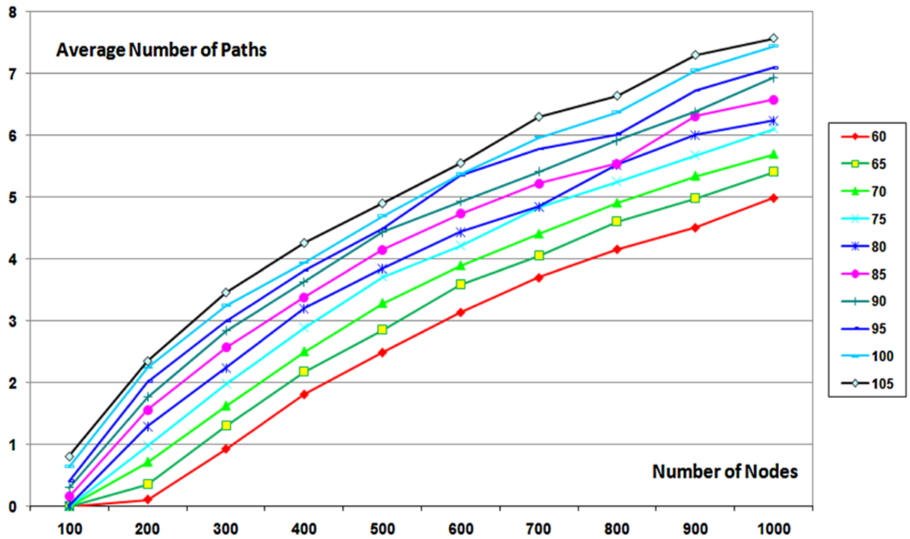
$$D_{e2e} = k * (D_{hop} + D_{otherfactors}),$$

where D_{hop} is the delay for transmission and $D_{otherfactors}$ stands for the delay contributed by all other factors, such as MAC layer delay and queuing delay. In this paper, for the sake of simplicity, we consider the average delay of each hop $D_{hop} + D_{otherfactors}$ as a fixed value.

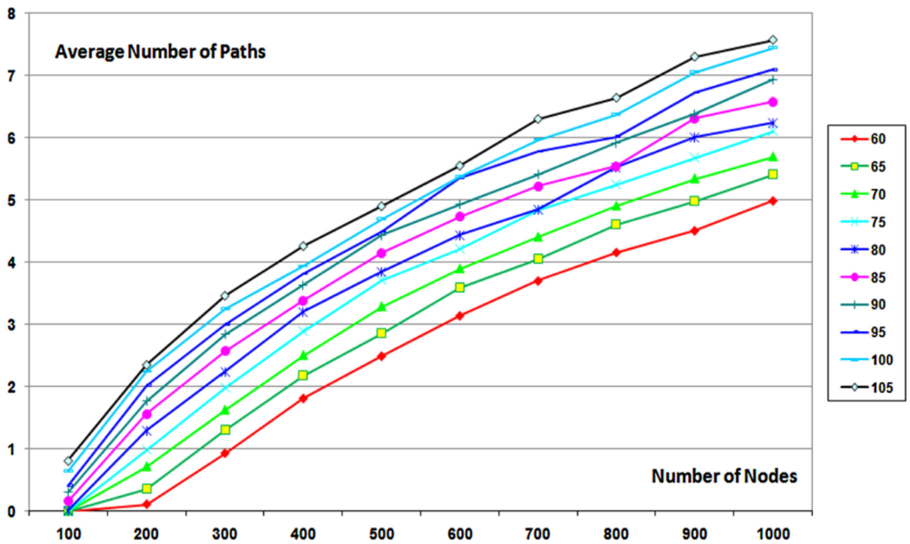
Based on the simulation goals and the definition of the end-to-end transmission delay, the two major comparison metrics in this simulation are: (1) the average number of paths by repeatedly using this same algorithm in the WSN; (2) the average path length from the source node to the sink node.

