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A Novel Opportunistic Greedy Forwarding Scheme in Wireless Sensor Networks

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Abstract

Greedy forwarding is a key mechanism of geographic routing using distance as a metric. As greedy forwarding only uses 1-hop neighbor node information, it minimizes routing overhead and is highly scalable. In existing greedy forwarding schemes, a node selects a next forwarding node based only on the distance. However, the signal strength in a realistic environment reduces exponentially depending on the distance, so that by considering only the distance, it may cause a large number of data packet retransmissions. To solve this problem, many greedy forwarding schemes have been proposed. However, they do not consider the unreliable and asymmetric characteristics of wireless links and thus cause the waste of limited battery resources due to the data packet retransmissions. In this paper, we propose a reliable and energy-efficient opportunistic greedy forwarding scheme for unreliable and asymmetric links (GF-UAL). In order to further improve the energy efficiency, GF-UAL opportunistically uses the path that is expected to have the minimum energy consumption among the 1-hop and 2-hop forwarding paths within the radio range. Comprehensive simulation results show that the packet delivery rate and energy efficiency increase up to about 17% and 18%, respectively, compared with the ones in PRR×Distance greedy forwarding.

Keywords: Asymmetry, unreliability, energy-efficiency, 2-hop forwarding, greedy forwarding

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1. Introduction

Geographic routing is a typical routing technique used to forward packets from the source node to the destination node based on geographic information in Wireless Sensor Networks (WSN) [1][2][3]. As the geographic routing only uses the local information of neighbor nodes within the radio range, it requires little maintanence of the status information such as routing table and has great scalability. These advantages are quite adequate for WSN which is characterized by high node density, no network infrastructure, and limited battery resources. Original greedy forwarding (OGF) is a typical geographic routing scheme in which each node selects the neighbor node closest to the destination as the next forwarding node and forwards the packet [4]. This scheme considers the distance between two nodes to reduce the number of hops to the destination node. However, it only works efficiently under the idealistic assumption of perfect packet reception within the radio range which is not valid in a realistic environment due to the unreliable and asymmetric link characteristics [5][6][7][8].

The reliability of a wireless link is affected by fading, attenuation, and interference that commonly occur in WSN [9][10][11][12]. Woo *et al*. and Couto *et al*. have reported that the reliability of the link in the sensor network has a great impact on the performance of existing routing schemes [13][14]. Zuniga and Krishnamachari have shown the existence of a transitional region where the link reliability varies widely claiming that it is necessary to consider the link reliability for packet forwarding [15]. In other words, the possibility of data packet loss is very high when using OGF which chooses the neighbor node closest to the destination as the next forwarding node without considering the link reliability. Therefore, existing routing schemes use an automatic repeat request (ARQ) which controls the number of packet retransmissions in order to guarantee data packet delivery. The packet delivery rate decreases significantly when ARQ is not considered. On the other hand, if ARQ is considered, the network lifetime will decrease greatly due to that the limited battery resources of the sensor nodes which will be wasted by the number of retransmissions. As discussed above, several recent studies emphasize that the link reliability decreases greatly in realistic WSN environments such that the reliability must be considered for successful packet forwarding with minimum energy consumption.

Several greedy forwarding schemes have been proposed to solve the above problem caused by the unreliability of wireless links. Lee *et al*. have proposed a normalized advance (NADV) scheme to balance the link quality and the proximity to the destination node and optimize the energy and delay by applying this scheme [16]. Seada *et al*. forward packets by considering not only the distance to the destination but also packet reception rate (PRR) in order to guarantee the reliable data packet transmission [17][18]. In realistic wireless environments, the links are generally both asymmetric and unreliable. Existing routing schemes that guarantee the reliability do not consider the asymmetry of the link. Consequently, the packet delivery rate and energy efficiency decrease greatly when the PRR of the link for ACK packet transmission drops. Moreover, the existing schemes sometimes select the link with lowest PRR for packet forwarding as the effect of the distance on the next forwarding node selection is high, i.e., as the destination node gets closer. This significantly increases the number of data packet retransmissions, thus reducing packet delivery rate and increasing energy efficiency.

Forwarding packets by selecting the links with a high PRR within the radio range can reduce energy consumption since the number of retransmissions decreases. On the downside, it can increase the total number of hops to the destination. If only the distance to the destination node is considered, the number of hops will decrease as in the OGF while the energy consumption will increase due to a large number of retransmissions. In this paper, we propose a reliable and energy-efficient opportunistic greedy forwarding scheme for unreliable and asymmetric links (GF-UAL) which balances energy consumption and the number of hops. GF-UAL significantly reduces retransmission cost and maximizes the energy efficiency of the limited battery resources of sensor nodes [19]. This paper is an extended version of our earlier work [20], which contains the following enhancements:

- We analyzed the impact of unreliable and asymmetric links on the existing schemes in WSNs where the reliable efficient packet transmissions are crucial.
- We presented the impact of ARQ policy and network size on the existing schemes and GF-UAL in realistic WSN through comprehensive simulations and analysis.
- We introduced a global optimal ETX with our local optimal scheme, GF-UAL to show that GF-UAL gets closer to the optimal value without having overhead from the use of global information and high scalibility [14].

1.1 Our Contributions

A novel link metric, called expected delivery cost (EDC), is defined which represents the expected data packet delivery cost. GF-UAL selects a forwarding path with the least EDC for efficient routing in realistic environments. By determining a forwarding path using EDC, GF-UAL uses the neighbor node with the smallest value of the multiplication of the expected energy cost and expected number of hops to the destination node instead of using the neighbor node closest to the destination node. That is, it selects a path with the smallest expected energy consumption when delivering data packets to the destination node. Unlike the 1-hop forwarding method that existing schemes use, GF-UAL considers not only 1-hop forwarding but also 2-hop forwarding within the radio range where 1-hop forwarding can be arranged. With the help of this mechanism, GF-UAL reduces the total number of data and ACK packet transmissions and thus enhances energy efficiency and packet delivery rate when compared with existing schemes. Simulation results show that GF-UAL improves packet delivery rate up to about 17% and energy efficiency up to about 18% compared with PRR×Distance greedy forwarding [17][18].

We characterize the proposed greedy forwarding scheme by addressing the following contributions:

- We show the impact of both unreliable and asymmetric link characteristics in WSNs and propose GF-UAL which reduces data delivery failure and unnecessary retransmission cost from the characteristics.
- We introduce a new forwarding concept, i.e., 2-hop forwarding within the radio range, considering connected region which can be more efficient than 1-hop forwarding.
- By considering both Expected Transmission Cost(ETC) and Expected Hop Count(EHC), we balance between the energy consumption for packet transmission within the radio range and the distance to the destination.
- As a packet gets closer to the destination, it is very likely that previous schemes select a neighbor which is closest to the destination with very low PRR. Due to this, many retransmissions may occur. To mitigate the problem, we introduce a new metric Expected Delivery Cost(EDC). We explain about the problem more specifically in subsection 4.1 with Fig. 3.

- Previously proposed schemes do not consider the energy consumption for ACK packet transmission. However, it is unrealistic where asymmetric links commonly exists. Therefore, we propose a more realistic energy consumption model which considers energy consumption for sending and receiving both data and ACK packets.

The remainder of this paper is organized as follows. Related works are presented in Section 2. Section 3 provides assumptions, notation, link loss model, and energy consumption model used in the paper. Section 4 describes GF-UAL in detail. Section 5 discusses simulation results of GF-UAL and existing geographic routing schemes. Finally, Section 6 concludes the paper.

