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# RGF: Receiver-based Greedy Forwarding for Energy Efficiency in Lossy Wireless Sensor Networks

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## *Abstract*

Greedy forwarding is the key mechanism of geographic routing and is one of the protocols used most commonly in wireless sensor networks. Greedy forwarding uses 1-hop local information to forward packets to the destination and does not have to maintain the routing table, and thus it takes small overhead and has excellent scalability. However, the signal intensity reduces exponentially with the distance in realistic wireless sensor network, and greedy forwarding consumes a lot of energy, since it forwards the packets to the neighbor node closest to the destination. Previous proposed greedy forwarding protocols are the sender-based greedy forwarding that a sender selects a neighbor node to forward packets as the forwarding node and hence they cannot guarantee energy efficient forwarding in unpredictable wireless environment. In this paper, we propose the receiver-based greedy forwarding called RGF where one of the neighbor nodes that received the packet forwards it by itself. In RGF, sender selects several energy efficient nodes as candidate forwarding nodes and decides forwarding priority of them in order to prevent unnecessary transmissions. The simulation results show that RGF improves delivery rate up to maximum 66.8% and energy efficiency, 60.9% compared with existing sender-based greedy forwarding.

***Keywords:*** Wireless sensor networks, geographic routing, greedy forwarding, unreliability, energy-efficiency

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## 1. Introduction

Geographic routing [1][2] is a key paradigm that forwards the packet by using geographic location information and is one of the techniques used most commonly in wireless sensor networks. Geographic routing transmits packets to the destination based on the local information only and that it does not create the overhead for maintaining routing table and has excellent scalability. This advantage is quite suitable for the dense and energy-restricted wireless sensor networks without using any permanent network infrastructure. Generally, geographic routing uses greedy forwarding to send packets to the destination. Greedy forwarding (or original greedy forwarding) sends the packet to the neighbor node located closest to the destination and is the key mechanism of geographic routing.

Existing geographic routing protocols hypothesize the wireless sensor network environment where there is no packet loss within the transmission range and the forwarding succeeds invariably. However, the realistic wireless sensor networks does lose packets due to the characteristics of wireless environment such as signal interference, attenuation, and the success of forwarding within the range is not guaranteed [3][4]. Recent studies show through experiments that the link between two nodes within the range of the realistic wireless sensor networks is quite unreliable, and this unreliable link causes rapid increase of packet loss, retransmissions, and high energy consumption in forwarding process [5]. Especially, the greedy forwarding that chooses the neighbor node closest to the destination can easily choose unreliable link that it causes the waste of energy above the expected level in the realistic wireless sensor networks.

Recent studies concerned with reducing energy waste and packet loss in greedy forwarding in the actual wireless sensor network environment proposes statistical link layer model based energy efficient greedy forwarding. This method uses the 1-hop neighbor node's Packet Reception Rate (PRR) defined through statistical link layer model in the packet forwarding process to avoid unreliable link and minimizes the waste of energy due to retransmissions. However this method is a sender-based forwarding where the sender node determines the forwarding node just as in greedy forwarding that it is not appropriate for the realistic wireless sensor networks where it is difficulty determine whether the packet is successfully delivered or not.

In this paper, we propose Receiver-based Greedy Forwarding (RGF) to supplement the weakness that existing sender-based greedy forwarding has in the realistic wireless sensor network. In the proposed scheme, RGF, the sender node does not determine the forwarding node but the neighbor nodes that received the packet determine whether they become the forwarding nodes. RGF selects a number of highly reliable and efficient neighbor nodes as candidate forwarding node, and determines the forwarding priority based on the distance to the destination. Also, the candidate forwarding node with the highest priority among the candidate forwarding nodes which received packets acts as the next-hop forwarding node. This paper is extended version of our earlier work [6]. This version presents further analysis and supporting implementation results; thus, followings are the contribution of RGF:

- Sender-based forwarding which the sender node determines the forwarding node that it is not appropriate for the realistic wireless sensor networks where it is difficulty determine whether the packet is successfully delivered or not. To solve the problem of sender-based forwarding, we first consider a receiver-based forwarding scheme.

- Compared with the sender-based greedy forwarding that selects a fixed node as the forwarding node, the forwarding nodes of receiver-based greedy forwarding are selected among neighbor nodes which received a packet, so it enhances the network lifetime.
- In detailed, RGF hardly wastes energy as it minimizes the number of retransmissions due to packet loss unless all candidate forwarding nodes fail to receive the packet. The neighbor node that received the packet becomes the forwarding node depending on its own energy efficiency, that RGF selects the best forwarding node.

According to the simulations performed with various topologies, RGF shows higher packet delivery rate than existing sender-based greedy forwarding protocols and reduces the number of unnecessary retransmissions to enhance energy efficiency. Via detailed simulations, RGF has higher packet delivery rate and energy efficiency in an environment with higher node density that it is quite effective for the wireless sensor networks. Also, the measurement of residual energy of all nodes shows that RGF has higher residual energy and lower deviation than existing greedy forwarding that it appears to be effective also in terms of network lifetime.

The remainder of this paper is organized as follows: The related work is briefly described in Section 2. Our proposed protocol RGF is presented in Section 3. In Section 4, we evaluate the performance of RGF via various simulations and compare its performance with previous greedy forwarding protocols in Section 4. Finally, we conclude our work in Section 5.