To evaluate TPGF routing algorithm, we implemented both TPGF and GPSR in NetTopo [24]. NetTopo is released as an open source sensor network simulator on the SourceForge. Currently, it has been implemented with more than 80 java classes and more than 11,000 Java lines source codes.

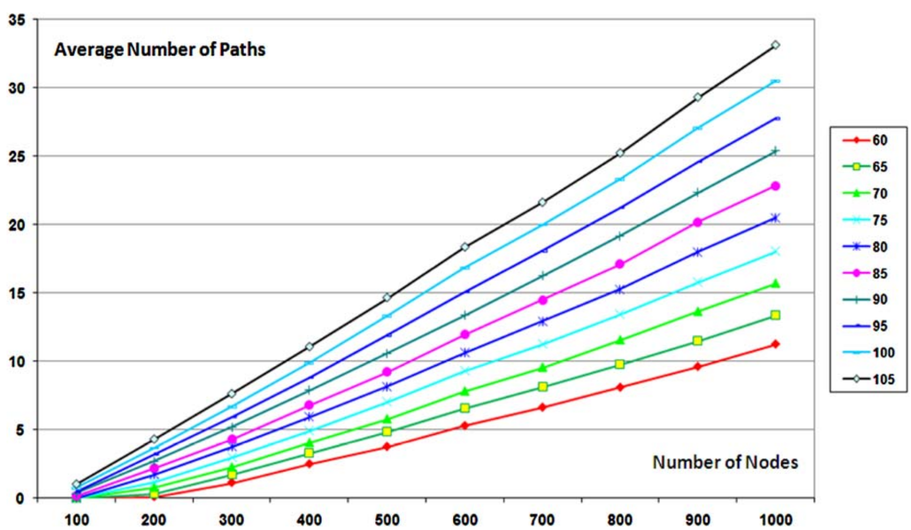
Fig. 12 (**a**) GPSR on GG planar graph: average number of paths vs. number of nodes. (**b**) GPSR on RNG planar graph: average number of paths vs. number of nodes. (**c**) TPGF: average number of paths vs. number of nodes



(a)

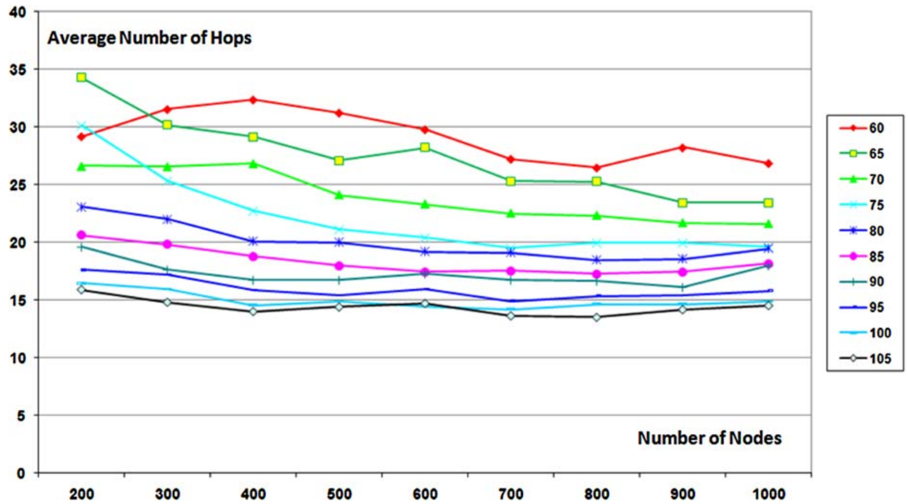


(b)