2. Related Work

Original greedy forwarding (OGF) is a typical geographic routing scheme. In this scheme, each node knows the geographic information of itself and neighbor nodes located within the radio range, and the source node knows the location of the destination node. Based on this information, existing geographic routing schemes select the neighbor node closest to the destination node as the next forwarding node to forward data packet [4]. The advantage of the OGF is that it does not need to maintain a routing table since it only uses the location information of the neighbor nodes. However, this scheme has a problem of low packet delivery rate when the link reliability between nodes is low. By considering the use of ARQ, the delivery rate can be increased. However, it can lead to the waste of a large amount of energy due to a large number of packet retransmissions as it forwards data and ACK packets through the links with low PRR.

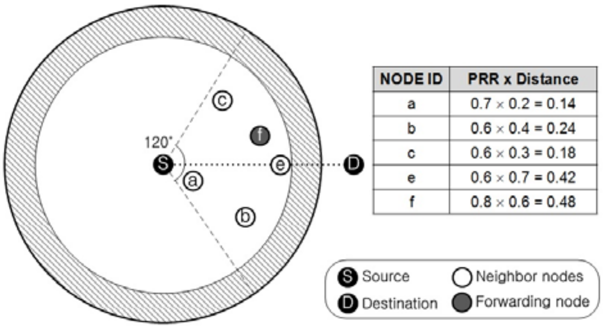
Idealistic radio models considered in existing schemes are not adequate for realistic WSN environments in that the link reliability drops greatly due to fading, attenuation, and interference [9][10]. To solve this problem, several schemes have been proposed that consider PRR [13][16][17][18][21][22]. In a realistic wireless network environment, the PRR varies widely depending on the distance and the packet loss takes place when the PRR of the link is low even if the sender node is close to the receiver node [23]. In addition, the wireless link is intrinsically asymmetric and unreliable. These characteristics of the link have a great impact on the higher-layer protocol in the transitional region within the radio range where PRR fluctuates widely [24].

Couto *et al.* have proposed a scheme of selecting a data packet delivery path based on the entire network information [14]. In an expected transmission count (ETX) scheme, the source node selects a path where the sum of ETX is the smallest among all paths to the destination node. ETX is the expected number of data packet transmissions between the node with packets to forward and the neighbor node. ETX scheme sets a path from the source node to the destination node by considering the PRR of the links for both data and ACK packet transmissions to solve the unreliability and asymmetry problem. However, it comes with a huge overhead compared with the existing geographic routing schemes because it uses the entire network information to select the delivery path. Therefore, it is inadequate for the realistic WSN environment.

Seada *et al.* have proposed an energy-efficient routing scheme by considering the packet loss depending on the distance [17][18]. PRR×Distance greedy forwarding scheme proposed to select the neighbor node with the highest PRR×Distance value as the next forwarding node. The distance represents the distance improvement to the destination node and it is defined as:

$$\text{Distance} = 1 - \frac{d(neighbor, destination)}{d(current, destination)} \tag{1}$$

where $d(neighbor, destination)$ represents the distance between a neighbor node and the destination node and $d(current, destination)$ represents the distance between the current forwarding node and the destination node. In **Fig. 1**, source node S selects node f which has the highest PRR×Distance value among the 5 neighbor nodes as the next forwarding node. By multiplying PRR and Distance, it strikes a balance between the node which is far from the destination node but has a high PRR and the node which is close to the destination node but has a low PRR. In addition, it mathematically proves that energy efficiency increases when PRR×Distance value increases in symmetric link environments.



NODE ID	PRR x Distance
a	0.7 × 0.2 = 0.14
b	0.6 × 0.4 = 0.24
c	0.6 × 0.3 = 0.18
e	0.6 × 0.7 = 0.42
f	0.8 × 0.6 = 0.48

Fig. 1. Next forwarding node selection of PRR×Distance greedy forwarding.

3. Preliminaries

In this paper, we propose a reliable and energy efficient data transmission scheme in a realistic WSN. We consider network topologies with various node densities and network sizes where sensor nodes are randomly deployed. The PRR representing the link quality between nodes reflects the unreliability and asymmetry of the wireless link in a realistic network environment. In the following, we introduce assumptions and notation used in this work.

3.1 Assumptions and Notation

Table 1 presents notation used in this work.

Table 1. Notation

Symbol	Description
$d(A,B)$	distance between nodes A and B
$PRR_{A\to B}$	PRR used to forward a packet from node A to B
P_{src}	number of data packets sent from source node
t_{data}	number of expected data packet transmissions
t_{ACK}	number of expected ACK packet transmissions
e_{data}	energy consumption to tx and rx a data packet
e_{ACK}	energy consumption to tx and rx an ACK packet
s_{data}	size of data packet
s_{ACK}	size of ACK packet
E_{eff}	energy efficiency
R	end-to-end packet delivery rate
γ	signal to noise ratio (SNR)
η	path loss exponent
ρ	encoding ratio
F	frame size

In this work, we consider the following assumptions:

- Each node has its own ID and same constant radio range.
- Each node knows its location information via GPS or some distributed localization methods when GPS is not available.
- Source node knows the position of the destination node.
- Each node knows the location and the PRR of its neighbor nodes by exchanging HELLO messages.
- Our study does not consider other means of energy savings such as sleep/awake scheduling and transmission power control.
- The network is static and has relatively low congestion.
- Computation cost is very small compared with transmission cost.

3.2 Link Loss Model

A link loss model is required to analyze and simulate data transmission protocols that consider the unreliable and asymmetric link characteristics. We use PRR as the link quality between two nodes. The PRR of data and ACK packet forwarding links are distinguished based on the asymmetry of a link in a realistic WSN environment. The value of PRR ranges from 0 to 1, and a link loss model proposed in [10][24] is used to calculate its value. The PRR is given by:

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

where d is the distance between two nodes; f is the size of a frame length in *bytes* which is multiplied by 8 to convert it into *bits*; $\gamma(d)$ is the signal to noise ratio (SNR) in *dB*. $\gamma(d)$ in Eq. (2) is the difference between the output power (P_t) and noise floor (P_n) as in Eq. (3) [17]:

$$\gamma(d) = P_r(d) - P_n = P_t - PL(d_0) - 10\eta \log_{10}(\frac{d}{d_0}) + N(0,\sigma) - P_n \tag{3}$$

where $P_r(d)$ is the received power at a distance of d which follows the log normal path loss model; $PL(d_0)$ is the power reduction by the reference distance d_0; $N(0,\sigma)$ is a Gaussian random variable of mean 0 and variance σ^2 considering multi-path effects. This model considers various radio parameters such as the path-loss exponent (η) and log-normal shadowing variable (σ). In our simulation, η and σ are 3.0 and 3.8, respectively. Eq. (2) follows MICA2 that uses the NCFSK modulation method and Manchester Encoding. All other detailed information such as data rate, Rx, Tx, etc follows the specification of MICA2 [25].

Recently, Zuniga *at el*. have shown that link quality is divided into three distinct regions: i) connected region, ii) transitional region, and iii) disconnected region [17]. As shown in **Fig. 2**, connected region is 0 - 8 *m*, transitional region is 8 - 33 *m*, and disconnected region is 33 - 40 *m*. In the connected region, nodes can transmit packets reliably; in the transitional region, PRR varies widely; in the disconnected region, nodes usually fail to transmit packets. It is shown that their unreliability and asymmetry have a significant impact on the performance of high-layer protocols [24]. Therefore, we should consider these three distinct regions, especially the transitional region with widely-varying PRR commonly resulted from the link unreliability and asymmetry.

