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Transmitting and Gathering Streaming Data in Wireless Multimedia Sensor Networks Within Expected Network Lifetime

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Abstract Using multimedia sensor nodes in wireless sensor networks (WSNs) can significantly enhance the capability of WSNs for event description. Different kinds of holes can easily appear in WSNs. How to efficiently transmit multimedia streaming data and bypass all kinds of holes is a challenging issue. Moreover, some applications do not need WSNs to work for a long lifetime, e.g. monitoring an erupting volcano. These applications generally expect that WSNs can provide continuous streaming data during a relatively short expected network lifetime. Two basic problems are: (1) gathering as much data as possible within an expected network lifetime; (2) minimizing transmission delay within an expected network lifetime. In this paper, we proposed a cross-layer approach to facilitate the continuous one shot event recording in WSNs. We first propose the maximum streaming data gathering (MSDG) algorithm and the minimum transmission delay (MTD) algorithm to adjust the transmission radius of sensor nodes in the physical layer. Following that the two-phase geographical greedy forwarding (TPGF) routing algorithm is proposed in the network layer for exploring one/multiple optimized hole-bypassing paths. Simulation results show that our algorithms can effectively solve the identified problems.

Keywords cross layer design · wireless multimedia sensor networks · geographical multipath routing

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1 Introduction

Wireless sensor networks (WSNs) aim to collect sensed data in a variety of applications. Image, audio and video sensors can provide the information which cannot be easily described by simple sensor nodes. Using multimedia sensor nodes in WSNs can significantly enhance the capability of event description. Consequently, efficiently transmitting multimedia streaming data in WSNs is necessary when the underlying infrastructure, such as 3G cellular networks or WLANs, do not exist.

In WSNs, energy efficiency is one of the most significant research challenges since sensors are normally battery-powered. How to effectively use the limited power and achieve a long lifetime is considered to be a critical issue. However, different scenarios, environments and applications may have different requirements. In a variety of scenarios, the sensor networks are not deployed to work for an extremely long time. Instead, the sensor networks aim to deliver continuous and reliable multimedia data as much as possible within an expected network lifetime without sleeping. These applications include monitoring an erupting volcano [1], rescue in a sudden earthquake and monitoring hazardous situations [2], etc. When a WSN is not intended to work very long, the design emphasis of the routing protocol shall be put on the full utilization of the limited energy to maximize the data gathering performance, e.g. gathering as much multimedia streaming data as possible or transmitting multimedia streaming data as fast as possible. Here, the expected network lifetime refers to the working time that all sensor nodes in the network are expected to achieve before any of them run out of energy.

Additionally, 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 [3]. This requires that multipath transmission should be used to increase transmission performance in WSNs. However, *dynamic hole*s might occur if several sensor nodes in a small area overload due to the transmitting multimedia streaming data. Efficiently bypassing these dynamic holes is necessary for transmission in WSNs. This is different from the traditional routing algorithms in WSNs that focus only on either multipath routing or *static hole* bypassing. In contrast, transmitting multimedia streaming data inside WSNs requires a new routing protocol which can support both hole-bypassing and multipath routing.

These kinds of applications with short expected network lifetime and high possibility of holes existing inside WSNs cause us to ask the following three questions: (1) how to gather as much multimedia streaming data as possible within an expected network lifetime; (2) how to minimize multimedia streaming data transmission delay within an expected network lifetime; (3) how to efficiently transmit multimedia streaming data to the base station while bypassing holes? After theoretical analysis we found that the physically allowed maximum transmission radius of sensor nodes and the expected network lifetime are the two major factors that can affect the results of streaming data gathering and transmission delay. We first propose the MSDG (maximum streaming data gathering) and the MTD (minimum transmission delay) algorithms to solve the problems (1) and (2) respectively. In these two algorithms the transmission radius of sensor nodes is adjusted in the physical layer according to the changed expected network lifetime towards different optimization goals. We then propose a new two-phase geographical greedy forwarding (TPGF) routing algorithm in the network layer. TPGF uses the adjusted transmission radius in the physical layer to explore one or multiple hole-bypassing paths to facilitate the multimedia streaming data transmission in WSNs.

Research work in this paper contributes the following six aspects: (1) To the best of our knowledge, TPGF is the first routing algorithm that focuses on providing transmission for multimedia streaming data in WSNs; (2) TPGF provides a better solution for hole-bypassing in WSNs than other related research works; (3) TPGF can guarantee the exploration result to find the routing paths if they exist in WSNs; (4) TPGF can optimize the routing path with the least number of hops; (5) the MSDG can successfully adjust the transmission radius of sensor nodes for maximizing the multimedia streaming data gathering within an expected network lifetime; (6) the MTD can successfully adjust the transmission radius of sensor nodes for minimizing the transmission delay within an expected network lifetime. Our algorithms can be used in various applications when multimedia sensor nodes are deployed in WSNs for transmitting and gathering multimedia streaming data continuously during a short period of time. We believe that our research results can make a strong impact to both mobile multimedia and WSNs research communities.

The rest of this paper is organized as follows. Section 2 describes the related work. Section 3 shows the network model. Section 4 discusses the condition under which the expected network lifetime can be guaranteed. The MSDG and MTD algorithms are presented in Sections 5 and 6. Section 7 presents the TPGF routing protocol. Simulation results are presented in Section 8, and this paper is concluded in Section 9.

2 Related works

2.1 Related work on data gathering in WSNs

The problem of data gathering in WSNs has been investigated by many researchers. We can classify them into three categories: (1) maximizing lifetime of WSNs; (2) balancing data gathering in WSNs; (3) maximizing data gathering in WSNs.

Maximizing lifetime of WSNs The LEACH protocol [4] presents a solution for this data gathering problem where a small number of clusters are formed in a self-organized manner. A node in each cluster designated as the cluster head, it collects and fuses data from other nodes in its cluster and transmits the result to the base station. In [5], the authors consider the problem of placing nodes in the monitoring area and assigning roles to them such that the system lifetime is maximized, while ensuring that each region of interest is covered by at least one sensor node. This is a maximum lifetime sensor deployment problem with coverage constraints. In [6], data gathering is assumed to be performed in *rounds* in which each sensor can communicate in a single hop with the base station and all other sensors. The total number of rounds is then maximized under a given energy constraint on the sensors. In [7], the authors study the problem by proposing another protocol called PEDAP, which uses heuristics to assign weights to links and finds a minimum spanning tree rooted at the base station in terms of total transmission energy consumption. In [8], the authors study the data gathering problem in a cluster-based WSN. During data gathering, sensors have the ability to perform in-network aggregation of data packets and route to the base station while maximizing the system lifetime given the energy constraints. In [9], the authors focus on data gathering problems in energy-constrained networked sensor systems, proposing optimal algorithms based on network flows and heuristics based on self-stabilizing spanning trees and shortest paths.

Balancing data gathering in WSNs In [10, 11], the balanced data transfer problem is formulated as a linear programming problem, where a minimum achieved sensing rate is set for every individual node. This is done to balance the total amount of data received from a sensor network during its lifetime against a requirement of sufficient coverage for all the sensor locations surveyed. The authors outline an algorithm for finding optimal placements for the relay nodes, given a system of basic sensor locations, and compare it with a straightforward grid arrangement of the relays.

Maximizing data gathering in WSNs In [12], the data gathering problem is formulated as a linear programming problem and an approximation algorithm is proposed. This algorithm leads to a distributed heuristic. In [13], a nonlinear programming formulation is proposed to explore the trade-offs between energy consumed and the transmission rate in sensor networks. It models the radio transmission energy according to Shannon's theorem. In [14], the authors aim to maximize the throughput or volume of data received by the base station. By modeling the energy consumption associated with each sending and receiving operation, the authors formulate the data gathering problem as a constrained network flow optimization problem. The authors develop a decentralized and adaptive algorithm for the maximum network flow problem. This algorithm is a modified version of the Push–Relabel algorithm [15].

To the best of our knowledge, we find that there is no research work that has ever considered taking expected network lifetime as an important design parameter for multimedia streaming data gathering in WSNs. This area is the first focus of this paper.