## 2. Related Work

Early work in geographic routing consider only original greedy forwarding [7] by using the location information of neighbor nodes to forward the packet closest to the destination at each hop. Because it selects the next forwarding node using only the location information of the neighbor nodes, the original greedy forwarding can be efficient, low-overhead method of packet delivery if it is reasonable to assume high link reliability independent of distance within the physical radio range. Greedy forwarding fails when reaching a local minimum, a node that has no neighbors closer to the destination. A number of papers in the past few years have been proposed to efficiently avoid a local minimum and enhance greedy forwarding [8][9][10][11]. More details about geographic routing schemes can be found in the following surveys [1][2].

Much of these prior research done in wireless ad hoc and sensor networks, including geographic routing schemes has been based on a set of simplifying idealized assumptions about the wireless channel characteristics, such as perfect coverage within a circular radio range. In realistic wireless sensor networks, however, pertaining to the idealized assumptions is unlikely to be valid because of wireless characteristics. Several researchers have pointed out how simple radio models(e.g., the idealized assumption that there are perfect links between pairs of nodes within a given radio range, beyond which there is no link) may lead to wrong results in wireless ad hoc and sensor networks.

Kotz *et al.* [12] enumerate the set of common assumptions used in wireless ad hoc and sensor networks research, and provide data demonstrating that these assumptions are not usually correct. The real connectivity graph can be much different from the ideal disk graph, and losses due to fading and obstacles are common at a wide range of distances. The communication area covered by the radio is neither circular nor convex, and is often noncontiguous. On the same line of work, Woo *et al.* [13] study the effect of link connectivity on distance-vector based routing in wireless sensor networks. They too identify the existence of the three distinct reception regions: connected, transitional, and disconnected region. The authors of [14][15], they show that wireless links can be highly unreliable and that this must explicitly taken into account when evaluating the performance of higher-layer protocols. The existence of such unreliable links exposes a key weakness of greedy forwarding in wireless sensor networks. Finally, Li *et al.* propose a new DTN routing protocol [16] for Delay-Tolerant Vehicular Sensor Networks, Packet-Oriented Routing protocol (POR), which is designed to emphasize neighbor selection based on awareness of packets to be sent and in consideration of probability to complete transferring of these packets. In this scheme, the neighbor selection process selects the neighbor candidate to construct a connection based on awareness of packets to be sent and in prior consideration of the probability of successful transferring of these packets. However, our study does not consider Vehicular Sensor Networks.

To avoid selecting unreliable links, several noteworthy greedy forwarding protocols that transmit packets effectively to the destination considering the link quality (same as PRR) in realistic wireless sensor networks have recently been proposed. Seada *et al.* [17][18] proposed the PRR × Distance greedy forwarding that selects the next forwarding node by multiplying the PRR by the distance to the destination. They proved, based on a mathematical analysis, that the energy efficiency becomes largest when the packet is forwarded to the node that has the largest value after the multiplication of the PRR by the distance. Therefore, PRR × Distance greedy forwarding forwards packets by multiplying the PRR between the sender node to the neighbor node and the distance between the neighbor node and the destination, and selecting, as the next forwarding node, a neighbor node that has the largest value after the multiplication. In other words, by selecting a forwarding node with a good PRR, which is the link quality between the two nodes that is closest to the destination, PRR × Distance greedy forwarding avoids to select a neighbor within unreliable region as a forwarding node.

In [19], Couto *et al.* have measurements for DSDV and DSR, over a 29-node 802.11b test bed and show that the minimum hop-count metric has poor performance, since it is not taking the channel characteristics into account, especially with the fact that minimizing the hop count maximizes the distance traveled by each hop, which is likely to increase the loss ratio. They present the expected transmission count metric (ETX) that finds high throughput paths by incorporating the effects of link loss ratios, asymmetry, and interference. Draves *et al.* [20] extend the study of the ETX by comparing it with other metrics: per-hop round trip time and per-hop packet pair. Based on a wireless test bed running a DSR-based routing protocol, they confirm that the ETX has the best performance when all nodes are stationary. The minimum ETX, however, is a global path metric so that not suitable for scalable routing protocols such as geographic routing.

## 3. Preliminaries

In this section, we introduce the system model used to model the realistic wireless sensor network in this study before explaining the proposed scheme. We also proves how much packet delivery rate the receiver-based forwarding improves compared with the sender-based forwarding which chooses a single forwarding node by mathematically analyzing the probability that a number of nodes will receive the packet.

### 3.1 System Model

Analyzing and simulating a reliable data transmission protocol requires a realistic link layer model. In this paper, we use the PRR as the link quality between two nodes. The PRR takes its value from 0 to 1; and to calculate it, the following link layer model is used [21][22]:

$$PRR(d) = \left(1 - \frac{1}{2} e^{-\frac{\gamma(d)}{2} \frac{1}{0.64}}\right)^{\rho 8 f} \tag{1}$$

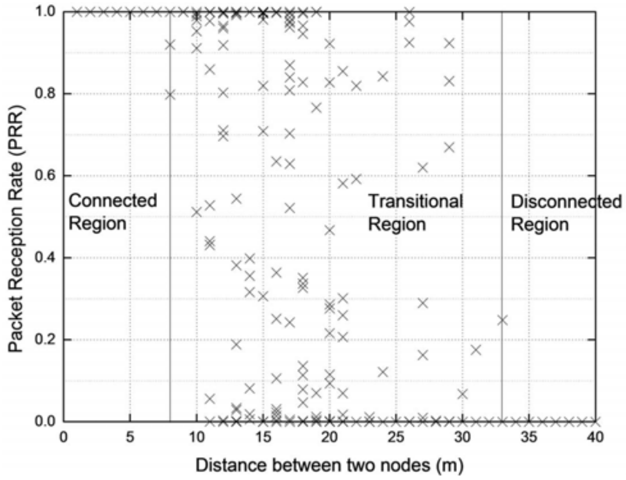


**Fig. 1**. Sample from a realistic link layer model

Where $d$ is the distance between the nodes, $\gamma(d)$ is the Signal to Noise Ratio (SNR), $f$ is the frame length. This model considers various radio parameters, such as the path-loss exponent ($\eta$) and the log-normal shadowing variable ($\sigma$). In a simulated environment, and are 3.0 and 3.8, respectively. Formula (1) reflects the MICA2 mote that uses the NCFSK modulation method and Manchester Encoding. The other detailed information follows the MICA2 specifications [23].