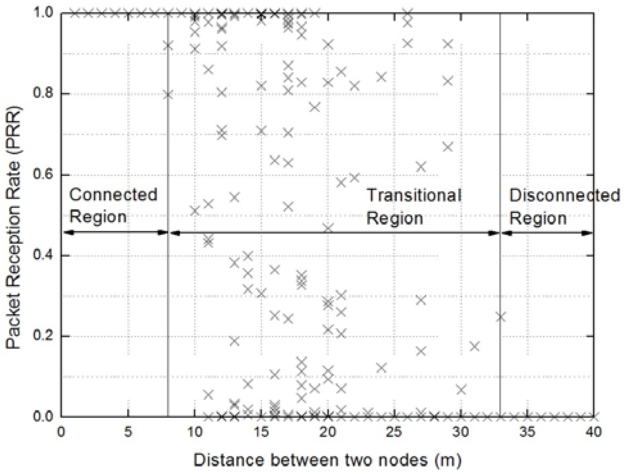


Fig. 2. Link loss model.

3.3 Energy Consumption Model

For reliable data packet transmissions, ACK packet transmission for the received data packet is required. In realistic WSN environments, data and ACK packet retransmission may occur many times when PRR is low, and thus consume a lot of energy. Existing schemes, however, do not consider the energy consumed by ACK packet transmissions when calculating the energy efficiency. In order to include such energy consumption into the measurement of energy efficiency, we calculate the amount of energy consumed to transmit and receive 1bit data using MICA2 power model shown in **Table 2** and then based on this, we define the energy consumption for data and ACK packet transmission and reception to redefine the energy efficiency. **Table 2** represents the current consumption (I) for the given transmission power (Tx) and reception power (Rx). First, we measure the power (P) used for transmitting and receiving data for each unit time in a sensor node which is given by:

$$P = I \times V \tag{4}$$

where V is the supplied voltage. Based on the transmission and reception power calculated from Eq. (4), e ($\mu J/bit$), energy required to transmit (e_{Tx}) or receive (e_{Rx}) 1 *bit*, is given by:

$$e = \frac{P}{DT} \tag{5}$$

where DT is data transferred for unit time. Now, energy consumption (e_{data}) for data packet transmission and reception, and energy consumption (e_{ACK}) for ACK packet transmission and reception can be respectively given by:

$$e_{data} = (e_{Tx} + e_{Rx}) \times s_{data} \tag{6}$$

$$e_{ACK} = (e_{Tx} + e_{Rx}) \times s_{ACK} \tag{7}$$

For instance, when T is 1 sec, and P is -5*dBm*, and the data rate is 19.2*kbps*, the energy consumptions to forward the data and ACK packets are e_{data}=1762.5μJ and e_{ACK}=193.875μJ [26][27], respectively.

Finally, by using the energy consumption rates e_{data} and e_{ACK}, the energy efficiency of E_{eff} is calculated by:

$$E_{eff} = \frac{p_{src} \times 8 \times s_{data} \times r}{e_{data} \times t_{data} + e_{ACK} \times t_{ACK}} \text{ [17][18]} \tag{8}$$

where $e_{data} \times t_{data} + e_{ACK} \times t_{ACK}$ is the energy consumed (μJ) in the network to deliver $P_{src} \times 8 \times s_{data} \times r$ *bit* data to the destination node; $P_{src} \times 8 \times s_{data}$ is the size (*bit*) of data transmitted from the source node; $e_{data} \times t_{data}$ and $e_{ACK} \times t_{ACK}$ are the quantities of energy consumed (μJ) to forward the data and ACK packet, respectively; P_{src}, e_{data}, and e_{ACK} are constants and t_{data} and t_{ACK} are values determined by the network environment. Energy efficiency is defined by considering r which reflects PRR of links between the sender and receiver node. That means r varies depending on the reliability of the links and the link reliability itself reflects the lost of packet. Therefore, the destination node receives a packet with probability of r and the packet loss occurs with probability of 1-r. In this paper, to evaluate the energy efficiency, we use the following metrics:

- *Energy Efficiency* (E_{eff}): size of data forwarded to the destination per energy unit
- *Delivery Rate (r)*: rate of packets sent from the source node and packets received by the destination node

In the following Section 4, we introduce our proposed scheme in detail and in Section 5, we evaluate the performance of our proposed scheme GF-UAL and existing schemes by using the above two metrics.

Table 2. Mica2 power model [27]

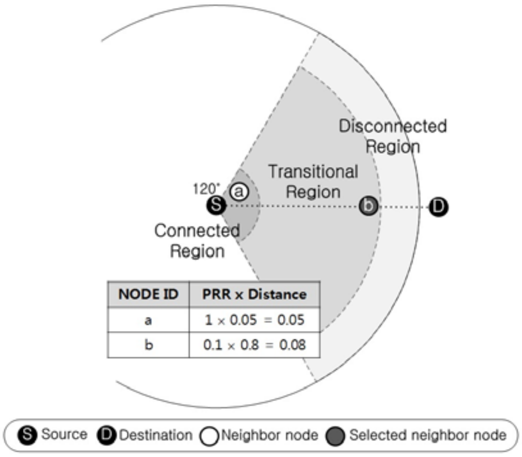
Mode	Current	Mode	Current
Rx	7.0 *mA*	*Tx* (-5 dBm)	7.1 *mA*
Tx (-20 *dBm*)	3.7 *mA*	*Tx* (0 *dBm*)	8.5 *mA*
Tx (-19 *dBm*)	5.2 *mA*	*Tx* (+4 *dBm*)	11.6 *mA*
Tx (-15 *dBm*)	5.4 *mA*	*Tx* (+8 *dBm*)	17.4 *mA*
Tx (-8 *dBm*)	6.5 *mA*	*Tx* (+10 *dBm*)	21.5 *mA*

4. Greedy Forwarding for Unreliable and Asymmetric Links (GF-UAL)

4.1 Motivation and Overview

PRR×Distance greedy forwarding increases energy efficiency by reducing the total number of transmissions from source node to destination node. However, it is not efficient when the PRR of the ACK transmission link is low since the asymmetry of the wireless link is not considered. The ETX scheme considers the unreliability and asymmetry of the wireless link. However, it generates a large overhead due to its use of global information. In the scheme, each node has to spend a large amount of time and energy to update the entire network information it keeps when the network topology changes. Due to these overheads, the scalability of the ETX scheme is much lower when compared with existing schemes that only use local information.

Existing schemes consider both PRR and the distance to the destination node simultaneously to reduce the number of hops and the number of data packet retransmissions. These existing schemes select the node that is closest to the destination node. However, the PRR of the selected node is low when the effect of the distance from the neighbor node to the destination node on the selection of the next forwarding node increases. This phenomenon is more likely to occur when the position of the current forwarding node gets closer to the destination node. In **Fig. 3**, the existing schemes select node b, which is closest to the destination node but PRR is 0.1 where the expected number of data packet transmissions is 10. The amount of energy consumed by using node b is higher than that of multi-hop forwarding through neighbor nodes with high PRR links. Likewise, forwarding packets through low PRR links results in a low packet delivery rate and low energy efficiency due to many data and ACK packet retransmissions. This means that the unreliable and asymmetric link problems must be solved only with the local information for energy efficient routing. At the same time, it is necessary to consider the balance between the distance to the destination node and the PRR of the links.



NODE ID	PRR x Distance
a	1 × 0.05 = 0.05
b	0.1 × 0.8 = 0.08

Fig. 3. Next forwarding node selection of the existing schemes.

The goal of GF-UAL is to provide energy efficient forwarding within the radio range by considering the unreliable and asymmetric link characteristics. Unlike the existing greedy forwarding schemes, which consider only 1-hop forwarding paths, GF-UAL considers 1-hop and also 2-hop forwarding paths within the radio range in forwarding data and ACK packets. Each node searches for 2-hop forwarding paths using the geographical information within the radio range and the connected region explained in Section 3. GF-UAL is comprised of three phases. First, each node searches for 1-hop and 2-hop forwarding paths and calculates the expected delivery cost (EDC) of each forwarding path. Next, it selects a forwarding path based on the EDC and creates a forwarding set using the neighbor nodes on the selected forwarding path. Finally, it forwards data packets based on the forwarding set. GF-UAL enhances the reliability and energy efficiency of data packet transmissions through the above three phases. This section first explains how to find a forwarding path within the radio range, EDC used for the forwarding path selection, and then how to form a forwarding set. Finally, the overall packet delivery process is described in detail.

