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Energy Efficient and Reliable Geographic Routing in Wireless Sensor Networks

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***Abstract*—**The wireless link can be unreliable in realistic wireless sensor networks (WSNs). Energy efficient and reliable data forwarding is important because each node has limited resources. Therefore, we must suggest an optimal solution that considers using the information of the node's characteristics. Previous routing protocols were unsuited to realistic asymmetric WSNs. In this paper, we propose a ***P**rotocol that considers **B**oth sides of **L**ink-quality and **E**nergy* (*PBLE*), an optimal routing protocol that balances modified link-quality, distance and energy. Additionally, we propose a node scheduling method. *PBLE* achieves a longer lifetime than previous routing protocols and is more energy-efficient. *PBLE* uses energy, local information and both sides of PRR in a 1-hop distance. We explain how to send data packets to the destination node using the node's information. Simulation shows PBLE improves delivery rate and network lifetime compared to previous schemes. Moreover, we show the improvement in various WSN environments.

***Keywords*—**energy-efficient, lifetime, PBLE, unreliable

I. INTRODUCTION

WE can meet various transmission protocols in sensor networks due to the rapid improvement of the ubiquitous environment and wireless network. Especially, WSNs (Wireless Sensor Networks) are core technologies in a wide range of environments, such as observing ecosystems, car navigator systems, and our life [1]-[3]. However, we meet difficultly constructing an ideal network environment, because sensor nodes have use limitations in real WSNs [4]-[6]. The limited lifetime due to the sensor node's battery is a typical problem. That is, it decreases the network lifetime in data transmission. Therefore, it is essential to increase network lifetime in wireless sensor networks [7].

A protocol that is reliable and efficient in data transmission from the source node to destination node is essential since the network's object is data collection and transmission. *Original Greedy Forwarding* and *PRR×Distance Greedy Forwarding* are two popular protocols for this purpose [8]-[10].

Original Greedy Forwarding forwards data packets to the neighbor node nearest to the destination node. This is a simple data transmission protocol in geographic routing, as each node only has local information on neighbor nodes. It guarantees a relatively low distance (or hop count). However, *Original Greedy Forwarding* does not focus on link quality. That is, it incurs excessive energy waste in each node caused by retransmission.

PRR×Distance Greedy Forwarding was proposed to solve this problem. It focuses on link quality compared to *Original Greedy Forwarding*. *PRR×Distance Greedy Forwarding* sends data packets that it considers between the location and link quality of neighbor node. However, this method does not consider other characteristics of neighbor nodes, such as limited energy.

Therefore, we proposed a method that considers the residual energy of neighbor nodes with *PRR×Distance Greedy Forwarding* in our previous research. The method increased network lifetime by achieving high performance in terms of energy-efficiency. However, this method did not consider an asymmetric network. Moreover, the method did not consider ACK transmission. In real WSNs, the method has many problems, such as retransmission caused by the loss of ACK transmission [11].

In this paper, we propose *PBLE* (Protocol considering Both sides of Link-quality and Energy) to consider asymmetric and unreliable links with residual energy of a node. The main contribution of this work includes:

1) Proposing new route-selection and blacklisting methods suitable for geographic routing over distance, both sides of PRR and energy, and their combination.
2) Mathematical analysis of network's efficient working that is applied to both sides of link-quality and blacklisting methods.
3) Validation of PBLE with results to compare to other geographic routing.

The remainder of this article is organized as follows. We describe other geographic routing protocols in section 2. In section 3, we propose a new geographic routing protocol, PBLE, with the research background. In section 4, we describe the results of simulation that evaluates the performance of PBLE against other protocols. Finally, we discuss the implications of our results and future work.

II. RELATED WORK

A. Original Greedy Forwarding

Original Greedy Forwarding is a famous geographic routing

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protocol. In *Original Greedy Forwarding*, each node has its local information that of and neighbor nodes. The source node uses the local information of neighbor nodes to select the next node for data transmission. Additionally, the source node knows the location of the destination node.