Recent researches [14][21] have shown three distinct data reception regions; connected, transitional, and disconnected. In the connected region, nodes can transmit packets reliably in the absence of congestion: in transitional region, some links have high PRR while others the opposite. Therefore, when we design routing protocol, we should consider about this region; in disconnection region, no links or very weak link exists. In **Fig. 1** depicts the link layer model where the observed connected region from 0 to 8 *m*, transition region from 8 to 33 *m*, disconnected region from 33 *m*.

Our study is based on the following assumptions:

- Each node knows its location information and the position of the destination via GPS or some distributed localization methods [24] when GPS service is not available.
- Each node knows location and the PRR of their neighbor nodes by exchanging HELLO messages.
- Our study does not consider other means of energy savings such as sleep/awake scheduling, transmission power control.
- We also do not address MAC-layer behavior such as contention.

### 3.2 Mathematical Analysis

In this study, the probability that the packet will be successfully delivered to the forwarding node within the range is defined as 1-hop delivery success rate. 1-hop delivery success rate influences the delivery rate, the probability that the packet will reach the destination, and delivery rate increases when 1-hop delivery success rate is high. Therefore, this subsection will prove that the 1-hop delivery success rate of the Sender-based forwarding is greater than that of Receiver-based forwarding through the mathematical analysis of 1-hop delivery success rate of them.

First, the 1-hop delivery success rate of Sender-based forwarding is defined as $P_s$ and the 1-hop delivery success rate of Receiver-based forwarding when $n$ candidate forwarding nodes are selected at 1-hop, $P_r(n)$. Also, the link quality of each candidate forwarding node $i$ is defined as $PRR_i$. If the link quality of the neighbor node selected by Sender-based forwarding is $PRR_s$, the 1-hop delivery success rate $P_s$ of Sender-based forwarding is $PRR_s$ and this is same as when a single candidate forwarding node is selected in the Receiver-based forwarding that $P_r(1)$ equals $PRR_s$. This can be represented in Formula (2).

$$P_s = PRR_s = P_r(1), (0 \le PRR_s \le 1) \tag{2}$$

When Receiver-based forwarding chooses two candidate forwarding nodes and the link quality of the two nodes are named as $PRR_s$ and $PRR_1$ respectively, $P_r(2)$ can be expressed as follows as the delivery fails only when all two nodes are not received in Receiver-based forwarding.

$$\begin{aligned} P_r(2) &= 1-(1-PRR_s) \\ &= PRR_s + PRR_1 - PRR_s \times PRR_1, (0 \le PRR_1 \le 1) \end{aligned} \tag{3}$$

$PRR_s$ and $PRR_1$ will have a value between 0 and 1 that $PRR_s \times PRR_1$ is small than $PRR_1$. Therefore $P_r(2)$ is greater than $P_r(1)$ by $PRR_1 - PRR_s \times PRR_1$. 1-hop delivery success rate $P_r(3)$ when three nodes are selected as candidate forwarding nodes can be calculated as follows by using Formula (3).

$$\begin{aligned} P_r(3) &= 1-(1-PRR_s)(1-PRR_1)(1-PRR_2) \\ &= P_r(2) + PRR_2 - P_r(2) \times PRR_2, (0 \le PRR_2 \le 1) \end{aligned} \tag{4}$$

Formula (4) shows that $P_r(3)$ is greater than $P_r(2)$ by $PRR_2 - P_r(2) \times PRR_2$. $P_r(n)$ can be defined as follows through the formulas above.

$$P_r(n) = \begin{cases} PRR_s, (n=1) \\ 1-(1-PRR_s)\prod_{i=1}^{n-1}(1-PRR_i), (n \ge 2) \end{cases} \tag{5}$$

Where $n$ is the number of candidate forwarding nodes. The following is when $n$ is 2 or greater in Formula (5).

$$P_r(n) = P_r(n-1) + PRR_{n-1} - P_r(n-1) \times PRR_{n-1} \tag{6}$$

As represented in Formula (6), when $n$ candidate forwarding nodes are selected in Receiver-based forwarding, it will have higher 1-hop delivery success rate than when $n$ - 1 candidate forwarding nodes are selected. Therefore, when there are more than one candidate forwarding nodes, 1-hop delivery success rate is always greater compared with the Sender-based forwarding where one candidate forwarding node is selected thereby increasing the delivery rate. The important fact is that 1-hop delivery success rate will increase when there are more candidate forwarding nodes. In other words, 1-hop delivery success rate of Receiver-based forwarding appears higher in the wireless sensor network environment where the node density is high.