2.2 Related work on multimedia streaming in WSNs

In [16–18], three surveys on multimedia communication in WSNs have been well conducted. The authors analyzed and discussed the existing research works from both mobile multimedia and WSNs fields. These surveys showed that current existing protocols from the mobile multimedia and WSNs fields did not consider the characteristics of multimedia streaming data and natural constrains of WSNs at the same time. These papers also concluded that there exists a clear need for a great deal of research effort to focus on developing new efficient communication protocols and algorithms. In [19], the authors also conducted a study on several typical transport protocols in the WSNs field. The performance evaluation results clearly show that the existing transport protocols far from satisfy the requirements of multimedia communication in WSNs. Hence, there is a need for new effective multimedia delivery protocols for WSNs. All the above mentioned research work clearly suggest that a cross-layer designed approach could be used to address the multimedia challenges in WSNs.

Therefore, to propose a new cross-layer approach for addressing the routing problems of multimedia streaming data in WSNs is the second focus of this paper.

2.3 Related work on hole-bypassing routing in WSNs

Several research works on hole-bypassing routing in WSNs have been conducted. These research works can be classified into two categories: (1) hole-bypassing without knowing the hole information in advance [20]; (2) hole-bypassing with the hole information and boundary nodes information known in advance [22–24].

Hole-bypassing without knowing the hole information in advance In [20], a greedy forwarding routing algorithm GPSR was proposed. The input parameters of GPSR include: (1) the location information of base station; (2) the location information of one-hop neighbor nodes. A *local minimum problem* was identified in this paper. In GPSR, before meeting the local minimum problem, a sensor node always chooses the next-hop node which is closer to the base station than itself. When a local minimum problem is met in GPSR the *right hand rule* is adopted to solve it. The key drawback of GPSR is that it does not guarantee that it can find the routing paths when holes exist under realistic conditions [21].

Hole-bypassing with the hole information and boundary nodes information known in advance In [22, 23], the authors use graph theory to identify the hole boundary nodes first, then use the knowledge of these identified boundary nodes to facilitate routing bypassing the holes. Especially in [23], if a node can find a next-hop node to the base station, it is considered as a first-class node; otherwise, it is considered as a second-class node. Every sensor node is requested to identify 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. The key drawback of this research work is that the identified "hole nodes" are only suitable for the predefined base station. If the location of the base station changes, some nodes will no longer be "hole nodes". The proposed algorithm must be executed in all sensor nodes again, which is not flexible at all. In [24], the authors try to find an optimized hole-bypassing routing path by using geometric modeling of holes while having advanced knowledge of holes. In this paper the hole information is obtained by using the algorithm proposed in [22].

To find a reliable routing algorithm which dose not need to identify the hole information in advance but can always find routing paths when they exist is the third focus of this paper.

3 Network model

We consider a WSN consisting of N sensor nodes and a base station, which are randomly distributed over a region of interest. The location of sensor nodes and the base station are fixed. The base station is aware of the locations of all sensor nodes, which can be obtained by using GPS. The initial energy of sensor node is $E_{nerSensNode}$. The initial total energy of whole WSN is fixed as $N \times E_{nerSensNode}$. Each sensor node has its transmission radius $T_{ransRadius}$ and M one-hop neighboring sensor nodes. The maximum transmission radius of sensor nodes is M_{axTR}. Each sensor node can dynamically adjust its transmission radius. The maximum transmission capacity of sensor nodes is $T_{ransCapa}$. Among N sensor nodes $C_{SourceNode}$ sensor nodes work as multimedia source nodes. All source nodes continuously generate sensed data with the minimum data generation rate R kbps, which is not larger than $T_{ransCapa}$. Each source node can dynamically adjust its data generation rate. The data from source nodes is gathered at the base station for further processing.

The energy model for sensor nodes is based on the first order radio model described in [25–27], which is a widely used energy model in sensor network research. In this model, the radio dissipates E_{elec} to power the transmitter or receiver circuitry and E_{amp} for the transmit amplifier. The energy consumed to transmit a k-bit message to a distance d is ETx(k, d):

$$\mathrm{ETx}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^2, \tag{1}$$

while the energy expended to receive this message is ERx(k):

$$\mathrm{ERx}(k) = E_{elec} \times k, \tag{2}$$

which is a constant for a fixed-size message. We consider the transmission radius of sensor node $T_{ransRadius}$ as the distance d.

4 The guarantee of expected network lifetime

Definition 1 *Real lifetime of a sensor network* For a given sensor network, we define the real network lifetime $R_{ealLifeTime}$ as the working time until any sensor node runs out of energy.

The real energy consumption rate of a sensor network $\mathrm{ECR}(R_{ealSensNetwork})$ can be defined as:

$$\mathrm{ECR}(R_{ealSensNetwork}) = N \times E_{nerSensNode} / R_{ealLifeTime}. \tag{3}$$

Definition 2 *Expected lifetime of a sensor network* For a given sensor network, we define the expected network lifetime $E_{xpeLifeTime}$ as the working time that all sensor nodes are expected to achieve before any of them runs out of energy.

The expected energy consumption rate of a sensor network $\mathrm{ECR}(E_{xpeSensNetwork})$ can be defined as:

$$\mathrm{ECR}\left(E_{xpeSensNetwork}\right) = N \times E_{nerSensNode} / E_{xpeLifeTime}. \tag{4}$$

Theorem 1 *For a given sensor network, to guarantee the expected network lifetime $E_{xpeLifeTime}$, the appropriate data generation rate R and transmission radius $T_{ransRadius}$ should be found to satisfy:*

$$R \times \left(2 \times E_{elec} + E_{amp} \times T_{ransRadius}{}^2\right) \leq E_{nerSensNode} / E_{xpeLifeTime}. \tag{5}$$

Proof In order to guarantee the expected network lifetime, the real lifetime must be no smaller than the expected network lifetime as shown in Eq. 6:

$$R_{ealLifeTime} \geq E_{xpeLifeTime}, \tag{6}$$

which implies that the real energy consumption rate must not be larger than the expected energy consumption rate:

$$ECR(R_{ealSensNetwork}) \leq ECR\left(E_{xpeSensNetwork}\right), \tag{7}$$

which in turn means that any sensor node's energy consumption rate should not be larger than one Nth of the expected energy consumption rate of the whole WSN as shown in Eq. 8:

$$E_{nerSensNode} / R_{ealLifeTime} \leq E_{nerSensNode} / E_{xpeLifeTime}. \tag{8}$$

For end-to-end streaming data transmission, any sensor node within a transmission path has the energy consumption rate ECR($S_{ensNode}$):

$$\mathrm{ECR}(S_{ensNode}) = R \times \left(2 \times E_{elec} + E_{amp} \times {T_{ransRadius}}^2\right). \quad (9)$$

Thus, to guarantee the expected lifetime, we must find a suitable data generation rate R and transmission radius $T_{ransRadius}$ to satisfy the Eq. 10:

$$R \times \left(2 \times E_{elec} + E_{amp} \times {T_{ransRadius}}^2\right) \leq E_{nerSensNode} / E_{xpeLifeTime}. \quad (10)$$

5 Maximum streaming data gathering

5.1 Problem formulation

Definition 3 *Total gathered data* Within $E_{xpeLifeTime}$, a base station can receive the total data D from $C_{SourceNode}$ source nodes as shown in Eq. 11.

$$D = C_{SourceNode} \times R \times E_{xpeLifeTime}.\left(R \leq T_{ransCapa}\right) \quad (11)$$

According to Definition 3 and Theorem 1, the maximum streaming data gathering problem can be formulated as:

$$\text{Maximize } D = S_{SourceNode} \times R \times E_{xpeLifeTime} \quad (12)$$

Subject to:

$$R \leq T_{ransCapaSour} \quad (13)$$

$$T_{ransRadius} \leq M_{axTR} \quad (14)$$

$$R \times \left(2 \times E_{elec} + E_{amp} \times {T_{ransRadius}}^2\right) \leq E_{nerSensNode} / E_{xpeLifeTime} \quad (15)$$

Since both $C_{SourceNode}$ and $E_{xpeLifeTime}$ are fixed parameters, to maximize D means to maximize R. Therefore, we should explore in what kind of situation the data generation rate R can be increased.