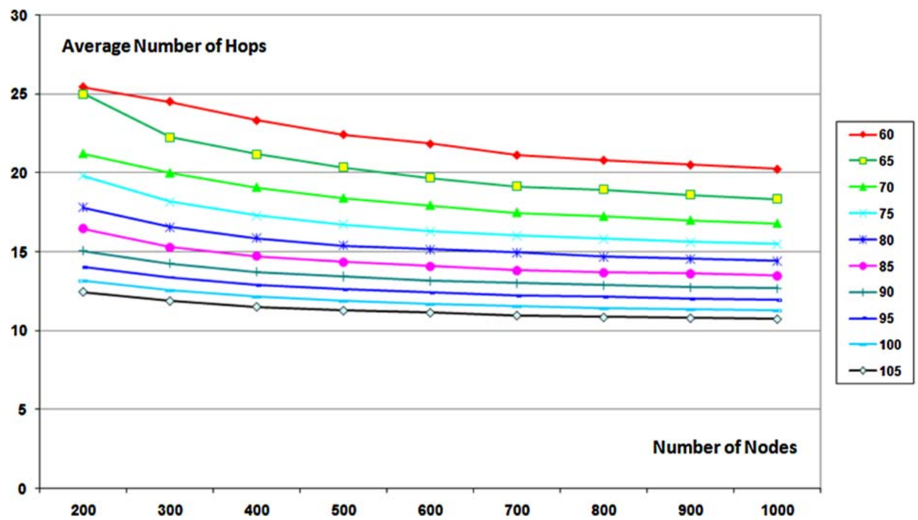


(c)

Fig. 13 (**a**) TPGF: average number of hops before optimization vs. number of nodes. (**b**) TPGF: average number of hops after optimization vs. number of nodes



(a)



(b)

The source code of both TPGF and GPSR are available in NetTopo as examples. Users can freely download the latest version of NetTopo to play with these two routing algorithms by accessing the website on [25].

In the simulation, the network size is fixed in 600 M × 400 M (1 pixel on the canvas is considered as 1 meter). For each fixed number of sensor nodes (network density) and transmission radius (network degree), the average number of paths and the average path length are computed from 100 simulation results using 100 different random seeds for network deployment. Then, we change the node number (from 100 to 1000) and transmission radius (from 60 M to 105 M) to obtain different values.

The GPSR is simulated in both GG and RNG graphs. The planarization algorithms are repeatedly applied when using GPSR to repeatedly explore each new routing path. By the repeated using of planarization algorithms, the source node in GPSR can actually explore all its 1-hop neighbor nodes. According to the three factors in Sect. 5.3, we can easily know that the difference between TPGF and GPSR in the exploration results of the average number of paths is mainly caused by the different approaches in these two different algorithms.

Figures 12(a), (b) and (c) are the simulation results on the average number of paths found by applying TPGF and GPSR respectively. By comparing the average number of paths in Figs. 12(a), (b) and (c), we can easily see that TPGF can find much more number of paths than that of GPSR on both GG and RNG planar graphs.

Figure 13(a) is the simulation results on the average path length of TPGF before applying optimization and Fig. 13(b) is the simulation results on the average path length of TPGF after applying optimization. It is easy to conclude that after optimization the average path length of TPGF is much shorter.