## 4. Receiver-based Greedy Forwarding

In this Section, we propose Receiver-based Greedy Forwarding, RGF.The goal of the proposed scheme is to reduce the number of retransmissions and eliminate unnecessary energy consumption by increasing delivery rate in the realistic wireless sensor networks with unreliable links. The basic idea of RGF to have a node located closest to the destination among energy efficient nodes that received packets play the role of forwarding node by itself to forward the packet. In this study, the energy efficient nodes capable of forwarding the packet are defined as candidate forwarding node. In the forwarding process, each forwarding node selects its candidate forwarding node at each hop, adds this information to the packet header and broadcasts. If all candidate forwarding nodes receiving the packet forward packets, it will cause repeated forwarding and RGF determines forwarding priority to prevent the redundancy transmission. RGF has three steps: (1) candidate forwarding nodes selection, (2) forwarding priority decision, (3) packet and ACK forwarding, and these three steps are repeated until the destination receives the packet.

### 4.1 Candidate Forwarding Nodes Selection

The node that will forward packet selects the node with the highest energy efficiency among its neighbor nodes first and then selects a number of candidate forwarding nodes based on that node to realize energy efficient forwarding in RGF method. Energy efficiency refers to the number of packets that successfully arrived at the destination node per unit energy and is calculated by using the following equation.

$$E_{eff} = \frac{p_{src} r}{kt} \tag{7}$$

$p_{src}$ represents the number of packets sent by source node and $r$, successful delivery rate and $t$, the number of forwarding and $k$, the constant referring to the energy used for each forwarding. In [7], the authors proves that the highest energy efficiency is achieved when PRR × Distance value is maximum through Formula (7).

$$Distance = 1 - \frac{d(nbr, dst)}{d(crnt, dst)} \tag{8}$$

Here, Distance is a ratio calculated with the following formula. In Formula (8), *d(nbr, dst)* refers to the distance between neighbor node and destination and d(crnt, dst), the distance between current forwarding node and destination.

The source node $S$ to send packets selects the neighbor node with the highest PRR × Distance value. This is defined as Centroid in this study. After selecting Centroid, the source node selects neighbor nodes located within connected region centering on the centroid as candidate forwarding nodes. A set of candidate forwarding nodes of the source node *S* is defined as *C(S)*, where $Centroid \in C(S)$. **Fig. 2** is the example showing source node *S* selecting Centroid and candidate forwarding nodes. If PRR × Distance value of node *d* is the largest among the neighbor nodes of source node *S* as shown in Figure 2, source node *S* will select *d* which has the highest PRR × Distance value as Centroid and select neighbor nodes *a, b, c, e,* and *f* located within connected region centering on *d* as candidate forwarding nodes. This forms a set of candidate forwarding nodes *C(S)={a, b, c, d, e, f}*. Since the source node in greedy forwarding only considers the neighbor nodes closer to the destination than it is, it restricts the range of neighbor nodes to consider as lower bound and upper bound as shown in **Fig. 2**.

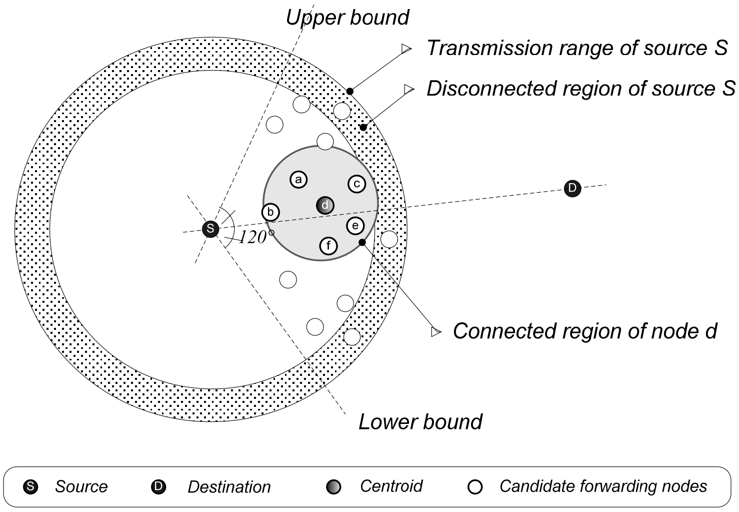


**Fig. 2**. Example of candidate forwarding nodes selection

## 4.2 Forwarding Priority Decision

If all candidate forwarding nodes that received packet from source node forward the same packet at the same time, it will cause packet collisions and unnecessary waste of energy. To prevent this, RGF sets the forwarding priority for each candidate forwarding node to make only one candidate forwarding node received the packet forwards the packet. The sender node calculates the distance between each of its candidate forwarding node and the destination and determines the priority, higher priority to the node closer to the destination. It guarantees that only one candidate forwarding node forwards the packet by setting the forwarding priority of candidate forwarding nodes to let them send packets in the order of forwarding priority. The sender node adds the information of the set of candidate forwarding nodes and priority information to the header of the packet to send and broadcasts.

**Fig. 3** shows the result after source node *S* determines the forwarding priority of each candidate forwarding node. Source node *S* sets the highest forwarding priority since candidate forwarding node *c* is located closest to the destination. It also sets the forwarding priority to the rest of candidate forwarding nodes *a, b, d, e,* and *f*, higher priority to the node closer to the destination. As a result, the forwarding priority of *C(S)* becomes *c, e, d, f, a,* and *b*. After determining forwarding priority, source node *S* attaches the information of *C(S)* and forwarding priority into the packet's header and then broadcasts.

The RGF algorithms is shown in Algorithm 1 and it starts when the sender node *s* has the packet to forward the specific destination *d*. First sender node *s* decides its Centroid to select the candidate forwarding nodes based on PRR and Distance (lines 2-4). Sender node *s* selects the candidate forwarding nodes by considering distance between the Centroid and neighbors (lines 5-9).