5.2 Minimum energy consumption for multi-hop routing

When source nodes transmit streaming data to a base station with the minimum generation rate R by using the geographical greedy forwarding algorithms, such as GPSR [20] or our following TPGF, a general problem can be formulated as: given a distance $D_{istance}$ between a source node S_i and the base station, to find the optimal $T_{ransRadius}$ so that the total energy used for multi-hop routing can be minimized. The transmission hop K is equal to:

$$K = \lceil D_{istance} / T_{ransRadius} \rceil. \quad (16)$$

Thus, the total consumed energy E_{ner} for multi-hop routing in one second can be formulated as:

$$E_{ner} = \lceil D_{istance} / T_{ransRadius} \rceil \times R \times (2 \times E_{elec} + E_{amp} \times {T_{ransRadius}}^2). \quad (17)$$

Mathematically, it is a convex optimization problem [26]. The optimal transmission radius O_{ptTR} can be found as:

$$O_{ptTR} = \left(2 \times E_{elec} / E_{amp}\right)^{1/2}. \quad (18)$$

5.3 Energy consumption rate

Sensor nodes are physically allowed to use the maximum transmission radius M_{axTR} to transmit data, thus the energy consumption rate ECR(M_{axTR}) of sensor nodes when they use M_{axTR} can be formulated as:

$$ECR(M_{axTR}) = R \times \left(2 \times E_{elec} + E_{amp} \times {M_{axTR}}^2\right). \quad (19)$$

When sensor nodes use the O_{ptTR} to transmit streaming data, the energy consumption rate ECR(O_{ptTR}) can be formulated as:

$$ECR(O_{ptTR}) = R \times \left(2 \times E_{elec} + E_{amp} \times {O_{ptTR}}^2\right). \quad (20)$$

When sensor nodes consume the same energy as the expected energy consumption rate, we can calculate the allowed transmission radius E_{xpTR} as:

$$E_{xpTR} = \left(\left(E_{nerSensNode} / \left(E_{xpeLifeTime} \times R\right) - 2 \times E_{elec}\right) / E_{amp}\right)^{1/2}. \quad (21)$$

Thus, the energy consumption rate of sensor nodes when using E_{xpTR} can be formulated as:

$$ECR(E_{xpTR}) = R \times \left(2 \times E_{elec} + E_{amp} \times {E_{xpTR}}^2\right). \quad (22)$$

5.4 Choosing the smallest transmission radius

Different transmission radii should be used in different conditions. By analyzing three different energy consumption rates, we propose the following criteria to choose the smallest transmission radius for streaming data transmission.

- If ECR(E_{xpTR}) is less than ECR(M_{axTR}) and ECR (O_{ptTR}), then we can only choose E_{xpTR} for streaming data transmission. If we consume energy with a larger energy consumption rate than ECR(E_{xpTR}), the expected network lifetime cannot be guaranteed.

- Otherwise, if ECR(M_{axTR}) is less than ECR(E_{xpTR}) and ECR(O_{ptTR}), then we can only choose M_{axTR} for streaming data transmission. If the M_{axTR} is the physically allowed maximum transmission radius, it is impossible to have a longer transmission radius beyond the hardware constraint.
- Otherwise, if ECR(O_{ptTR}) is less than ECR(M_{axTR}) and ECR(E_{xpTR}), then we can choose O_{ptTR} for streaming data transmission, because using O_{ptTR} can minimize the energy consumption for multi-hop transmission.

5.5 Increasing the data generation rate

When sensor nodes use E_{xpTR} for transmission there is no more space for source nodes to increase the data generation rate R. However, when sensor nodes use M_{axTR} or O_{ptTR} for transmission, there are still some space for source nodes to increase the data generation rate R. The maximum R can be formulated as follows:

$$R_{MAX\_MaxTR} = ECR\left(E_{xpTR}\right) / \left(2 \times E_{elec} + E_{amp} \times {M_{axTR}}^2\right). \tag{23}$$

$$R_{MAX\_OptTR} = ECR\left(E_{xpTR}\right) \Big/ \left(2 \times E_{elec} + E_{amp} \times {O_{ptTR}}^2\right). \tag{24}$$

Thus, the maximum streaming data gathering can be calculated using:

$$D = C_{SourceNode} \times R_{MAX} \times E_{xpeLifeTime} . \left(R_{MAX} \le T_{ransCapa}\right) \tag{25}$$

5.6 The MSDG algorithm

We propose the maximum streaming data gathering (MSDG) algorithm to maximize streaming data gathering in WSNs within an expected network lifetime. The flowchart of MSDG is presented in Fig. 1.

5.6.1 MSDG algorithm

- *Input:*
- $E_{xpeLifeTime}$, $E_{nerSensNode}$, M_{axTR}
- *Output:*
- Chosen $T_{ransRadius}$ and R_{MAX}

Step 1: Calculate ECR (M_{axTR}), ECR(O_{ptTR}) and ECR (E_{xpTR}) based on Eqs. 19, 20, 22;

Step 2: Choose the appropriate transmission radius for streaming data transmission based on criteria presented in Section 5.4;

Step 3: Calculate the maximum R_{MAX} based on Eqs. 23 or 24;

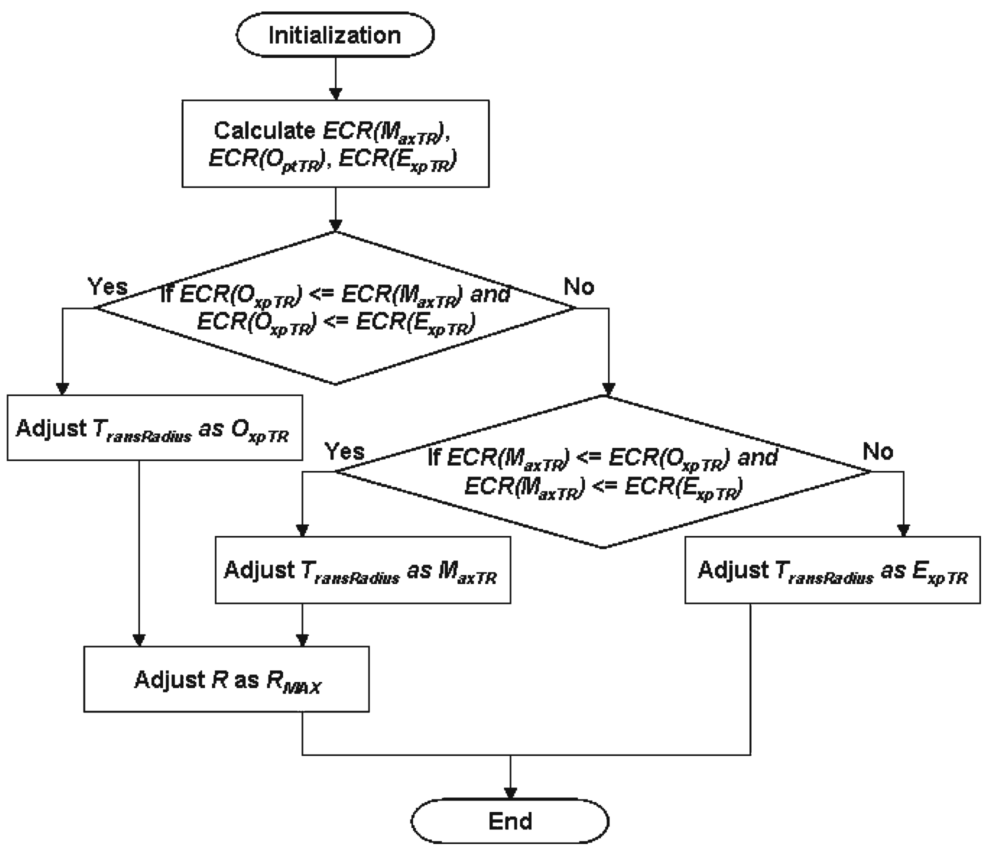


Figure 1 Flowchart of the MSDG algorithm

Step 4: Use chosen $T_{ransRadius}$ and calculated R_{MAX} to transmit streaming data to base station.