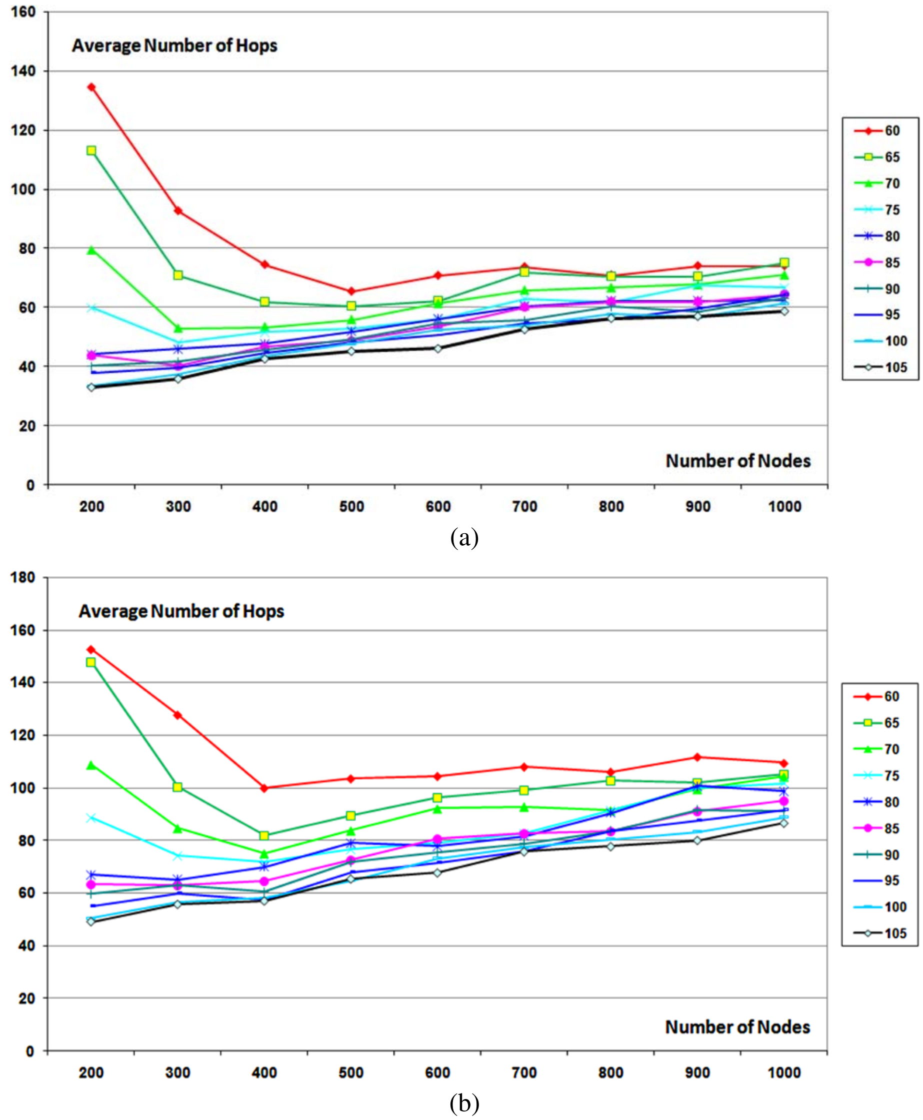


Fig. 14 (**a**) GPSR on GG planar graph: average number of hops vs. number of nodes. (**b**) GPSR on RNG planar graph: average number of hops vs. number of nodes

Figures 14(a) and (b) are the simulation results of GPSR on the average path length on both GG and RNG planar graphs. Comparing Figs. 13(b), 14(a) and (b), it is proved that TPGF can have shorter average path length than that of GPSR. Furthermore, the changing of average path length in GPSR is strongly affected by the changing of transmission radius, but in TPGF it is not.

6.2 Execution demonstration of TPGF

In Figs. 15(a), (b), (c) and (d), the execution of TPGF is demonstrated.

7 Conclusion

Using multimedia sensor nodes can enhance the capability of WSNs for event description. Efficiently transmitting multimedia streaming data in WSNs is a basic requirement. In this paper, a new Two-Phase geographic Greedy Forwarding (TPGF) routing algorithm is proposed to facilitate the multimedia streaming data transmission in WMSNs. TPGF does not adopt face routing to bypass holes, which makes TPGF be different from many existing geographic routing algorithms. Both theoretical analysis and simulation comparison in this paper show that TPGF is more suitable for transmitting multimedia streaming data than other geographic routing algorithms in geographic WMSNs. We believe that our research result can make a significant impact on both mobile multimedia and WSNs research communities.

Acknowledgements The work presented in this paper is funded by Science Foundation Ireland under Grant No. SFI/08/CE/I1380 (Lion-2). The work of Yu Wang was supported in part by the US NSF under Grant No. CNS-0721666 and funds provided by the University of North Carolina at Charlotte.