4.2 Forwarding Path Search

Each node with a packet to forward choose an energy efficient path within its own radio range. To achieve this goal, GF-UAL requires each node to calculate the distance to its neighbor nodes within the radio range using Eq. (1). Then, each node calculates PRR×Distance value between itself and neighbor nodes, and sets a 1-hop forwarding path first by referring to the neighbor node with the highest PRR×Distance value. It reduces the cost of setting a 2-hop forwarding path by not using the links with a lower PRR than the links used by the 1-hop forwarding path when searching for 2-hop forwarding paths.

GF-UAL also searches for 2-hop forwarding paths using the connected region other than the 1-hop forwarding path as shown in **Fig. 4**. There are 5 neighbor nodes: a, b, c, e, and f within the radio range of node S. Node S calculates the distance between nodes a and b using their geographical information only, and if the two nodes are within the connected region it can obtain the PRR of the link between the two nodes. In **Fig. 4**, since the distance d_1 between nodes a and b is shorter than the maximum distance of the connected region, they are located within the connected region. Node S can calculate the distance between nodes a and b and come to realize that the PRR of the link is 1. From this, GF-UAL can calculate the EDC of a 2-hop forwarding path. The definition and calculation method of EDC is presented in detail in the following section. To forward packets, a current forwarding node constructs a forwarding set as explained in subsection 4.4 and nodes such as a in the forwarding set only participate in forwarding packets. In other words, node a on the 2-hop forwarding path is a relaying node and only forwarding nodes such as S can decide the path.

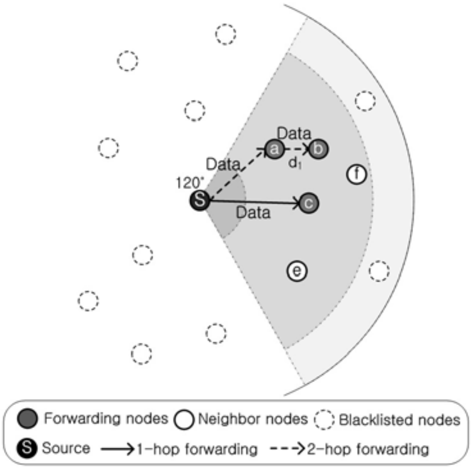


Fig 4. 2-hop forwarding path selection.

4.3 Expected Delivery Cost

We propose EDC for the selection of energy efficient forwarding path when data and ACK packets are sent from the current forwarding node to a destination node. EDC is defined as the cost of total energy that can be generated when forwarding data and ACK packets through the forwarding path within the radio range. When selecting a forwarding path, EDC considers not only the energy consumption of the path but also the number of hops between the source node and the destination node. EDC is calculated as follows:

$$EDC = ECF \times EHC \tag{9}$$

where energy cost for forwarding (ECF) represents the expected energy consumption taken by data and ACK packet forwarding through the corresponding path; expected hop count (EHC) represents the expected average number of hops required in forwarding the data packet to the destination node using the selected path. By using EDC, GF-UAL selects the path to balance between energy and the number of hops and calculates the expected energy cost in delivering data packets to the destination. ECF is used for selecting the path that takes the least energy in forwarding data and ACK packets among the forwarding paths available within a radio range.

ECF considers the energy consumed for the transmission of each packet that is calculated based on the size of data and ACK packets and MICA2 power model. ECF is the sum of the energy consumed by the network when transmitting and receiving data and ACK packets and is given by:

$$ECF = s_{data} \times t_{data} + s_{ACK} \times t_{ACK} \tag{10}$$

$$t_{data} = \frac{1}{PRR_{crnt \to nbr} \times PRR_{nbr \to crnt}} \tag{11}$$

$$t_{ACK} = \frac{1}{PRR_{nbr \to crnt}} \tag{12}$$

where s_{data} and s_{ACK} are the sizes of data and ACK packets and they are 100 *bytes* and 11 *bytes*, respectively in the paper [26]. t_{data} and t_{ACK} are the expected number of data and ACK packet transmissions at each node. The values are calculated by using the PRR of the links for both data and ACK packet transmissions as shown in Eqs. (10), (11), and (12). $PRR_{crnt \to nbr}$ is the PRR from the current forwarding node (*crnt*) to a neighbor node (*nbr*) and $PRR_{nbr \to crnt}$ is the PRR from the neighbor which has received data packet to the current forwarding node, i.e., PRR for ACK transmission.

By using ECF, the amount of energy required in transmitting and receiving packets within the radio range is minimized. However, it uses a longer path to the destination node to forward packets, hence the number of hops to the destination node increases. When the number of hops increases, the number of total data and ACK packet transmissions from the source node to the destination node also increases, thus increasing the total energy consumption. Therefore, we propose EHC to avoid the use of the path in the case where the ECF is small but the destination is far. EHC is given by:

$$EHC = \frac{d(crnt, dst)}{d(crnt, ncrnt)} \tag{13}$$

where *d*(*crnt, ncrnt*) is the distance between the node *crnt* with a packet to forward and next forwarding node *ncrnt*; *d*(*crnt, dst*) is the distance between the node *crnt* and the destination *dst*. By using these two values, the expected number of hop counts is calculated. In **Fig. 5**, d_1 is *d*(*crnt, ncrnt*) and d_2 is *d*(*crnt, dst*). **Fig. 5-(a)** illustrates 1-hop forwarding where node *e* is *ncrnt* while **Fig. 5-(b)** illustrates 2-hop forwarding where node *c* is *ncrnt*. As GF-UAL aims at finding an efficient forwarding path within the radio range by using EDC, the 2-hop forwarding selected by GF-UAL has a higher hop count but has less energy consumption compared with the 1-hop forwarding. Therefore, the 2-hop forwarding selected has a smaller number of packet transmissions than that of the 1-hop forwarding.

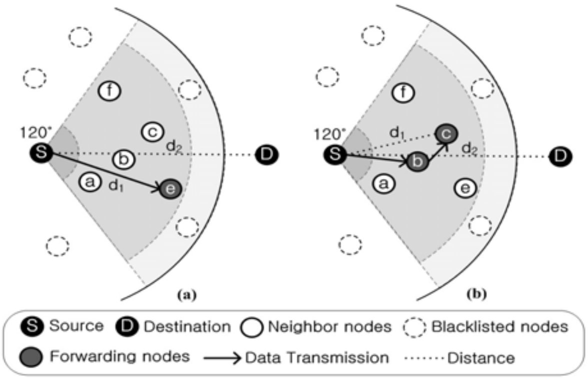


Fig. 5. EHC setup **(a)** 1-hop forwarding **(b)** 2-hop forwarding.