6 Minimum transmission delay

6.1 Problem formulation

Definition 4 *End-to-end transmission delay* Given a distance $D_{istance}$ between a source node S_i and the base station, when using any greedy forwarding routing protocol, with the average delay of each hop $D_{hop} + D_{otherfactors}$, the end-to-end transmission delay D_{e2e} can be defined as

$$D_{e2e} = \lceil D_{istance} / T_{ransRadius} \rceil \times (D_{hop} + D_{otherfactors}), \tag{26}$$

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.

According to Definition 4 and Theorem 1, the minimum transmission delay problem can be formulated as:

$$\text{Minimize} \quad D_{e2e} = \lceil D_{istance} / T_{ransRadius} \rceil \times (D_{hop} + D_{otherfactors}) \tag{27}$$

Subject to:

$$T_{ransRadius} \leq M_{axTR} \tag{28}$$

$$R \leq T_{ransCapaSour} \tag{29}$$

$$R \times \left(2 \times E_{elec} + E_{amp} \times T_{ransRadius}{}^2\right) \leq E_{nerSensNode} \big/ E_{xpeLifeTime} \tag{30}$$

Since $D_{istance}$, D_{hop} and $D_{otherfactors}$ are fixed parameters in Eq. 27, minimizing D_{e2e} is equivalent to maximizing $T_{ransRadius}$.

6.2 Choosing the larger transmission radius

Based on Section 5.3 we have energy consumption rates ECR(M_{axTR}) and ECR(E_{xpTR}). We propose the following criteria to choose the largest transmission radius to minimize the number of hops used for routing.

- If ECR (E_{xpTR}) ≤ ECR(M_{axTR}), then we can only choose E_{xpTR} for streaming data transmission. If we consume energy with a larger energy consumption rate than ECR (E_{xpTR}), the expected network lifetime cannot be guaranteed.
- Otherwise, if ECR(M_{axTR}) < ECR(E_{xpTR}), then we can only choose M_{axTR} for streaming data transmission. If the M_{axTR} is the physically allowed maximum transmission radius, it is impossible to have a transmission radius larger than the hardware constraint.

When sensor nodes use M_{axTR} for transmission, we can still use the source node to increase the R to maximize the streaming data gathering as Eq. 23.

6.3 Choosing the larger transmission radius

We propose the minimum transmission delay (MTD) algorithm to minimize transmission delay for streaming data gathering in WSNs within an expected network lifetime. The flowchart of the MTD is presented in Fig. 2.

6.3.1 MTD algorithm

- *Input:*
- $E_{xpeLifeTime}$, $E_{nerSensNode}$, M_{axTR}
- *Output:*
- Chosen $T_{ransRadius}$ or E_{xpTR}, R_{MAX} or R

Step 1: Calculate ECR(M_{axTR}), ECR(E_{xpTR}) based on Eqs. 19, 22;

Step 2: Choose the larger transmission radius for streaming data transmission based on criteria presented in Section 6.2;

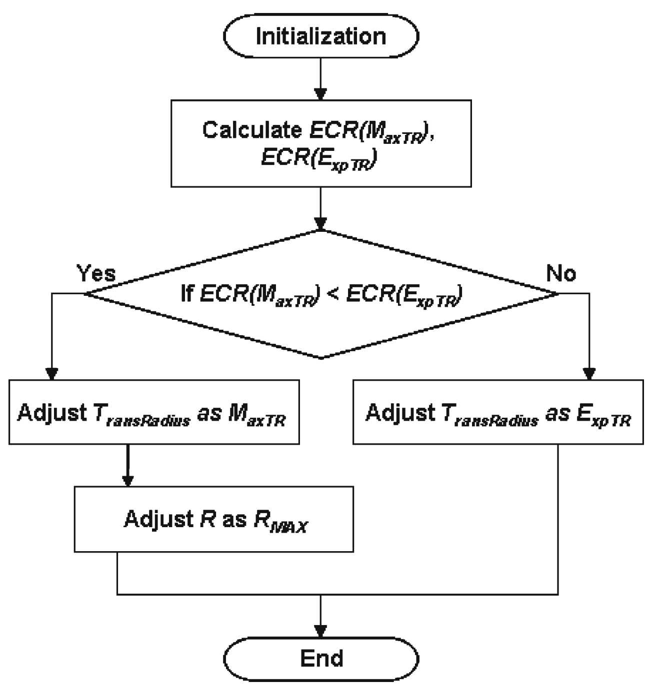


Figure 2 Flowchart of the MTD algorithm

Step 3.1: If ECR(M_{axTR}) < ECR(E_{xpTR}), calculate the maximum R_{MAX} based on Eq. 23 then use the chosen $T_{ransRadius}$ and the calculated R_{MAX} to transmit streaming data to base station;

Step 3.2: If ECR (E_{xpTR}) ≤ ECR(M_{axTR}), then use E_{xpTR} and minimum R to transmit streaming data to base station.

7 TPGF routing protocol

In this section we introduce the two-phase geographical greedy forwarding (TPGF) routing algorithm in network layer. TPGF uses the adjusted transmission radius to explore one or multiple hole-bypassing paths.

7.1 Design goal of TPGF

Definition 5 *Node-disjoint routing path* A node-disjoint routing path is defined as a routing path which consists of a set of sensor nodes, excluding the source node and the base station, none of these sensor nodes can be reused for forming another routing path.

Limited transmission capacity of sensor nodes can easily cause dynamic holes inside WSNs when tens of nodes in a small area overload because of transmitting multimedia streaming data. These dynamic holes combined with static holes, which can easily exist in WSNs, deem it necessary for creating a new hole-bypassing routing algorithm. This new routing algorithm should guarantee that the routing paths will be found if they exist. Moreover, this new routing algorithm should be repeatedly executable, in order to explore multiple additional routing paths if they are needed. The feature of *node-disjoint* should be used because generally multimedia streaming data transmission will use the maximum transmission capacity of each path, which does not allow the sharing of a transmission path. In short, we summarize our design goals as the following three aspects:

- *Hole-bypassing*, the new routing algorithm should be able to bypass holes
- *Guarantee path exploration result*, the new routing algorithm should be able to find the routing paths when they exist
- *Node-disjoint multipath transmission*, the new routing algorithm should be repeatedly executable, in order to find multiple node-disjoint routing paths.

7.1.1 Hole-bypassing

Among the three design goals, the hole-bypassing has the highest priority in protocol realization, because it will highly affect the performance of multimedia streaming data transmission if some holes hinder the routing paths. In this paper, we classify holes into the following two categories: *closed-circle hole* and *open-circle hole*.

Definition 6 *Closed-circle hole* A group of unavailable sensor nodes inside a WSN that are fully surrounded by other active sensor nodes is defined as a *closed-circle hole*.

Definition 7 *Open-circle hole* A group of unavailable sensor nodes inside a WSN that are partially surrounded by other active sensor nodes is defined as an *open-circle hole*.

When both closed-circle hole and routing paths (dynamic hole) exist in the same WSN, the dynamic open-circle hole will sometimes appear. In other words, the routing path nodes can enlarge the holes, because these routing path nodes cannot be reused in other routing paths (node-disjoint).

Research work [22–24] only focus on the closed-circle hole-bypassing. Only the research work [20] has the potential to bypass the open-circle hole because of using the right hand rule, but its result is not always guaranteed. The probability of bypassing a closed-circle hole based on the approach of [22] is 100%, because when the routing path meets the boundary node of a hole it can successfully go further along the boundary of the hole either from the clockwise or the counterclockwise side.

The probability of bypassing a closed-circle hole based on GPSR is also 100%, because the right hand rule can always find the first counterclockwise node as the next-hop node. The probability of bypassing an open-circle hole based on the approach of [22] is only 50%, because the routing path can only successfully go further along the boundary of the hole from the clockwise side, (in other situation maybe only from the counterclockwise side).

The probability of bypassing an open-circle hole based on GPSR is not guaranteed[1], because even though the right hand rule can explore all the neighbor nodes of any sensor node it does not handle the situation when no neighbor node is available for the next-hop transmission, and actually there is an available path which can connect the source node and the base station. For example, in Fig. 3, the exploration of GPSR will stop at the *block node*. However, the dotted routing path (blue color) can lead the source node to the base station.

Definition 8 *Block node and block situation* For any sensor node, during the exploration of a routing path in a WSN, if it has no next hop node that is available for transmission, this node is defined as a *block node* and this kind of situation is defined as a *block situation*.