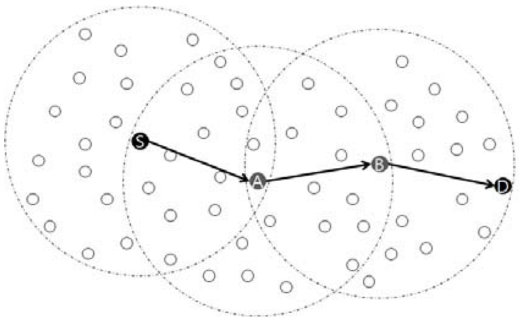

Fig. 1. An example of *Original Greedy Forwarding*. Source node (S) selects node A that is the closest to destination node (D) in radio range. Node (A) selects node (B) to use same rules. Lastly, node (B) sends data packets to destination node (D)

When a transmission begins, the source node selects a candidate node for data transmission in neighbor nodes. A candidate node that is selected by the source node is the closest to the destination node using the local information. If there is packet loss in data transmission, the source node will transmit repeatedly (Fig. 1). A candidate node receives the data packet perfectly; it sends ACK packets to the source node. *Original Greedy Forwarding* repeats this pattern, until data packets reach the destination node. It only uses local information, so it does not need to have the information of the neighbor node's status [8].

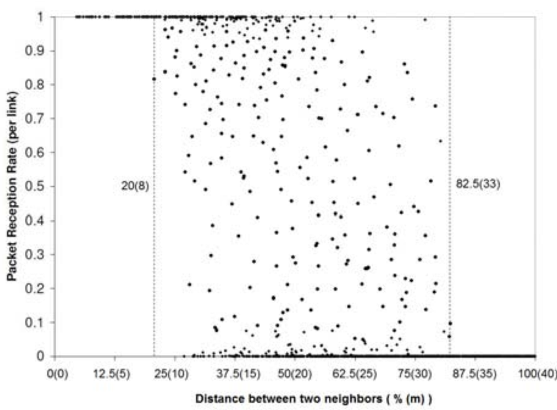

Fig. 2. A sample from a realistic wireless link-layer model. It shows a different environment between the idealized model and the realistic model.

However, *Original Greedy Forwarding* assumes an ideal network model that always completes data transmission. If a candidate node has bad link quality, the retransmission would increase extremely. Therefore, the node energy is consumed wastefully in real WSNs. In real WSNs, we find a disconnected region in the source node's radio range in which data transmission is impossible (Fig. 2). That is, it is impossible for neighbor nodes in the farthest 20% of the radio range to send data packets. Finally, the failure of data transmission incurs retransmission. This decreases network lifetime [9][10].

B. PRR×Distance Greedy Forwarding

Previously proposed geographic routing protocols assume an ideal network that guarantees perfect transmission. *Original Greedy Forwarding* is unsuited to real WSNs due to link-quality. That is, there is a huge difference between realistic networks and ideal networks [12]. *PRR×Distance Greedy Forwarding* makes up for the weaknesses in *Original Greedy Forwarding*. WSNs work in a real environment based on the link loss model in which we find the PRR concept (Packet Reception Rate). PRR is the ratio of data transmission success.

PRR×Distance Greedy Forwarding considers both sides of PRR and distance. That is, it strikes a balance between PRR and *Distance_Improvement* by multiplying the two values to solve problems of *Original Greedy Forwarding* and Absolute Reception-based Forwarding. In *PRR×Distance Greedy Forwarding*, we calculate *Distance_Improvement* to solve the problem of distance-hop energy tradeoff. *Distance_Improvement* is a normalized value of the distance between a neighbor node and destination node. It ranges from zero to one. *Distance_Improvement* is given by:

$$Distance\_Improvement = 1 - \frac{d(nbr,dst)}{d(crt,dst)} \quad (1)$$

$d(nbr,dst)$ is the distance between the destination node and a neighbor node. $d(crt,dst)$ is the distance between the current node and the destination node and the current node.

In this method, the source node selects a candidate node that is the highest *PRR×Distance_Improvement* value in neighbor nodes.