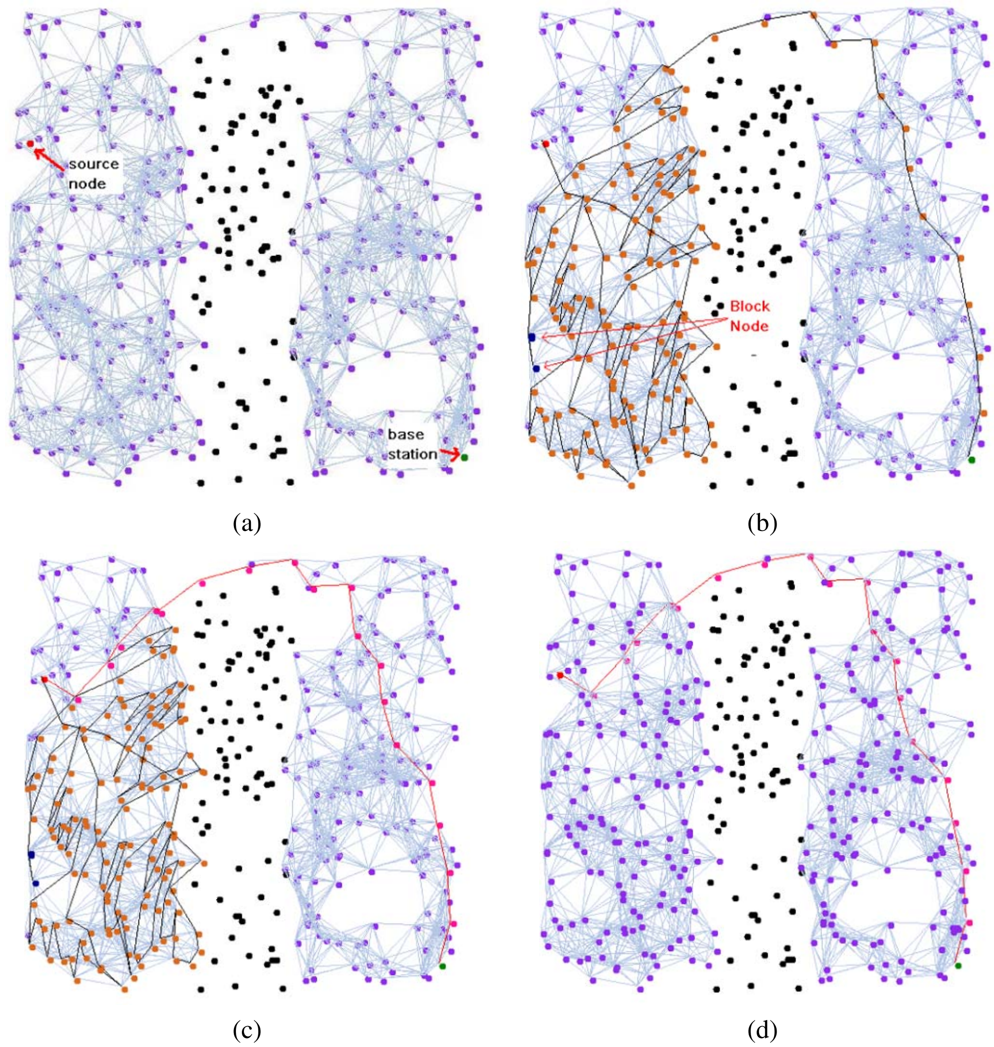


Fig. 15 (**a**) The deployed sensor network with one source node, one base station, and a set of dead nodes. (**b**) The source node tries to find the only available routing path. During the exploration, three nodes are marked as *block nodes*. (**c**) The found routing path is optimized by eliminating the *path circles*. The optimized routing path is much shorter. (**d**) The explored but unused nodes are released. These nodes can be reused for exploring another routing path

Appendix

The main graphical user interface (GUI) of NetTopo is shown in Fig. 16. It consist of three major components: (1) a display canvas (on the upper left), which can be dragged in case of viewing a large scale WSN, (2) a property tab for displaying node properties (on the upper right), and (3) a display console for logging and debugging information.

In Fig. 17, the red color node is the source node and the green color node is the sink node. As an example, Figs. 17(a), (b) and (c) give a direct impression to researchers that TPGF can have shorter average path length than that of GPSR in a single WSN deployment.

The Fig. 18 gives an example of multi-source multipath transmission by using TPGF.