[1] In [21], the authors proved that GPSR does not always find the routing path when the routing path actually exists.

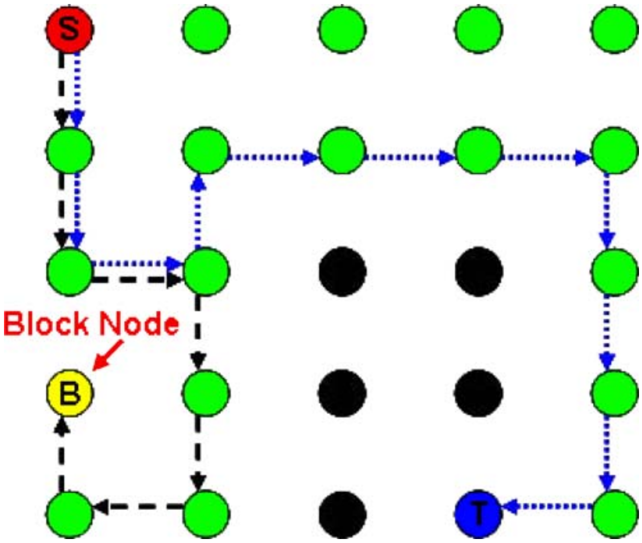


Figure 3 Block situation

7.1.2 Guarantee path exploration result

The guarantee path exploration result has the second priority among the four design goals, which is designed to handle the block situation.

To handle the block situation we propose the *step back & mark* approach: When a sensor node finds that it has no neighbor node available for the next-hop transmission it will mark itself as a Block Node and step back to its previous-hop 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 routing path to the base station.

Theorem 2 *For any given source node, using the step back & mark approach can guarantee that it can explore every connected sensor node, which can be reached in single or multiple hops*.

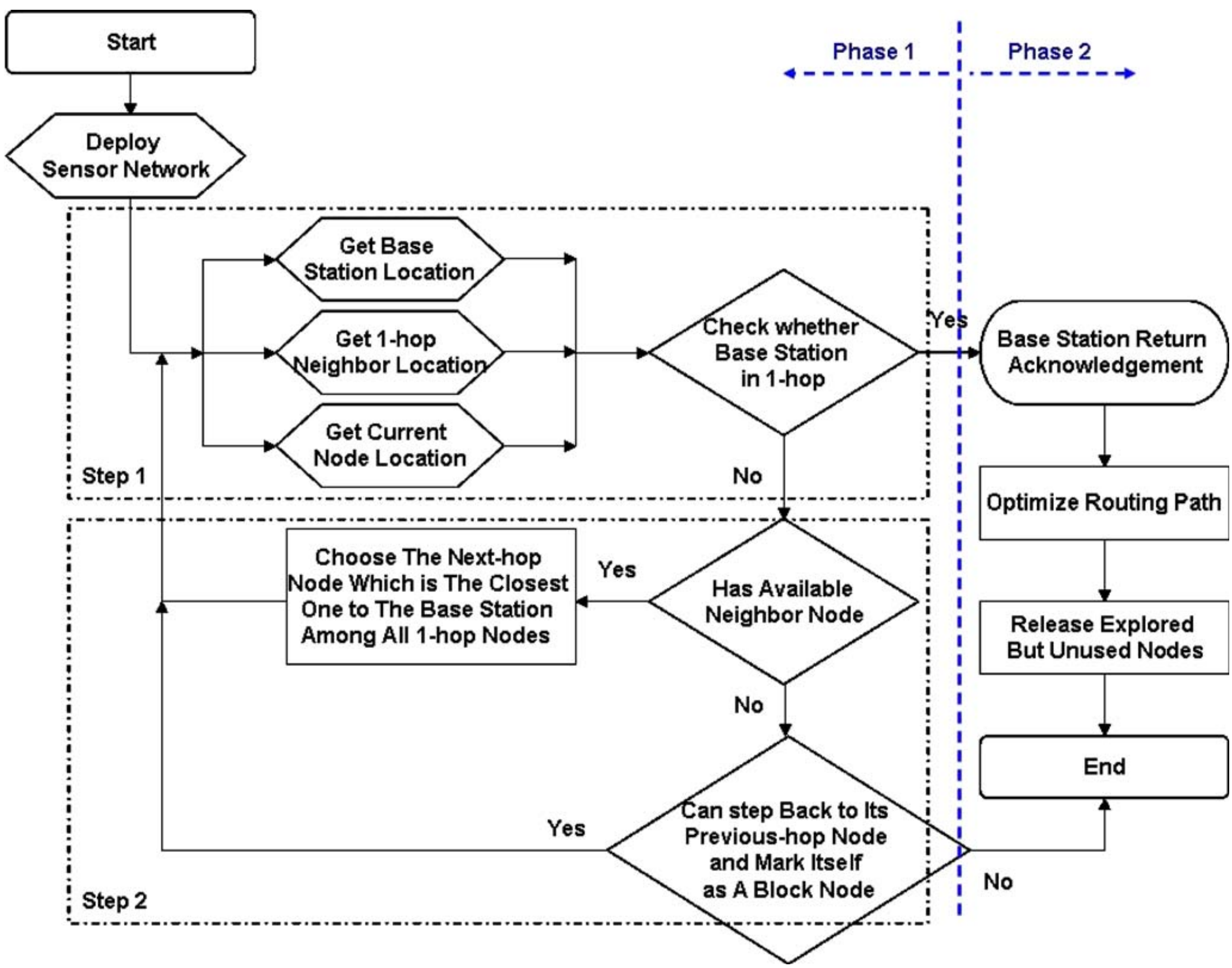


Figure 4 Flowchart of TPGF routing algorithm

Proof Refer to the backtracking algorithms in [28].

Using the *step back & mark* approach guarantees that: TPGF can explore every connected sensor node, which can be reached by the source node in any number of hops. Consequently, it can guarantee that the new TPGF routing algorithm can always find the routing paths if they exist.

7.1.3 Multipath transmission

Multipath transmission is used to increase transmission performance in WSNs. The node-disjoint multipath transmission has the lowest priority in the protocol realization, because once one routing path is created for a source node, at least some amount of data can be transmitted to the base station.

The feature of node-disjoint multipath transmission is that it can look for more routing paths to increase the multimedia streaming data transmission when it is necessary. However, multipath transmission is not always guaranteed because there may be no more existing routing path. The number of the routing paths is restricted by the number of neighbor nodes. For example, a source node has only two neighbor nodes, which limits the maximum number of routing paths to two. Moreover, the number of routing paths is also affected by the routing algorithm used [29].

In this paper, we do not explore the research issue of maximizing the number of routing paths. We set “always exploring the shortest transmission path” as the basic criteria, and then explore the possible number of routing paths based on our designed routing algorithm. The primary motivation is that the shortest transmission path generally has the smallest end-to-end delay which may satisfy the delay constraint of multimedia streaming data.

7.2 TPGF routing algorithm

Two-phase geographical greedy forwarding (TPGF) routing algorithm includes two phases. The first phase is responsible for exploring the possible routing path. The second phase is responsible for optimizing the discovered routing path with the shortest transmission distance (least number of hops). TPGF can be executed repeatedly to find multiple node-disjoint routing paths. In TPGF, we assume that only source nodes know the location of the base station. This assumption is the same as the assumption used in GPSR.

The inputs of TPGF are: (1) location of the current forwarding node; (2) location of the base station; (3) locations of the one-hop neighbor nodes. The outputs of TPGF are: (1) location of the next-hop node; or (2) successful acknowledgement; or (3) unsuccessful acknowledgement. It is noteworthy that the input information of TPGF is exactly the same as the input information of GPSR.