First, the source node selects the neighbor node, as a candidate node, whose location is within 1-hop distance for data packet forwarding. The distance of the neighbor nodes to the destination node is less than the distance between the source node and the destination node. Second, the source node sends data packets to the candidate node that has the highest *PRR×Distance_Improvement* value among neighbor nodes. Finally, it repeats these steps until data packets reach the destination node [9][10]. *PRR×Distance Greedy Forwarding* complements excessive data retransmission of *Original Greedy Forwarding*. In addition, it complements the problem that is an extreme increase of hop-count in *only PRR-based forwarding*.

Fig. 3 illustrates different selections of *Original Greedy Forwarding* and *PRR×Distance Greedy Forwarding*. In the former method, the source node selects node (B) that is the closest node destination node in the neighbor nodes. Node (B) selects node (K). In case of the latter method, however, the source node selects node E that has the highest *PRR×Distance_Improvement* value of the neighbor nodes. Node (E) selects node (H) in the same way. In addition, it applies the blacklisting method in data forwarding. The source node omits neighbor nodes, such as node (B) and (M) that do not attain the specific value of PRR.

This method solves the problem of *Original Greedy Forwarding*. However, if we use a fixed pair of source and destination node, the same route will always be selected and the nodes on the route will consume much energy compared to other nodes. This problem can decrease network lifetime greatly. In addition, it does not consider the PRR of the ACK message. It incurs a problem that makes retransmission due to transmission failure of the ACK message.

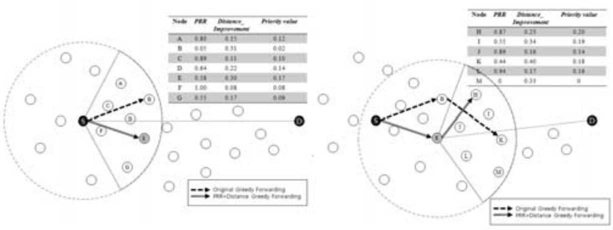

Fig. 3. Different selections of previous schemes (*Original Greedy Forwarding* and PRR×Distance Greedy Forwarding).

C. Previous Work

We considered the residual energy of the node to solve the problem of *PRR×Distance Greedy Forwarding*. Additionally, we balanced energy and PRR×*Distance_Improvement*. Therefore, we could increase network lifetime compared to *PRR×Distance Greedy Forwarding*. We applied it to the issue of residual energy for the case of the blacklisting method. Hence, we can achieve relatively efficient routing in WSNs [11].

However, in our previous work, we could not consider an asymmetric network environment in real WSNs. We could not consider the PRR degree made by the ACK message (reserve). We found discrepancies from real WSNs. Therefore, this research complements problems of the previous scheme. We propose *PBLE* that considers both sides of PRR and the scheduling method.

III. Geographic Forwarding Strategies

We propose *PBLE* suitable for geographic routing. It is an efficient routing protocol that considers both sides of PRR and the *Energy_level* with the scheduling method. Our proposed method uses some factors that are on both sides of PRR, energy factor, and the distance within a 1-hop distance. Our selection method for candidate nodes is similar to the previous method. However, we use reverse PRR and weight factors for efficient routing.

A. Assumption and Notation

PBLE assumes a general Wireless Sensor Network environment:

1) Every node knows the location of 1-hop neighbors and itself (using localization algorithms or GPS of WSNs).
2) Every node knows its PRR and the *Energy_level* and those of its 1-hop neighbors.
3) A source node knows the location of the destination node.

Table 1 shows our notation in this paper.

TABLE I
NOTATION

Description	Symbol
Packet Reception Rate of link from node A to B	$PRR_{A\rightarrow B}$
size of packet	S_{packet}
distance between node A and B	$d(A, B)$
node A's residual energy	$E_A(residual)$

B. Link Loss Model

We require a link loss model of a real environment to simulate reliable data transmission. We use the Packet Reception Rate (PRR) in this research. PRR presents the link quality between two nodes. It ranges from 0 to 1. It is denoted by [14][15]:

$$PRR(d) = (1 - \frac{1}{2} e^{-(\frac{\gamma(d)}{2})\frac{1}{0.64}})^{16f-8l} \quad (2)$$

d is the distance between two nodes, γ(d) is the signal to noise ratio for d, f is the length of a frame, and l is the length of a preamble. It considers various radio parameters in real WSNs. We use MICA2 motes in (2) with the Manchester encoding scheme. We consider other characteristics of MICA2. Other detailed information of characteristics follows [16].