4.4 Forwarding Set Construction

To form a forwarding set required for packet forwarding, current forwarding node calculates EDC of 1-hop and 2-hop forwarding paths and selects a forwarding path with the minimum EDC. In **Fig. 5**, EDC of 1-hop forwarding path from node S to e is $(100 \times t_{data_{s \to e}} + 11 \times t_{ACK_{e \to s}}) \times \frac{d(S,D)}{d(S,e)}$ and that of 2-hop forwarding path from node S to b to c is $\{100 \times (t_{data_{s \to b}} + t_{data_{b \to c}}) + 11 \times (t_{ACK_{b \to s}} + t_{ACK_{c \to b}})\} \times \frac{d(S,D)}{d(S,c)}$. 100 and 11 represent the sizes of data and ACK packets and D represents the destination. $d(S,c)$, $d(S,e)$, and $d(S,D)$ are the distance between nodes S and c, S and e, and S and D, respectively. $tdata_{s\rightarrow e}$, $tdata_{s\rightarrow b}$, and $tdata_{b\rightarrow c}$ are the expected number of data packet transmissions from S to e, S to b, and b to c and they are given by:

$$t_{data_{s\rightarrow e}} = \frac{1}{PRR_{s\rightarrow e} \times PRR_{e\rightarrow s}}$$

$$t_{data_{s\rightarrow b}} = \frac{1}{PRR_{s\rightarrow b} \times PRR_{b\rightarrow s}}$$

$$t_{data_{b\rightarrow c}} = \frac{1}{PRR_{b\rightarrow c} \times PRR_{c\rightarrow b}}$$

$t_{ACK_{e\rightarrow s}}$, $t_{ACK_{b\rightarrow s}}$, and $t_{ACK_{c\rightarrow b}}$ are the expected number of ACK packet transmissions from e to S, b to S, and c to b and they are given by:

$$t_{ACK_{e\rightarrow s}} = \frac{1}{PRR_{e\rightarrow s}}$$

$$t_{ACK_{b\rightarrow s}} = \frac{1}{PRR_{b\rightarrow s}}$$

$$t_{ACK_{c\rightarrow b}} = \frac{1}{PRR_{c\rightarrow b}}$$

EHCs of 1-hop and 2-hop forwarding paths are $\frac{d(S,D)}{d(S,e)}$ and $\frac{d(S,D)}{d(S,c)}$, respectively.

Each node with a packet to forward selects a forwarding path based on EDC and forms a forwarding set. The forwarding set is a set of neighbor nodes participating in packet forwarding. Existing schemes which only consider 1-hop forwarding, use IDs of itself and the selected neighbor node to forward data and ACK packets. GF-UAL uses IDs of two nodes in the case that 1-hop forwarding path is selected while it uses IDs of three nodes in the case that 2-hop forwarding path is selected to form a forwarding set. In **Fig. 5-(a)**, for 1-hop forwarding path from node S to e, the forwarding set is S, e and for 2-hop forwarding path in **Fig. 5-(b)**, the forwarding set is S, b, c. In GF-UAL, each node forwards data and ACK packets based on the forwarding set.

4.5 Packet Delivery Process

GF-UAL first searches for 1-hop and 2-hop forwarding paths within the radio range to forward the data and ACK packets. Then it compares EDC of the forwarding paths and selects a path with the minimum EDC as the most efficient path, and forms the forwarding set based on the selected path. Each node forwards the data and ACK packets based on the forwarding set. In 1-hop forwarding, the current forwarding node which is the first node in the forwarding set forwards data packet to the second node. In 2-hop forwarding, the first neighbor node is eliminated from the forwarding set when the data packet successfully reaches the first neighbor node and then forwards the data packet to the second neighbor node.

Table 3 shows the GF-UAL algorithm where *cnode* and *dnode* are the current forwarding node and the destination node, respectively; *fs* is the forwarding set in GF-UAL; nbr_i and *nbr_num* are *i*th neighbor node and number of neighbor nodes within the radio range; *fnode* and *fnode_1-hop* are the next forwarding node and the forwarding node on 1-hop forwarding path, respectively. In line 4-12, a neighbor node with the highest PRR×Distance value is found for 1-hop forwarding path and EDC of 1-hop forwarding path is calculated; In line 15-24, 2-hop forwarding paths are searched for and a path with the minimum EDC among 1-hop and 2-hop forwarding paths is selected; In line 27-29, forwarding set is formed and in line 32-35, packet forwarding occurs. These steps are repeated until the data packet reaches the destination node. GF-UAL has an additional computation cost compared with the previous schemes, however, it is not that significant because after applying blacklisting method, there remains a small number of available candidates to be a next forwarding node. In addition, as the computation cost is very small compared with the transmission cost, we focus only on packet transmission cost in the paper.

Table 3. GF-UAL algorithm

```
Algorithm of GF-UAL
Input: (cnode, dnode);
Output: (fs);
 1: while $cnode \neq dnode$
 2:
 3: /* Find 1-hop Forwarding Path*/
 4:     $highest\_prr{\times}d \leftarrow 0$
 5:     for some index $i \leq num\_nbr$
 6:         do calculate prr×d value for $nbr_i$
 7:         do if $prr{\times}d\_nbr_i > highest\_prr{\times}d$
 8:             then $fnode\_1\text{-}hop \leftarrow nbr_i$
 9:                  $highest\_prr{\times}d \leftarrow prr{\times}d\_nbr_i$
10:             else continue
11:     do $lowest\_EDC \leftarrow$ EDC($cnode$, $dnode$, $fnode\_1\text{-}hop$)
12:     do $fnode \leftarrow fnode\_1\text{-}hop$
13:
14: /* Find 2-hop Forwarding Paths and Select a Forwarding Path */
15:     for some index $j \leq num\_nbr$
16:         do if $prr\_fnode\_1\text{-}hop \geq prr\_nbr_j$
17:             then continue
18:         for some index $k < num\_nbr$
19:             do if 2-hop forwarding path exists
20:                 then $EDC\_2\text{-}hop \leftarrow$ EDC($cnode$, $dnode$, $nbr_j$, $nbr_k$)
21:             do if $lowest\_EDC > EDC\_2\text{-}hop$
22:                 then $lowest\_EDC \leftarrow EDC\_2\text{-}hop$
23:                      $rnode \leftarrow nbr_j$
24:                      $fnode \leftarrow nbr_k$
25:
26: /* Construct Forwarding Set */
27:     do if $fnode == fnode\_1\text{-}hop$
28:         then $fs \leftarrow$ Forwarding_Set($cnode$, $fnode$)
29:         else $fs \leftarrow$ Forwarding_Set($cnode$, $rnode$, $fnode$)
30:
31: /* Transmit Data and ACK Packets */
32:     while size($fs$) > 1
33:         do if ACK is received for data packet transmission
34:             then break
35:         do remove the last element of $fs$
36:     do $cnode \leftarrow fnode$
```

The entire process of GF-UAL is as shown in **Fig. 6**. In the radio range of the current forwarding node S, there are seven neighbor nodes, each with ID from a to h. First, the 1-hop forwarding path can be found with node g which has the highest PRR×Distance value among the neighbor nodes. Then, 2-hop forwarding paths utilizing the connected reason are searched for. In **Fig. 6**, 2-hop forwarding path is formed from nodes S, c, and f. Nodes c and f are in the connected region where successful packet forwarding is guaranteed. Node S selects a forwarding path with the minimum EDC among the searched 1-hop and 2-hop forwarding paths. If a 1-hop forwarding path is selected, the forwarding set is set to {S, g}. Based on the forwarding set, node S forwards the data packet to g and node g forwards the ACK packet to node S. On the other hand, when a 2-hop forwarding path is selected, {S, c, f} is set as the forwarding set. By using this forwarding set, node S forwards data packet to node c and after receiving the data packet, node c forwards ACK packet to node S. Then, node c updates the forwarding set to be {c, f} and forwards the data packet to node f. After receiving the data packet, node f forwards the ACK packet to node c. In such a way, GF-UAL utilizes both 1-hop and 2-hop forwarding paths for efficient routing in a realistic WSN environment.