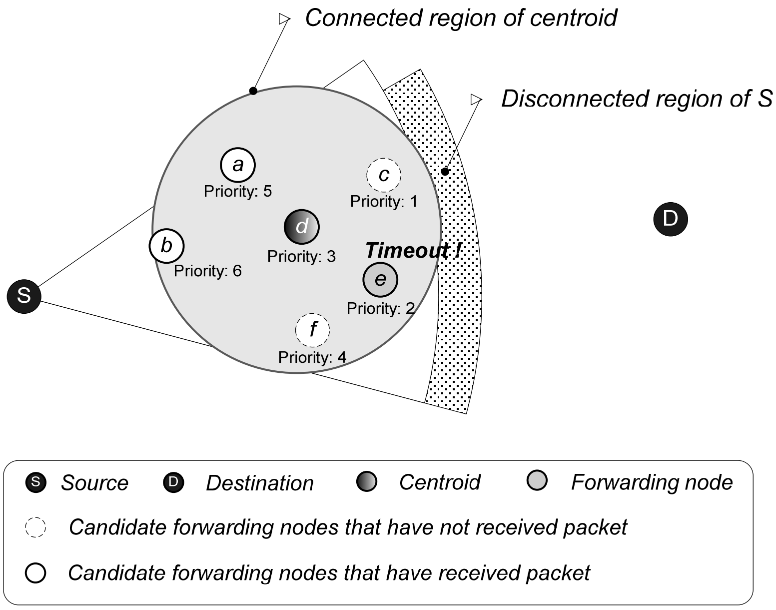


**Fig. 3**. Example of forwarding priority decision

After that, *s* calculates distance between candidate forwarding nodes and distance *d* and arranges the set of candidate forwarding nodes in order of shorter distance (lines 10-14).

## 4.3 Packet and ACK Forwarding

Neighbor nodes that received packets from source node *S* check the *C(S)* from the packet's header and determine whether they become candidate forwarding nodes. If they are not candidate forwarding node, they drop the packet and if they are, they set packet forwarding delay appropriate for their forwarding priority. If the priority is 1, packet forwarding delay is set to 0 and shorter packet forwarding delay is set for higher priority. All candidate forwarding nodes have different priorities that they have different packet forwarding delays. The packet forwarding delay of each candidate forwarding node is set to wait enough time until all candidate forwarding nodes with higher forwarding priority send packets and receive ACK sent from Centroid. Therefore, the packet forwarding delay, $delay_i$, of the candidate forwarding node having $i^{th}$ forwarding priority is configured through the following Formula.

$$delay_i = (i-1)(T_{pkt} + T_{ack}) + \Delta \tag{9}$$

$T_{pkt}$ and $T_{ack}$ in Formula (9) refers to the maximum time taken to send packet and ACK from 1-hop respectively, and $\Delta$ is the random variable to avoid the same value and has a very small value. The packet and ACK forwarding algorithm is shown in Algorithm 1 and it starts after the sender node s forwards the packet including the information of *C(s)* to its neighbor nodes. Each candidate forwarding node waits until their packet forwarding delay expires without sending the packet (lines 4–7). When the packet forwarding delay expires, candidate forwarding node calculates forwarding priority with its candidate forwarding nodes in the same method used by the source node (line 9), adds this information in the packet's header,and sends the packet. All candidate forwarding nodes are located within the connected region of the Centroid that the Centroid always overhears the packets sent by candidate forwarding nodes. When the Centroid can overhear candidate forwarding node's packet, it sends ACK to the sender node in place of that candidate forwarding node (lines 12–16). When each candidate forwarding node receives the ACK sent from the Centroid before its packet forwarding delay expires, it will drop the packet without waiting for its packet forwarding delay ends.

**Algorithm 1:** RGF Algorithm

**Input**: current sender node $s$, set of neighbor nodes of $s$ ($N(s)$), and destination $d$
**Output**: set of candidate forwarding nodes of $s$ ($C(s)$)

```
RGF($s, N(s), d$)
01: $k \leftarrow$ The number of neighbor nodes of $s$
//Centorid selection
02: for $i \leftarrow$ 1 to $k$
03:     do $Centroid \leftarrow n_i$ with highest $PRR \times Distance$ value among $N(s)$
           ,where $n_i \in N(s)$
04: end for
//Candidate forwarding nodes selection
05: for $i \leftarrow$ 1 to $k$
06:     if $d(n_i, Centroid) \leq$ Connected region
          ,where $d(n_{i,} Centroid)$ is distance between $n_i$ and $Centroid$
07:         then $C(s) \leftarrow n_i$
08:     end if`
09: end for
//Forwarding Priority Decision
10: $j \leftarrow$ The number of candidate forwarding nodes of $s$
11: for $i \leftarrow$ 1 to $j$
12: do calculate $d(c_i; d)$, where $c_i \in C(s)$
13: end for
14: MERGESORT($C(s)$) in order of shorter $d(c_i; d)$
```