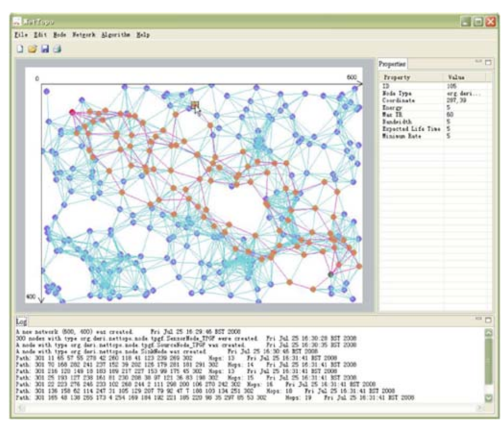


Fig. 16 NetTopo main GUI (the TPGF multipath routing algorithm is executed in the WSN)

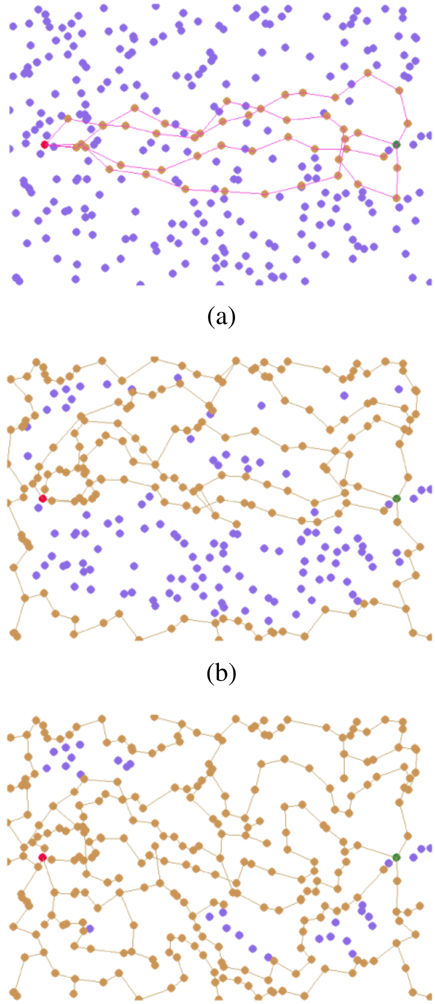


Fig. 17 (**a**) Running TPGF in the WSN with 4 routing paths when transmission radius of sensor node is set as 60 meters. (**b**) Running GPSR in the GG WSN with 4 routing paths when transmission radius of sensor node is set as 60 meters. (**c**) Running GPSR in the RNG WSN with 4 routing paths when transmission radius of sensor node is set as 60 meters

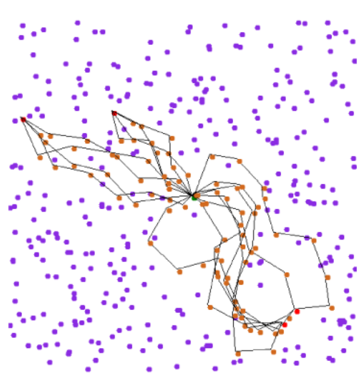


Fig. 18 An example: 4 source nodes, each node has 4 transmission paths found by using TPGF

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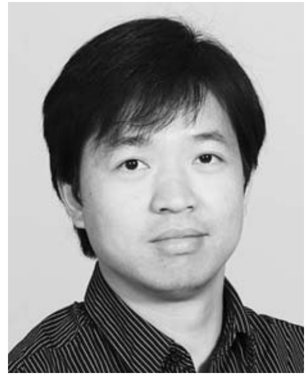

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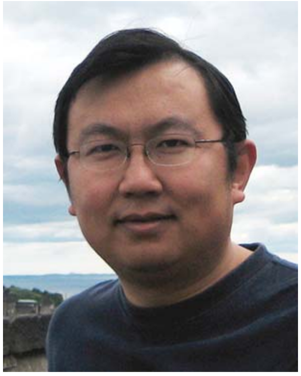

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