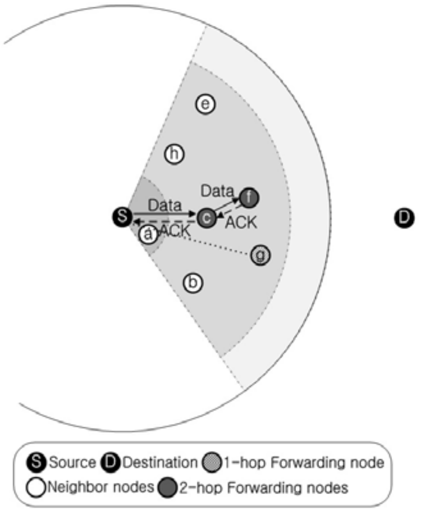


Fig. 6. Forwarding process of GF-UAL.

5. Performance Evaluation

In this section, we compare GF-UAL with original greedy forwarding (OGF) and PRR× Distance greedy forwarding schemes to evaluate the performance of GF-UAL. We first compare packet delivery rate and energy efficiency of GF-UAL with those of the other two schemes for various node densities and the distance between the source node and the destination node. Then, the effects of ARQ policy (i.e., number of maximum data packet retransmissions) and network size on the existing geographic routing schemes and GF-UAL are analyzed. In particular, GF-UAL and global optimal ETX scheme are compared to investigate how close GF-UAL approaches to the optimal value. We use the following two metrics below to evaluate the performance of GF-UAL.

- *Packet Delivery Rate* (r): percentage of packets transmitted from the source node and received by the destination node which ranges from 0 to 1.
- *Energy Efficiency* (E_{eff}): ratio of delivery rate to total number of transmissions or size (bit) of data transmitted per unit energy (μJ).

5.1 Methodology

We run the experiments using C++ and the parameters used are summarized in **Table 4**. Network topology is randomly constructed based on various node densities and network sizes. In the simulation, we mainly focus on evaluating the effects of physical-layer packet losses without being concerned about packet losses from extraneous factors such as MAC collisions.

Table 4. Simulation parameters

Radio Parameters			
Modulation	NC-FSK	Encoding	Manchester
Output Power	-5 dBm	Path Loss Exp	3
Noise Floor	-105 dBm	Data Rate	1.92 kbps
Deployment Configuration			
# of Nodes	100 ~ 1000	Radio Range	40 m
Network Height and Width		100 m ~ 450 m	

This section simulates networks with different number of nodes ranging from 100 to 1000 with 100 increments under the same propagation characteristics. In addition, it evaluates the performance by varying node density: 25, 50, 75, 100, 125, 150, 175, and 200 nodes/range. Node density is defined as the number of nodes within the radio range. When the data packet is dropped, two consequences can be expected depending on the use of ARQ. Packet delivery rate decreases as packet delivery fails when ARQ is not considered while there will be data packet retransmission cost when ARQ is considered. The performance is evaluated by varying ARQ policies to analyze the impact of ARQ on geographic routing: ARQ 0, ARQ 10 and ARQ ∞. If the PRR of either of the two directional links between the current forwarding node and the neighbor node is less than 1%, the neighbor node is excluded from the list of candidates.

In the simulation, the sizes of data and ACK packet are $100 bytes$ and $11 bytes$, the energy required to forward a data packet is $1762.5 \mu J$ and the energy required to forward an ACK packet is $193.875 \mu J$ [26][27]. Nodes are deployed randomly in the network and 1000 packets are forwarded between a randomly selected source node and a destination node. In the performance evaluation we use the average of 1000 runs.

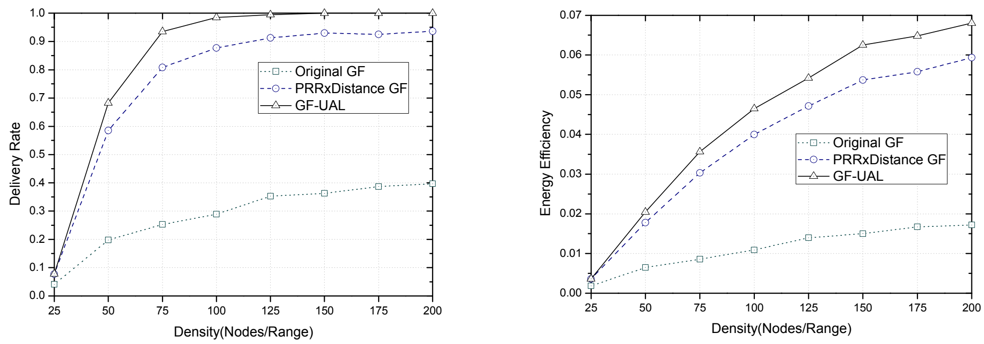
5.2 Packet Delivery Rate and Energy Efficiency with Various Node Densities

In this subsection, we vary the node density from 25 to 200 to simulate and compare the packet delivery rate and the energy efficiency of GF-UAL with those of the existing schemes. 1000 nodes are deployed and ARQ is 10. As ARQ is 10, each node can retransmit a data packet a maximum of 10 times. If the number of retransmissions is over 10, delivery failure occurs.

Fig. 7-(a) shows the packet delivery rate of three schemes including GF-UAL. GF-UAL has the highest packet delivery rate followed by PRR×Distance greedy forwarding, and OGF. The packet delivery rate in the realistic wireless environments drops generally due to two reasons: a weak link and a local minimum. The reason the packet delivery rate drops greatly when the node density is low (around 25 and 50) is that the local minimum occurs as there is no neighbor node closer to the destination node within the radio range. On the contrary, the delivery failure that takes place when the node density is high is mostly caused by the weak link problem. GF-UAL guarantees packet reception at almost 100% when the node density is 100 or higher. GF-UAL selects a neighbor node with higher PRR compared with the existing

schemes to obtain a higher packet delivery rate. GF-UAL enhances packet delivery rate up to about 17% compared with PRR×Distance greedy forwarding.

Fig. 7-(b) shows the energy efficiency of OGF, PRR×Distance greedy forwarding, and GF-UAL. The OGF selects the node closest to the destination node for packet forwarding and it does not consider the reliability of the link which results in a number of retransmissions. In addition, as the delivery rate is very low, it wastes a large number of data and ACK packet transmissions due to delivery failure and it results in a huge energy efficiency drop. PRR×Distance greedy forwarding has higher energy efficiency than OGF, however, it is less than GF-UAL due to the retransmissions of data packets caused by the asymmetry of links. The performance improvement increases with higher node density. GF-UAL enhances performance up to about 18% compared with PRR×Distance greedy forwarding.



(a) **(b)**

Fig. 7. **(a)** Packet delivery rate **(b)** Energy efficiency at different node densities.

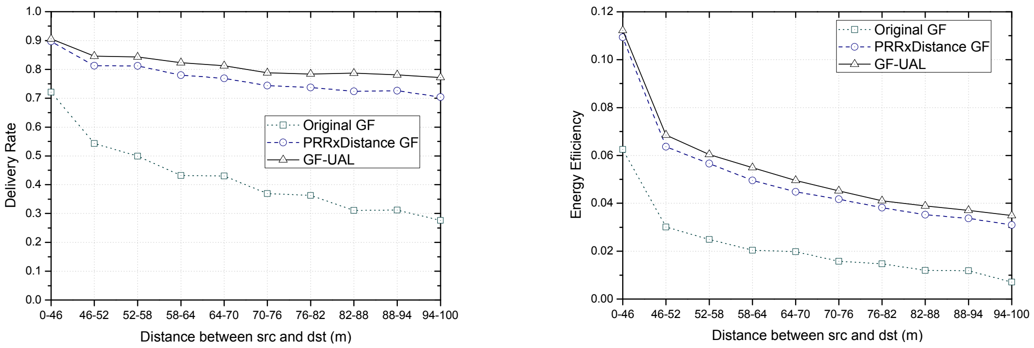
5.3 Packet Delivery Rate and Energy Efficiency with Source-Destination Distances

In this subsection, we vary the distance between the source node and the destination node to measure packet delivery rate and energy efficiency while fixing the node density as 50. At a low density of 50, we intend to focus only on the influence of the distance between source and destination on the performance. At the low density, after blacklisting neighbor nodes farther from the destination compared with the forwarding node itself or if it has a PRR less than the threshold value, there remain a very small number of neighbors available for selection as next hop forwarder. Therefore, GF-UAL and PRRxDistance GF have chances to select the same next forwarder. Due to this reason, the performance enhancement is not very significant. As the density increases, GF-UAL shows a better delivery rate and higher energy efficiency. Based on the simulation results, we compare and analyze the performance of the three schemes. The distances between the source node and the destination node are: 0 - 46, 46 - 52, … , 94 - 100 *m*. The maximum distance used in the simulation is 2.5 times that of the radio range. The network consists of 1000 nodes and the ARQ is 10.