**Algorithm 2:** Packet and ACK forwarding Algorithm

**Input:** neighbor node $n_i$, $Centroid$ of $s$, $C(s)$, destination $d$
**Output:** forwarding task

```
01: if $n_i$ receives the packet from $s$, where $n_i \in N(s)$
02:    if $n_i \in C(s)$
03:    then $delay_i = (k - 1)(T_{pkt} + T_{ack}) + \Delta$
          ,where $k$ is forwarding priority of $n_i$
04:        while $delay_i$ expires
05:            if overhear ACK from $Centroid$
06:            then break
07:            end if`
08:        end while
09:        RGF($n_i, N(n_i), d$)
10:    else drop the packet
11:    end if
12: else if $n_i$ overhears the packet from a $c_i$, where $c_i \in C(s)$
13:    if $n_i == Centroid$
```

```
    then forward ACK to $s$
    end if
else drop the packet
end if
```

Fig. 4 shows the process of ACK forwarding for the packet and the packet drop. Among candidate forwarding nodes that received the packet, the node with the highest forwarding priority becomes a forwarding node itself and waits for its own packet forwarding delay to end. When the packet forwarding delay expires the source node forwards the packet in the same method used by source node S and the Centroid overhearing this sends ACK to the source node S in place of the forwarding node. All candidate forwarding nodes are located within the connected region of the Centroid that they can overhear this ACK, and they drop the packet without waiting for their packet forwarding delay to expire. In Figure 3, the packet forwarding delay of e, the node with the highest priority among candidate forwarding nodes a; b; d; and e that received packet from source node S, expires first that it becomes the forwarding node itself and sends the packet to the destination in the same manner used by source node S. The Centroid that overheard this packet sends ACK to the source node S, and the candidate forwarding nodes a and b that overheard this ACK will drop the packet without waiting for the packet forwarding delay to expire.

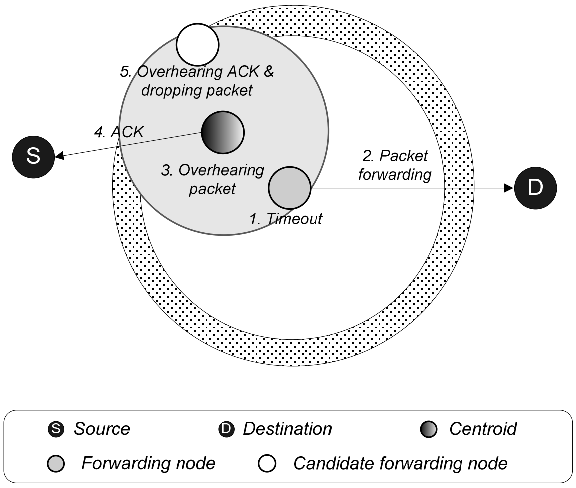


Fig. 4. Process of RGF's packet and ACK forwarding

## 5. Performance Evaluation

In this Section, we implement and compare the performance of RGF with sender-based greedy forwarding protocols: original greedy forwarding, PRR×Distance greedy forwarding in random topologies under different densities and network size by using C++. The main parameters which used in [21][25] are listed in Table 1. In this simulation, we mainly focus on evaluating the effects of physical-layer packet losses on geographic routing independent of the MAC layer used and without concerning ourselves with extraneous factors such as MAC collisions.

We simulate random static networks of sizes ranging from 100 to 1000 nodes having the same radio characteristics. We represent the density as the average number of nodes per a nominal transmission range and vary it over a wide scale: 25, 50, 75, 100, 125, 150, 175, 200 nodes/range. We define a nominal radio range in order to show the density as a function of that range, and set it to 40 *m*. For a node to be considered a neighbor it must have at least 1% reception rate.

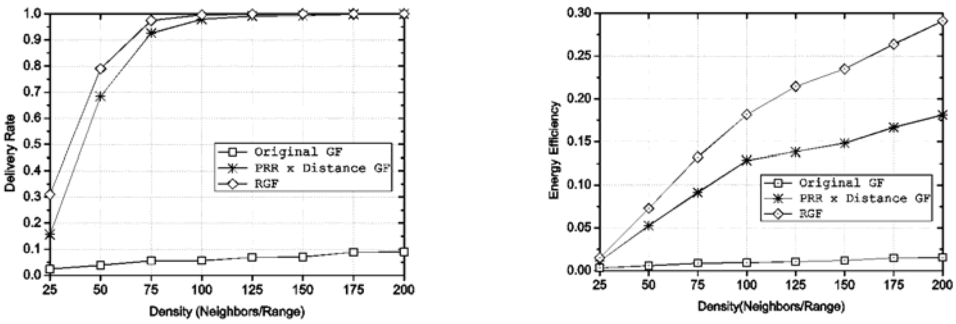
**Table 1**. Simulation parameters

| **Radio** | | | |
|---|---|---|---|
| Modulation | NCFSK | Encoding | Manchester |
| Output Power | -5 dBm | Frame Size | 50 Bytes |
| **Transmission Medium** | | | |
| Path Loss Exp | 3 | $PLD_0$ | 55 dBm |
| Noise Floor | -105 dBm | $D_0$ | 1 *m* |
| **Deployment Configuration** | | | |
| # of Nodes | 1000 | Radio Range | 40 *m* |
| Network Height and Width | | 160 *m* ~ 420 *m* | |

The performance metrics studied are the delivery rate and the energy efficiency (bits/unit energy). The delivery rate is the percentage of packets sent by the source node and received by the destination. The bits/unit energy is the ratio of the delivery rate to the number of transmissions (same as $E_{eff}$ in Formula (7)), and we use it to represent the amount of delivery contribution by each transmission. In each simulation run, nodes are placed at random locations in the topology and 100 packet transmissions are issued from a random source node to a random destination in the network. The results are computed as the average of 100 runs.