The flowchart of TPGF is presented in Fig. 4. The detailed description of TPGF routing algorithm is as follows: phase 1: step (1) the source node checks whether it has a usable one-hop neighbor node. If not, the source node produces an unsuccessful acknowledgement and stops transmitting. If it does, then the source node checks whether the base station is one of its one-hop neighbor nodes. If it is, then it builds up a routing path. If not, the source node tries to find the unlabeled (unoccupied) next-hop node which is the closest one to the base station. 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 among one of its one-hop nodes. If it is, then it builds up routing path. If not, the chosen sensor node always tries to find the closest neighboring next-hop node to the base station which has 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 for the next-hop transmission, which means the block situation is met, it will mark itself as a block node and step back to its previous-hop 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: 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 which belongs to this path

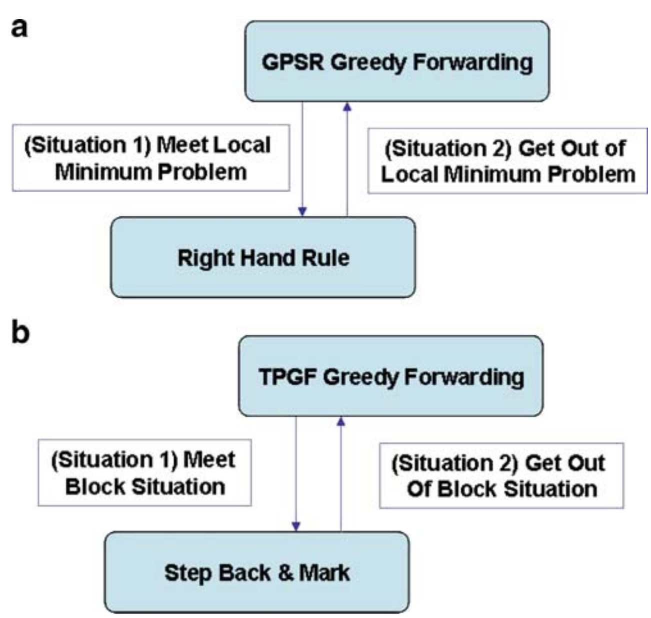
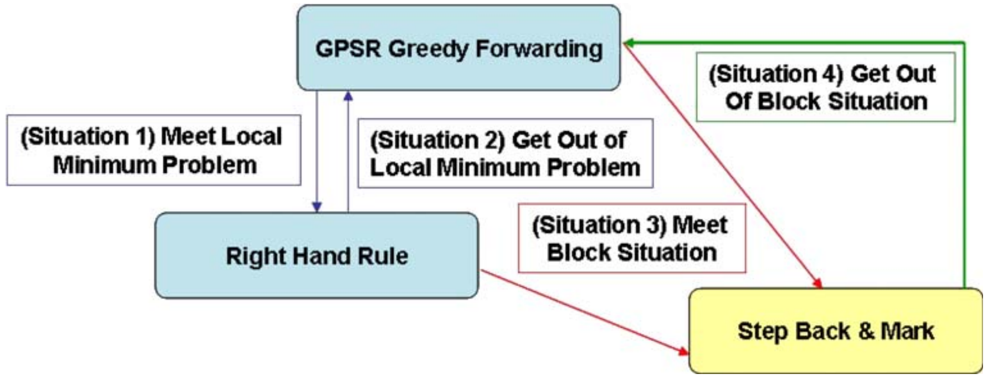


Figure 5 **a** Component based overview of GPSR; **b** component based overview of TPGF phase 1

Figure 6 Adding *step back & mark* component to GPSR



only relays packets to its one-hop neighbor node which is labeled in step (2) and has the largest 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.

The time complexity of this algorithm is $O(n)$ where n is the number of nodes in this sensor network, because at most $(n-1)$ edges would be traversed for a search and each edge can be traversed no more than twice.

7.3 High level comparison

We will now give a high level comparison with related research work to highlight the advantages of TPGF. The hole-bypassing part in TPGF is different from related work [22–24], because TPGF does not need to identify the hole information in advance, which reduces the complexity of hole-bypassing routing. Using hole information as the additional information for hole-bypassing actually makes the problem much easier. In this paper we do not compare TPGF with these three research works because the basic assumptions for algorithm inputs are different. TPGF can be categorized into as hole-bypassing without knowing the hole information in advance. In this paper, we focus on the comparison between GPSR and TPGF.

7.3.1 Function level comparison

Figure 5a shows the component-based overview of GPSR and Fig. 5b shows the component based overview of the first phase of TPGF. The slight changing from the GPSR greedy forwarding to TPGF greedy forwarding results in that the local minimum problem does not exist any more. Additionally, TPGF solves the block situation problem which GPSR cannot solve. If the *step back & mark* component can be added into GPSR as shown in Fig. 6, the GPSR can have the same functionality as TPGF in terms of solving the block situation, but with different performance.

7.3.2 Application environment comparison

GPSR is designed for two-dimension WSNs, which allows GPSR to use the right hand rule with the angle information, e.g. counterclockwise angle. If the GPSR is used in three-dimension WSNs, the definitions of "right-hand and counter/clockwise" do not exist any more, with the result that using GPSR cannot find the routing path. However, TPGF can still find the routing path because TPGF only compares the distance between the neighbor node and the base station but does not depend on the angle information.

7.3.3 Algorithm complexity comparison

GPSR is more complex than TPGF. The right hand rule component in particular needs more computation to choose the next-hop node when the local minimum problem is encountered. Figure 7 gives an example of this. In TPGF the decision of choosing the next-hop node can be easily

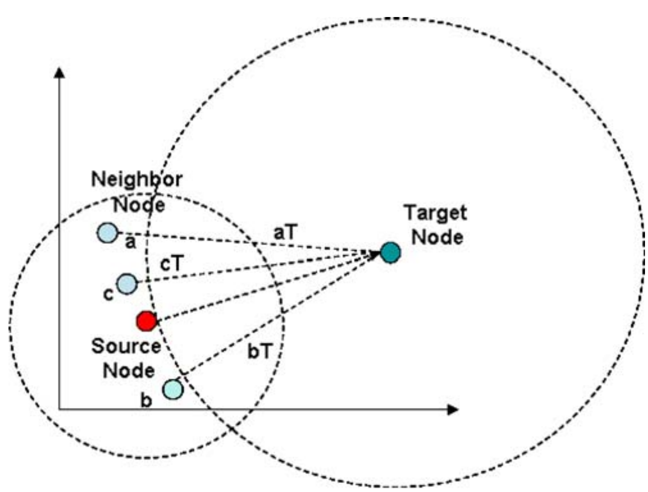


Figure 7 Local minimum problem

Table 1 GPSR vs. TPGF

Comparison point	GPSR	TPGF
Greedy forwarding	Current node always tries to find the next-hop node which is closer to the base station than itself	Current node always tries to find the next-hop node which is closest to the base station among all neighbor nodes, the next-hop node can be further to the base station than itself
Local minimum problem	Exists	Does not exist
Block situation	Exists, when the sensor node finds that it has no neighbor node available for the next-hop transmission	No block situation, it is solved by the Step Back & Mark approach
Maintenance of the underlying planar graph	Yes, required	Not required
Applicable for 3D sensor networks	Not applicable, because the *right hand rule* only works for 2D	Applicable, because only the distance between sensor nodes are compared
Guarantee exploration result	No, because the *block situation* exists	Yes, because the *step back & mark* approach solves the problem
Multipath transmission	No, GPSR is not designed for this, because the planar graph will make the graph lose many links, which could be used in the multiple paths	Yes, TPGF is designed for multipath transmission

made by comparing the three distances: aT, bT and cT. The node with the smallest distance is chosen. However, in GPSR, the right hand rule is used to choose the first counterclockwise node. The steps of the right hand rule realization are provided, which is used to demonstrate the complexity of GPSR[2]:

Realization steps of right hand rule

Step 1: Compare angle

In [20], GPSR routing algorithm uses the *bearing angle* brg = Math.atan2($y2-y1$, $x2-x1$) function to compare different angles. When brg<0, and they convert the as brg=brg+2* Math.PI. The nodes with the smallest bearing angle are chosen out. In Fig. 7, both node a and c have the smallest bearing angle.

Step 2: Compare the distance

If several nodes have the same bearing angle, GPSR chooses the one which has the *shortest distance*. For example, in Fig. 7 node a and c have the same bearing angle, then compare the distance between neighbor node and source node aT and cT. Since cS is short than aS, the node c is chosen as the next-hop node in this case.

[2] This realization steps are summarized from the GPSR source code at http://www.j-sim.org/contribute/jsim-gpsr1.01.tgz. The *Math.atan2* function used here actually hides the complexity of the real computation. The real computation of *Right Hand Rule* can be as complex as shown in http://sip.deri.ie/wiki/upload/leishu/doc/REALIZATION_STEPS_OF_RIGHT_HAND_RULE.doc.