Similar with other research [4][5][12][14][15], we can find distinct data reception regions in WSNs (Fig. 2). In the connected region (from 0 to 8*m*), nodes can transmit data packets perfectly, because PRR is always 1. In the transitional region (from 8*m* to 35*m*), we observe various link qualities between two nodes. In the disconnected region (from 35*m* to radio range), we find no link.

C. Design Concerns

1. Route Selection

Each node knows neighbor nodes within 1-hop radio range for efficient packet transmission. First, the source node calculates *Distance_Improvement* of the neighbor nodes using (1). Second, the source node eliminates some neighbor nodes by applying the blacklisting method of the energy factor and PRR factor. Third, the source node selects a candidate node that has the highest value of *Expected Priority Value* (*EPV*). *EPV* is explained in subsection 2. The blacklisting method is explained in subsection 3.

2. Expected Priority Value

We use both sides of PRR and *Energy_level* with distance to balance the distance-hop energy trade-off and residual energy. Each node has the information of location, *Energy_level* and PRR of its neighbor nodes. The current forwarding node (source node) selects a candidate node from one of its neighbor nodes to take into account the size of the ACK message's packet. A candidate node has the highest value of *EPV*. *EPV* is given by:

$$EPV = w_1 \times (MSL \times Distance\_Inproment) + w_2 \times Energy\_level \quad (3)$$

We use the *Modified Status of Link-quality* (*MSL*), *Energy_level*, *Distance_Improvement*, and weight factors (w_1 and w_2). *MSL* is denoted by:

$$MSL = (\frac{S_{data}}{S_{data} + S_{ACK}}) \times PRR_{src \to nbr} + (\frac{S_{ACK}}{S_{data} + S_{ACK}}) \times PRR_{nbr \to src} \quad (4)$$

MSL is the value that explains link quality between a source node and a neighbor node. We can describe the modified link quality of the route for data transmission based on the size of the data packet and ACK message packet. We apply two factors which decide the size of the packet (S_{data} and S_{ACK}) for various sizes of data packet. Additionally, we use both sides of PRR due to the asymmetric WSN.

We use the *Energy_level* of neighbor nodes to take into account the energy of a node. The *Energy_level* is a normalized value between 0 and 1. *Energy_level* is given by:

$$Energy\_level = \frac{E_A(residual)}{E_A(initial)} \quad (5)$$

In (5), E_{A}(*initial*) is the initial energy of node (A). E_{A}(*residual*) is the residual energy of node (A).

w_1 and w_2 are weight factors. Weight factors are defined by the *Energy_level* of neighbor nodes. If neighbor nodes in WSNs have sufficient energy to send or receive data packets, we do not need to consider the relative energy factor in data transmission. Therefore, we can send data packets focusing on link quality and distance, such as *Distance_Improvement* and *MSL*. Weight factors are decided within 1-hop, locally. We calculate weight factors from the average *Energy_level* of neighbor nodes. Weight factors are given by:

$$w_1 = \frac{\sum_{n=1}^{n} Energy\_level_{nbr(i)}}{n} \quad (6)$$

$$w_1 + w_2 = 1 \quad (7)$$

In (6), $Energy\_level_{\text{nbr}}$(i) is calculated by (5) about neighbor nodes.

3. Blacklisting Strategies

We use the blacklisting method in every data transmission process for reliable data transmission. We found the blacklisting method based on PRR value in *PRR×Distance Greedy Forwarding* [9][10]. In our previous work, we also applied the blacklisting method based on *Energy_level*.