## 5.1 Delivery Rate and Energy Efficiency

In this subsection, we vary the density from 25 to 200 in each simulation and show its effect on the delivery rate and energy efficiency. We use networks of 1000 nodes and set the number of ARQ retransmissions to 10. It means that the packet is retransmitted again until it is received by that neighbor of a maximum retransmission count 10 is reached.



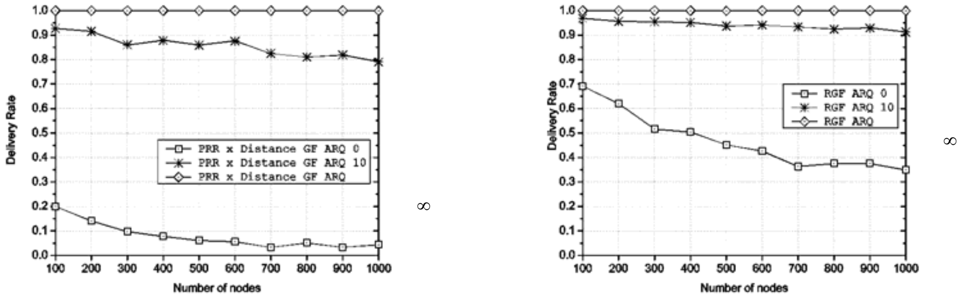
(a) (b)

**Fig. 5**. Delivery rate (a) and energy efficiency at different node densities (b)

In **Fig. 5(a)**, we show the delivery rate at different densities. The delivery rate is low at low densities, because of local minimum problem. The delivery rate of RGF is significant better than the delivery rate of original greedy forwarding and is slightly better than PRR × Distance greedy forwarding. It is because that RGF increase the possibility of transmission success by using several candidate forwarding nodes while the sender-based greedy forwarding protocols use only one next forwarding node. RGF also almost approaches 100 % delivery rate at density 100. Overall, the curve of three greedy forwarding protocols increase when the density increase, because there is greater chance of finding the next forwarding node which has good PRR except original greedy forwarding.

In **Fig. 5(b)**, we show the results for energy efficiency of three greedy forwarding protocols at different density. The RGF are the most energy efficient, followed by PRR × Distance greedy forwarding and original greedy forwarding. Higher density improves energy efficiency of three greedy forwarding protocols as a same reason in **Fig. 5(a)**. Since original greedy forwarding has very low delivery rate, it wastes significant energy resource. RGF which increases the possibility of transmission success has almost 2 times higher energy efficiency than PRR × Distance greedy forwarding.

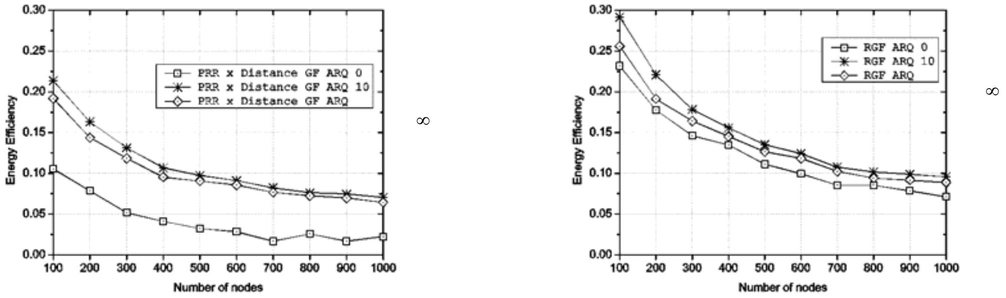
We have shown simulation results for ARQ with 10 retransmissions, since we believe that ARQ with a limited number of retransmissions is normally the practical choice for implementation. Now, we compare ARQ with 10 retransmissions to ARQ 0 and ARQ ∞. ARQ 0 means that packet is not delivered to the destination when packet loss occurs at least one time. ARQ ∞ also means that the packet is delivered until it arrives at the destination. We set the density to 50 nodes/range and vary the network size to observe the effect of ARQ on different network sizes. We only show the results for PRR × Distance greedy forwarding and RGF due to original greedy forwarding has very poor delivery rate and energy efficiency as proven in **Fig. 5(a)** and **5(b)**.



(a) (b)

**Fig. 6**. Delivery rate of PRR × Distance greedy forwarding (a) and delivery rate of Receiver-based greedy forwarding with different ARQ policy and varing network sizes (b)

**Fig. 6(a)** and **6(b)** show that the delivery rate of PRR × Distance greedy forwarding and RGF at different network sizes respectively. For each forwarding protocols, delivery rate with ARQ ∞ is almost maintained 100 % since the packet is delivered until it arrives to the destination. For PRR × Distance greedy forwarding with ARQ 0, the delivery rate is very low and its curve decreases as the network size increase. Thus, it is also difficult to forward the packet at a time in PRR £ Distance greedy forwarding because it hardly find the next forwarding node with good link quality in density 50. On the other hands, the delivery rate of RGF with ARQ 0 is significant higher than PRR × Distance greedy forwarding as well as the other ARQ policy. Note that the delivery rate of them decreases when the network size increases. The reason is that the path between source node and destination is longer when the network size is bigger so that the possibility of transmission success decreases.