7.3.4 Summary of comparison

We summarize the comparison between GPSR and TPGF as shown in Table 1.

8 Simulation

In order to evaluate the proposed algorithms, we have implemented a sensor network simulator called NetTopo. NetTopo allow users to simulate the deployment a sensor network with an area up to 500×500 m, up to 400 sensor nodes and up to 100 source nodes. Table 2 shows the parameters used in the simulation. The physically allowed transmission radius MTR is an important parameter that can

Table 2 Simulation parameters

Parameter	Value
Network size	500×500 m
Base station location	Corner or central
Number of base stations	1
Number of sensor nodes	390
Number of source nodes	16
Initial energy of base station	Not limited
Initial energy of sensor node	36 J (3 batteries)
Minimum flux of streaming data *R*	5 kbps
Sensor node maximum TC	20 kbps
Maximum TR MTR	Not fixed
E_{elec}	50 nj/bit
E_{amp}	0.1 nj/bit/m^2
Optimal TR OTR	100 m

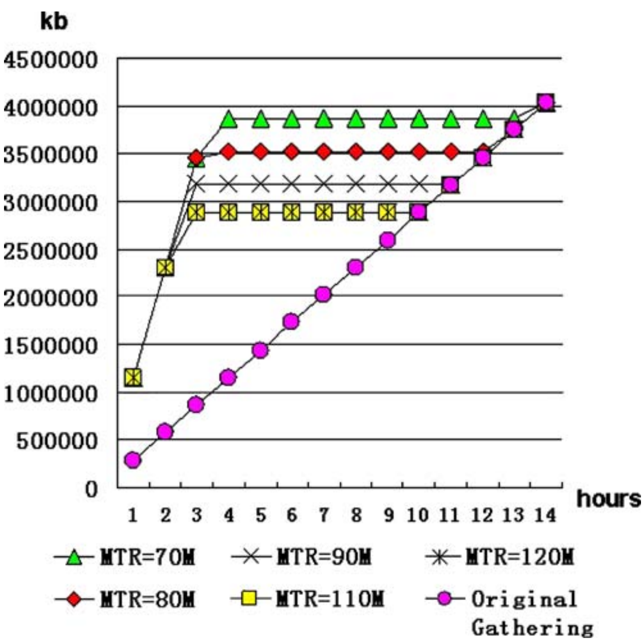


Figure 8 MSDG: Gathered streaming data vs. expected network lifetime

affect the amount of the streaming data received at the base station. In the simulation we set MTR=70, 80, 90, 110 and 120 m respectively.

8.1 Evaluation of MSDG algorithm

The line of original gathering in Fig. 8 shows the gathered streaming data without using MSDG algorithm. It can be seen from Fig. 8 that the MSDG algorithm maximizes the streaming data gathering given a fixed MTR within a fixed expected network lifetime. For example, by using the MSDG algorithm with MTR=110 m, the sensor nodes can maximize the gathering of streaming data within an expected network lifetime of 10 h.

From simulation results as shown in Figs. 9 and 10, we can see that a shorter MTR allows more streaming data to be gathered but it also needs more relay nodes to participate in every routing path and the corresponding average delay is also longer. When MTR ≥ OTR, sensor nodes only use OTR for streaming data transmission, the maximum amounts of gathered streaming data in two different conditions when MTR=110 m and MTR=120 m are the same.

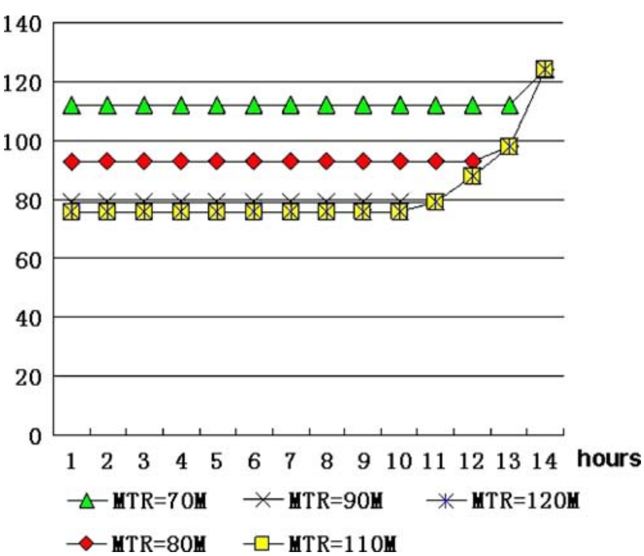


Figure 9 MSDG: Total number of relay nodes vs. expected network lifetime

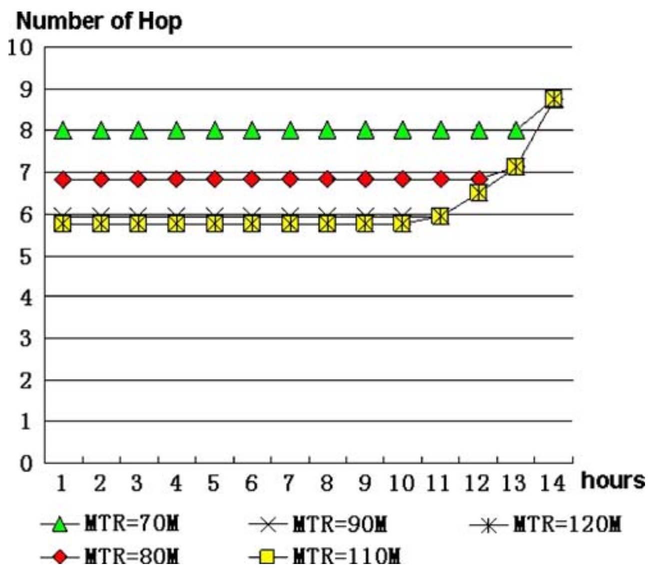


Figure 10 MSDG: Average end-to-end delay vs. expected network lifetime

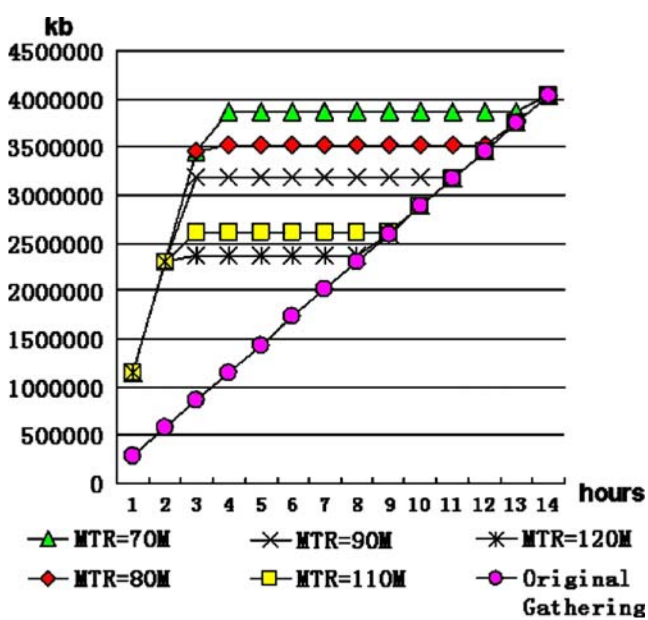


Figure 11 MTD: Gathered streaming data vs. expected network lifetime

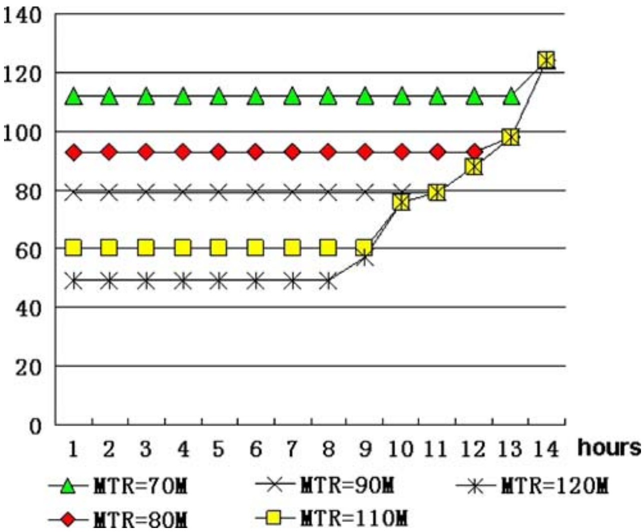


Figure 12 MTD: Total number of relay nodes vs. expected network lifetime

When the expected network lifetime increases to 14 h, sensor nodes have to use the expected transmission radius for transmission in any situation. Thus, the five lines in Fig. 8 finally converge at the same point.