PRR-based Blacklisting: we use both side of PRR value for the blacklisting method based on PRR, because we assume an asymmetric WSN environment. We use the value of the $PRR_{\text{threshold}}$ in each data transmission. If the value in both sides of PRR is less than the $PRR_{\text{threshold}}$, we will omit the neighbor node when selecting a candidate node.

Energy-based Blacklisting: we use the value of the $Energy_{\text{threshold}}$ to apply Energy-based blacklisting. The node should have sufficient energy for appropriate data transmission of the node. The current node omits neighbor nodes from the candidate node list that have a lower *Energy_level* than the $Energy_{\text{threshold}}$.

4. Node Scheduling

If the current node has sufficient neighbor nodes in the connected region, neighbor nodes can alternate the current node in the data transmission process. Every link can always make a complete transmission in the connected region (Fig. 2).

First, if the node has neighbor nodes within half the radius (Fig. 4a) in the connected region, the node can designate the neighbor nodes as alternative nodes. Second, the node sets the alternative region that is 45° to the left and right of the direction of a neighbor node (Fig. 4b). The node repeats this process (Fig. 4c). After finishing the process, if the node is encircled by alternative region from every angle (see Fig. 4d), the current node sends the dormant message to the neighbor nodes notifying that the current node will switch its condition to sleep mode. The current node sends the alternative message to the alternative nodes announcing its sleep time. In our simulation, we set the sleep time as 5% of the node's initial lifetime. Every time the node wakes, the node sends an appropriate message to alternative nodes. Alternative nodes send messages, including its current condition with its *Energy_level*. If any single alternative node does not reach the $Energy_{\text{threshold}}$, the current node will awake and send awaking messages to the neighbor nodes.

Some nodes can retrench their limited energy due to this node scheduling method. Thus, it increases network lifetime with efficient geographic routing.

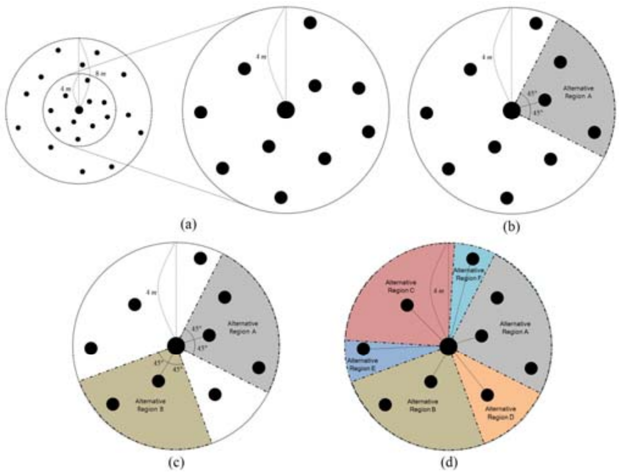

Fig. 4. The example of alternative region setting.

D.Data transmission

The current node omits some neighbor nodes using the blacklisting method in data transmission. Then, the current node sends data packets to a candidate node that has the highest *EPV* of the neighbor nodes (see Fig. 5). If the current node does not receive the ACK message from the candidate node perfectly, the current node should retransmit. Data delivery will fail, if the number of retransmission times exceeds *ARQ* (***A**utomatic **R**epeat re**Q**uest*). *ARQ* is the automatic repeat request. Each node updates the *Energy_level* of neighbor nodes at the end of each transmission. Each node repeats these steps until the destination node receives data packets.

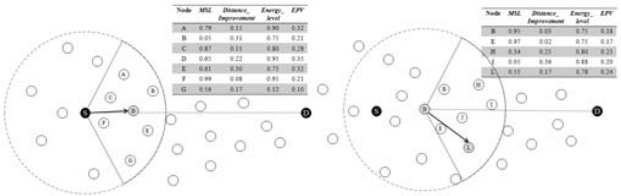

Fig. 5. The example of *PBLE*.