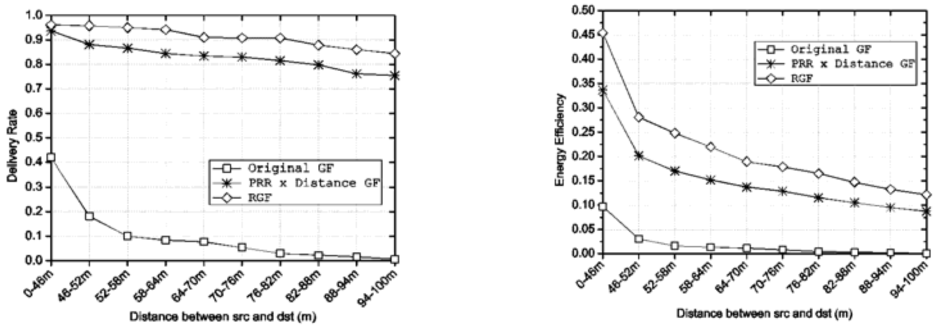


(a) (b)

**Fig. 7**. Energy efficiency of PRR × Distance greedy forwarding and Energy efficiency of receiver-based greedy forwarding with different ARQ policy and varing network sizes (b)

**Fig. 7(a)** and **7(b)** show that the energy efficiency of PRR × Distance greedy forwarding and RGF respectively. When the network size increases, the curves decreases due to low delivery rate. In Figure 9, the energy efficiency of ARQ 10 is the highest, since it has a high delivery rate. Actually, the delivery rate of ARQ ∞ is the highest as shown in **Fig. 6(a)**, however, it has significant retransmission so that the energy efficiency is lower than with ARQ 10. As we compare **Fig. 7(a)** and **7(b)**, we notice that the energy efficiency of RGF is higher PRR × Distance greedy forwarding. We notice that ARQ becomes more important as we increase the network size, which is also indicated by our analysis. The reason is that ARQ 0, the probability of delivering a packet between a source node and a destination over more hops decreases faster compared to ARQ. In addition, there is extra wasted overhead due to delivering packets over more hops before being dropped.

In the previous results, we have shown the average performance in delivering packets between random source-destination pairs. Since, the performance may depend on the distances between the expected sources and destinations, we study here the effect by the source-destination distance. **Fig. 8(a)** and **8(b)** show the simulation results with different distances between source and destination for a density of 50 nodes/range. The delivery rate and the energy efficiency decrease as the distance increases, since more hops (more transmissions) are required and the probability of packet drops becomes higher. RGF shows



(a) (b)

**Fig. 8**. Delivery rate (a) and energy efficiency with different distance between the source and the destination (b)

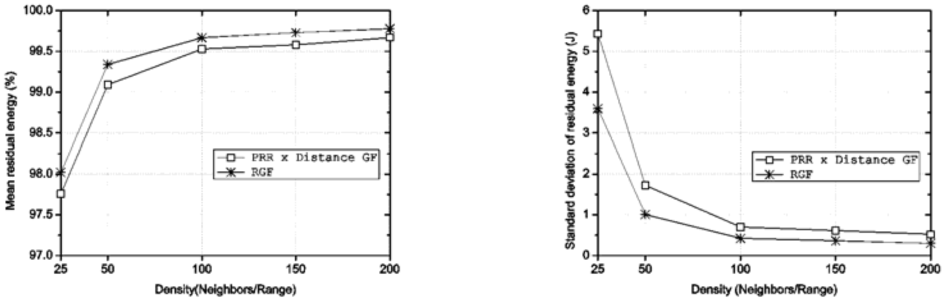
Higher performance in terms of delivery rate and energy efficiency than original greedy forwarding and PPR×Distance greedy forwarding as shown in **Fig. 8(a)** and **8(b)**.

## 5.2 Network Lifetime

In this subsection, we first define the following two metrics [26][27] to evaluate the network lifetime of PRR × Distance greedy forwarding and RGF.

- Mean residual energy: This metric calculates the average residual energy at the end of simulation for all the sensor nodes. It is an indicator of energy efficiency in the sense that it represents the level of remaining energy in the network. The higher the value is, the more the energy remains in the network, and the better the performance is. Note that due to the presence of the renewable energy sources, this metric cannot be replaced by a metric that measures the total energy consumed. A better routing protocol with renewable energy supply should achieve better residual energy when total energy consumption is the same or even higher.
- Standard deviation of residual energy: This metric measures the standard deviation of the residual energy of all nodes. This quantity indicates how well the traffic load/energy consumption is distributed among nodes. The smaller the value is, the better the capability the routing protocol has in balancing the energy consumption.

In order to evaluate the network lifetime, we vary the densities: 25, 50, 100, 150, 200 nodes/range in each simulation and show its effect on the mean residual energy and standard deviation of residual energy. We use networks of 1000 nodes and set the number of ARQ retransmissions to 10. As shown in **Fig. 9(a)** and **9(b)**, RGF is more energy efficient than PRR × Distance greedy forwarding in terms of having higher mean residual energy and smaller standard deviation of residual energy, so performance better than PRR × Distance greedy forwarding on efficiency and load balancing. This results can be explained by the fact that RGF takes into account the environmental energy harvesting rate as well as on node even though RGF does not consider energy level of the nodes actually.



(a) (b)

**Fig. 9**. Mean residual energy (a) and standard deviation of residual energy with different densities (b)

## 5. Conclusion

In this paper, we have addressed a novel greedy forwarding RGF for energy efficiency in lossy wireless sensor networks. In RGF, candidate forwarding nodes which received a packet decided whether forwards it or not based on its forwarding priority while previous sender-based greedy forwarding. In such a way, RGF improves the possibility of packet delivery success and reduces the number of retransmissions. We evaluated RGF using detailed simulations of a realistic wireless sensor network and showed that RGF has higher delivery rate and energy efficiency than the existing sender-based greedy forwarding protocols.

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