8.2 Evaluation of MTD algorithm

From our simulation results, as shown in Figs. 11, 12 and 13, we can see that a shorter MTR leads to a longer average transmission delay, and a longer expected network lifetime also leads to a longer average transmission delay.

When sensor nodes use the MTD algorithm to transmit streaming data the results of maximum streaming data gathering in Fig. 11 are different from Fig. 8 because in the MTD algorithm the MTR is used instead of OTR. However, the MTD algorithm can essentially reduce the end to end transmission delay. For example, given MTR= 120 m, the MTD algorithm can provide a smaller transmission delay when the expected network lifetime is shorter than 8 h.

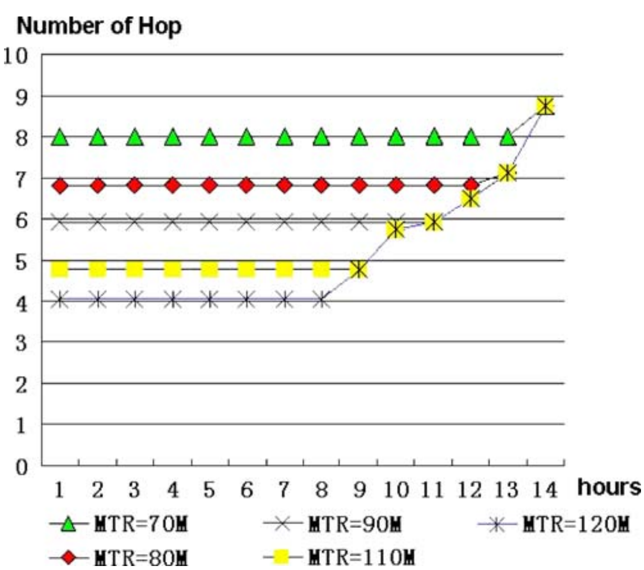


Figure 13 MTD: Average end-to-end delay vs. expected network lifetime

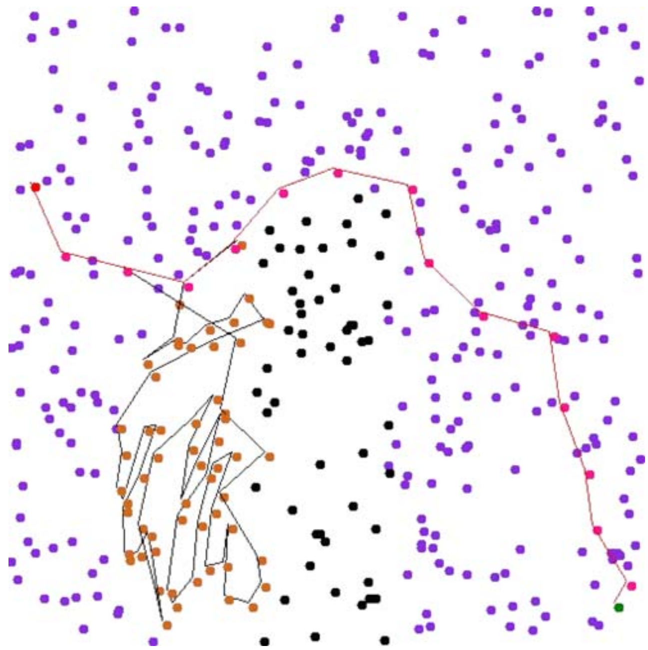


Figure 14 The number of TPGF searched sensor nodes is 71. After optimization, the number of actual used sensor nodes is 14

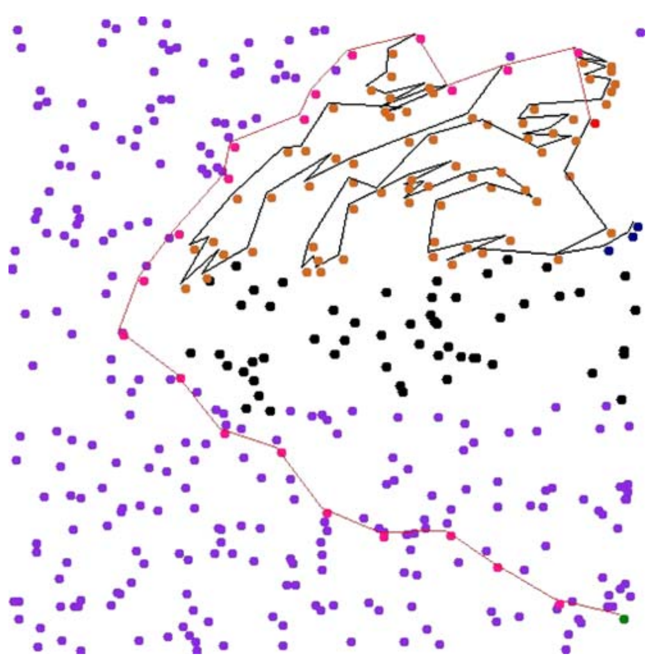


Figure 15 TPGF can find a path

8.3 Execution comparison: GPSR vs. TPGF

In this subsection, we demonstrate the execution comparison between GPSR and TPGF. We implemented two different versions of GPSR in NetTopo: clockwise and counterclockwise versions. The clockwise version of GPSR (GPSR_CW) means that when the local minimum problem is met, GPSR always tries to find the first clockwise neighbor node as the next-hop node. The counterclockwise version of GPSR (GPSR_CCW) means when the local minimum problem is met, GPSR always tries to find the first counterclockwise neighbor node as the next-hop node.

We set a large open-circle hole inside the sensor network as shown in Fig. 14. The number of sensor nodes explored by GPSR_CW is 118 and the number of sensor nodes explored by GPSR_CCW is 43. The sensor nodes explored by TPGF is 71. After optimization, the number of sensor nodes used for final streaming data transmission is only 14, which means the final transmission path of TPGF is much shorter when compared with both versions of GPSR.

We also provide an example to demonstrate that TPGF can guarantee the exploration result but GPSR cannot. In Fig. 15, no routing path can be found by using both the GPSR_CW and GPSR_CCW. However, using the TPGF can successfully find a routing path and, after optimizing the routing path, it uses only 20 sensor nodes.

9 Conclusion

Efficiently transmitting and gathering multimedia streaming data in WSNs raises several challenging issues. In this paper, we first studied two important problems for multimedia streaming data gathering: (1) gathering as much data as possible within an expected network lifetime; (2) minimizing transmission delay within an expected network lifetime. The MSDG and MTD algorithms are proposed to solve these two problems. Either of these two algorithms should be run during the initialization phase in every node in order to choose the appropriate transmission radius. When the data generating rate R of a source node is larger than the maximum transmission capacity $T_{ransCapa}$ of sensor nodes, we find that using node-disjoint multipath transmission can solve the problem. Therefore, we presented a new TPGF routing algorithm to address three key issues: (1) hole-bypassing; (2) guarantee path exploration result; (3) multipath transmission. Both high level and simulation comparisons show that TPGF is much better than the well known GPSR in both functionality and performance aspects. Simulation results show that our algorithms can solve the problems identified above. Our algorithms can be used in various applications when multimedia sensor nodes are deployed in WSNs for gathering streaming data continuously during a short period of time. We believe that our research results can make a strong impact on both mobile multimedia and WSNs research communities.

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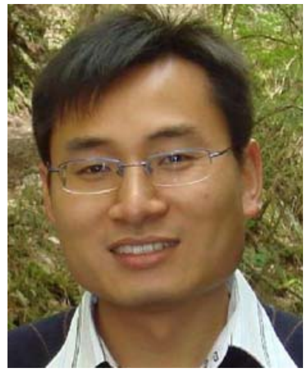

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