Fig. 8-(a) shows the decrease of the delivery rate in three schemes including GF-UAL in proportion to the increase of the distance between the source node and the destination node. The delivery rate drops since the packet loss and greedy disconnection occur very likely when the number of hops required in delivering a data packet from the source node to the destination node increases. The simulation result shows that GF-UAL has a higher delivery rate than PRR×Distance greedy forwarding and OGF. The difference between the delivery rate of GF-UAL and existing schemes gets bigger as the distance between the source node and the destination node becomes longer. GF-UAL exhibits a maximum of about 10% higher delivery

rate compared with PRR×Distance greedy forwarding. This reflects that the packet loss in the existing schemes compared with GF-UAL becomes greater as the distance increases due to the unreliability and asymmetry of wireless links.

In **Fig. 8-(b)**, energy efficiency of the schemes is presented in relation to the distance between source node and destination node. The energy efficiency drops in all three schemes as the distance increases. Since the number of hops increases as the distance increases the total number of retransmissions increases accordingly. GF-UAL chooses the forwarding path by considering the PRR of both directional links for data and ACK packet forwarding and shows higher energy efficiency than PRR×Distance greedy forwarding and OGF. The difference in energy efficiency in relation to the distance becomes greater with a higher node density. As the number of neighbor nodes increases then the possibility of having both directional links with high reliability increases when the node density increases. When the node density is 50, GF-UAL shows a maximum of about 13% performance enhancement compared with PRR×Distance greedy forwarding.



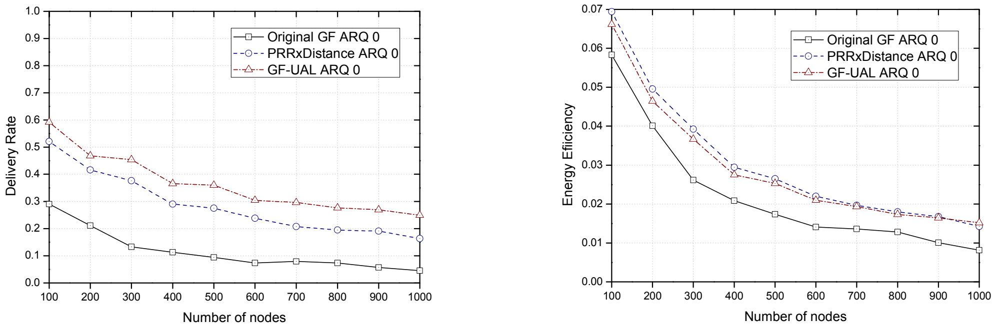
(a) **(b)**

Fig. 8. **(a)** Packet delivery rate **(b)** Energy efficiency at different S-D distances.

5.4 Packet Delivery Rate and Energy Efficiency with various ARQ policies and Network Sizes

In this subsection, we measure packet delivery rate and energy efficiency by varying the ARQ policy and network size to compare the performance of the schemes. Three ARQ policies are used, each with 0, 10, and ∞ retransmissions. When ARQ is 0, no retransmission occurs. When ARQ is ∞, the data packet is retransmitted until the current forwarding node receives an ACK packet of the transmitted data packet. In the simulation, we change the number of nodes in the network from 100 to 1000 while setting the node density to 50 to vary the network size.

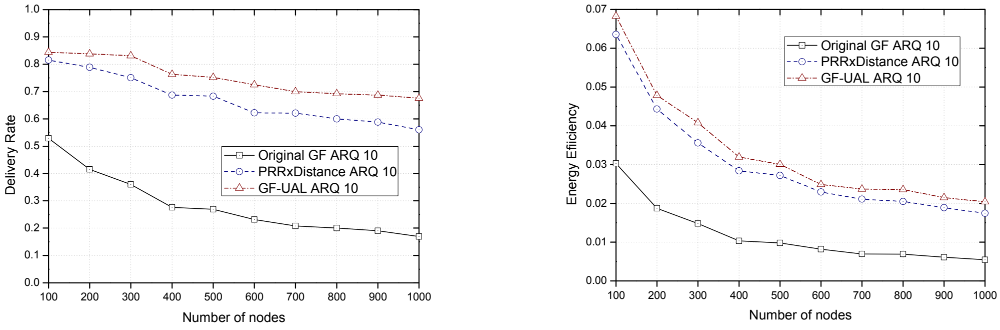
Figs. 9-(a) and **(b)** show the packet delivery rate and energy efficiency of GF-UAL, PRR×Distance greedy forwarding, and OGF, respectively, when ARQ is 0. When the number of nodes increases, the size of the network grows and the average distance between the source node and the destination node becomes longer. Therefore, the packet delivery rate and energy efficiency decrease. In **Fig. 9-(a)**, packet delivery failure occurs in the three schemes due to the local minimum and weak link problems. OGF only considers the distance factor which results in a decrease in energy efficiency. PRR×Distance greedy forwarding has a lower delivery rate than GF-UAL since the scheme does not consider the asymmetry of wireless links. Delivery failure occurs when the PRR of any link for both data and ACK transmissions is low. In **Fig. 9-(b)**, the energy efficiency of GF-UAL is a little lower than that of PRR×Distance greedy forwarding. The reason for this is twofold. First, when PRR is low, packet delivery rate decreases but retransmission does not occur. Second, GF-UAL has a slightly higher average hop count when compared with previously proposed schemes, so that the number of data and ACK packet transmissions increases.



(a) **(b)**

Fig. 9. **(a)** Packet delivery rate **(b)** Energy efficiency with various network sizes when ARQ is 0.

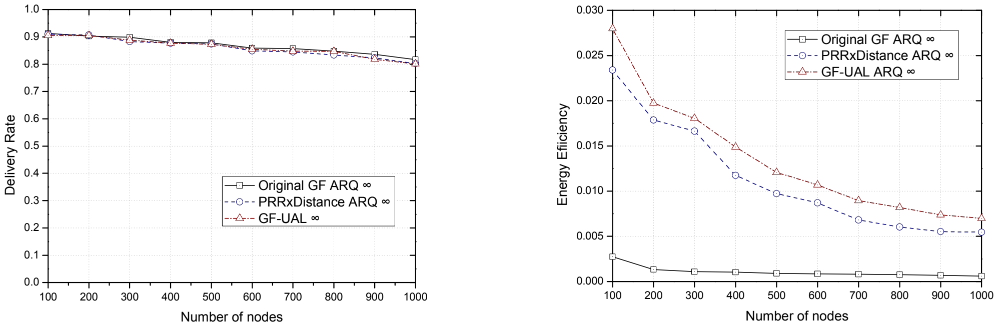
In **Fig. 10**, packet delivery rate and energy efficiency are shown in **(a)** and **(b)**, respectively for the schemes including GF-UAL when ARQ is 10. GF-UAL considers the unreliability and asymmetry of wireless links to avoid using the links with low PRR for data and ACK packet transmissions. Thus, GF-UAL has a higher delivery rate and energy efficiency than the existing greedy forwarding schemes. As shown in **Fig. 10-(a)**, when the number of nodes increases (i.e., the network size gets larger), the difference in packet delivery rate between GF-UAL and the existing schemes becomes larger. In a larger network, the average distance between the source node and the destination node is longer and the average hop count increases. In **Fig. 10-(b)**, packet delivery failure occurs as the existing greedy forwarding schemes select the links with low PRR. If the packet delivery fails, the transmission energy for packet delivery to the current hop will be wasted and it decreases energy efficiency.



(a) **(b)**

Fig. 10. **(a)** Packet delivery rate **(b)** Energy efficiency with various network sizes when ARQ is 10.

In **Fig. 11-(a)** and **(b)**, we compare the performance of the three schemes when ARQ is ∞. The three schemes have similar packet delivery rates with ARQ = ∞. As ARQ is ∞, packet delivery failure from the weak link problem does not occur. However, packet delivery rate is lower than 1 at the density of 50 because packet delivery failure occurs from the local minimum problem. When node density is sufficiently high, end-to-end packet delivery from the source node to the destination node is 100% guaranteed. With ARQ = ∞, packet retransmissions occur until the data packet is successfully transmitted to the next forwarding node. Therefore, the three schemes have lower energy efficiency than the cases of ARQ = 0 and ARQ = 10 shown in **Figs. 9** and **10**. Particularly, OGF which only considers the distance factor for packet forwarding is highly likely to select links with low PRR. Thus, the OGF experiences the unbounded number of retransmissions which results in low energy efficiency.



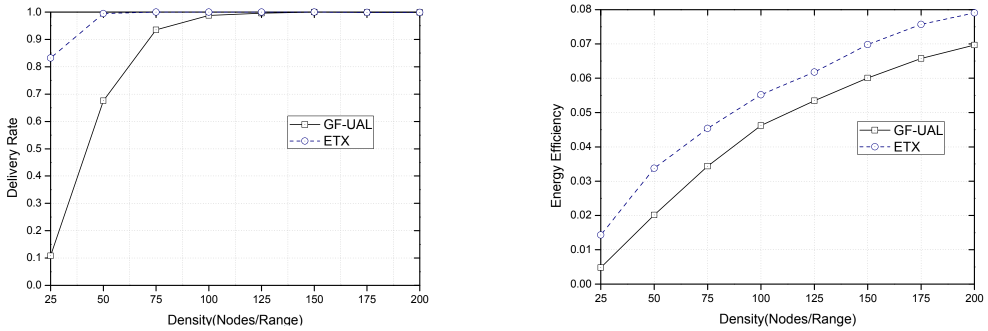
(a) **(b)**

Fig. 11. **(a)** Packet delivery rate **(b)** Energy efficiency with various network sizes when ARQ is ∞.

5.5 Comparison with ETX scheme

In this subsection, we compare GF-UAL using local information with global optimal ETX scheme in the aspect of total transmission number. We do not consider the existing schemes such as PRR×Distance greedy forwarding, as they are already compared in the previous subsections. To implement ETX scheme, dijkstra algorithm is used and a transmission number is used as the weight to find the shortest path from the source node to the destination node. We vary node density from 25 to 200 to compare delivery rate and energy efficiency of GF-UAL and ETX scheme. In addition, performance of the two schemes is compared by varying the distance between the source node and the destination node at a maximum of 2.5 times that of the radio range. The number of nodes deployed in the network is 1000 and ARQ is 10.

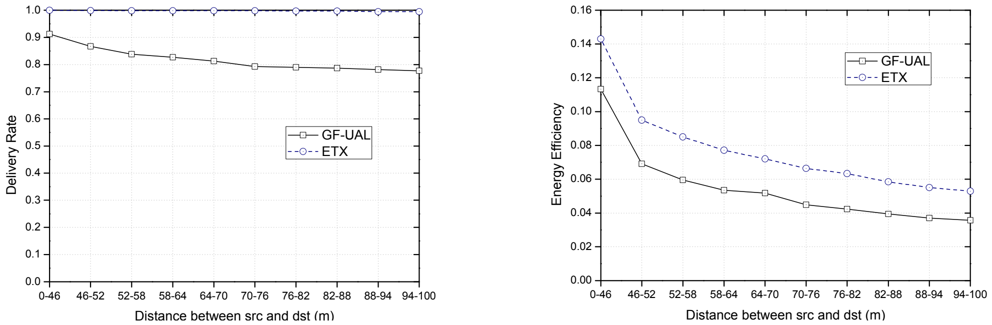
Fig. 12 shows delivery rate and energy efficiency of GF-UAL and ETX scheme with various node densities. When node density is low, as GF-UAL using local information has high possibility of greedy disconnection, ETX has relatively higher delivery rate. While node density is high, GF-UAL also shows high delivery rate as ETX scheme does. This is because GF-UAL considers unreliability and asymmetry of the links decreasing delivery failure from unreliable link problem. GF-UAL shows higher energy efficiency than that of the existing schemes however it is lower than that of ETX scheme. Even GF-UAL reduces energy consumption in the current hop by selecting the path with the minimum EDC, delivery failure in the next hop results in the waste of energy for packet delivery to the current hop.



(a) **(b)**

Fig. 12. **(a)** Packet delivery rate **(b)** Energy efficiency with different densities.

In **Fig. 13**, we show delivery rate and energy efficiency of the two schemes while varying the distance between source node and destination node. GF-UAL, utilizing only local information, experiences delivery rate decrease as the distance increases because the possibility of path disconnection increases with the higher number of hops. On the other hand, ETX, which uses the entire network information to select a packet delivery path, has very few delivery failures. Energy efficiency of the two schemes decrease as the distance gets longer. Because with the longer distance, number of hops increases and the possibility of using the links with low PRR increases which result in the increase of total number of transmissions including retransmissions.



(a) **(b)**

Fig. 13. **(a)** Packet delivery rate **(b)** Energy efficiency with different S-D distances.

6. Conclusions

In this paper, we proposed an energy-efficient greedy forwarding scheme for unreliable and asymmetric links (GF-UAL) which opportunistically uses either a 1-hop or 2-hop forwarding path within the radio range to reduce the number of unnecessary packet retransmissions. To achieve this goal, GF-UAL considered local radio link status information in a realistic WSN environment. In GF-UAL, each node calculates the expected delivery cost (EDC) to consider the unreliability and asymmetry of wireless links within radio range and selects a forwarding path with the minimum EDC. Hence, GF-UAL solved the problem of packet delivery rate and energy efficiency decrease of the existing schemes which do not consider the unreliability and asymmetry of links. In addition, GF-UAL utilized connected region based on link loss model so that each node can use the 1-hop and the 2-hop forwarding paths within the radio range.

Simulation results with varying node densities, ARQ policies, and network sizes demonstrated that GF-UAL is more energy efficient and has a higher packet delivery rate than the existing geographic routing schemes. In particular, we have compared GF-UAL with the ETX scheme and verified that the performance of GF-UAL is similar to that of global optimal ETX scheme. GF-UAL is expected to be applied to the management of facilities and structures such as the Golden Gate Bridge, intellectual farming, and environment monitoring. Each node in WSN has limited battery resources. Therefore, our future study will focus on the ways of using a sensor node's energy more efficiently by considering sensor duty cycle and power control.

In our future work, we plan to theoretically analyze the selection of next forwarding node within the radio range using the geometric probabilistic theory, and measure the impact of node density on this selection.

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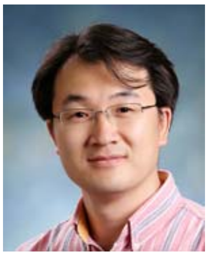

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