IV. Experimental Results

A. Simulation Environment

In this section, we use C++ to simulate and evaluate the performance of *PBLE* and compare it to *Original Greedy Forwarding* and *PRR×Distance Greedy Forwarding*. We construct network topologies randomly. Node density is the number of neighbor nodes within the sensor's radio range. We cannot consider data packet loss from other problems, including *MAC layer* collision.

In the simulation, the data packet size is 100 *bytes*, and the size of the *ACK* packet is 11 bytes. Therefore, the energy consumption of data transmission is 1762.5 μJ. The energy consumption of *ACK* transmission is 193.875 μJ [13]. Table II displays the variables of the simulation environment [17]. The radio model reflects MICA2 motes.

TABLE II
Simulation Parameters

Para	Value	Parameter	Value
Modulation	NC-FSK	Bandwidth	3000Hz
Mac Layer	IEEE 802.11	Data Rate	1.92kbps
Encoding	Manchester	Number of trials	1000
Output Power	-5 dBm	Data packet size	100 bytes
Path Loss Exp	3	ACK Packet Size	11 bytes
Baseline Routing Schemes			
Original Greedy Forwarding			
PRR×Distance Greedy Forwarding			

In subsection *B*, we simulate in various node densities: 25, 50, 75, 100, 125, 150, 175 and 200 (nodes/range) to portray various WSN statuses. We use typical values of $PRR_{\text{threshold}}$ and $Energy_{\text{threshold}}$. $PRR_{\text{threshold}}$ is 0.01. $Energy_{\text{threshold}}$ is 0.146. *ARQ* is 10 [11].

1) Delivery rate: the percentage of successful transmission from the source node to destination node in the transmission trial (from 0 to 1).
2) Lifetime rate: rate of network lifetime compared to an ideal network's lifetime without retransmission (from 0 to 1).
3) Relative retransmission rate (*R*): rate of number of retransmissions in each scheme compared to number of retransmissions in *Original Greedy Forwarding*. ($R_{\text{Original\_Greedy\_Forwarding}} = 1$)

B. Effect of Various Node Densities

1. Delivery Rate

We measure the delivery rate in various node densities (Fig. 6). Every forwarding method achieves an extremely low delivery rate in a low node density. Most transmission failure is due to the local minimum problem [18]. *PBLE* achieves a 94.8% delivery rate at node density 125. On average, *PBLE* achieves 8.79% higher delivery rate than *PRR×Distance Greedy Forwarding*.

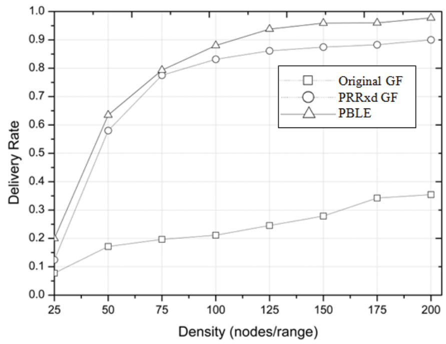

Fig. 6. Delivery rate at different densities.

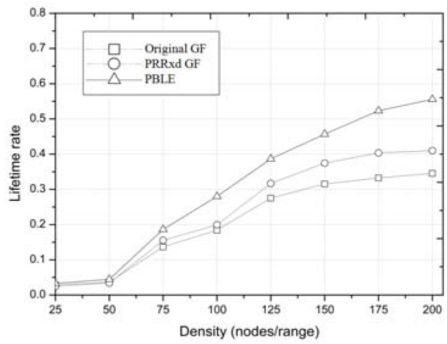

Fig. 7. Lifetime rate at different densities.

2. Lifetime Rate

We present lifetime rates under various node densities in Fig. 7. We cannot find a difference at a low node density, such as 25 and 50, because most nodes cannot find neighbor nodes using the scheduling method. Every forwarding method achieves an extremely low delivery rate at low node density. However, as node density gets increases, network lifetime increases. *PBLE* achieves the longest network lifetime. On average, *PBLE* achieves 51.03% and 30.28% higher lifetime rate than does *Original Greedy Forwarding* and *PRR×Distance Greedy Forwarding*. Especially, PBLE achieves 72.66% and 45.51% higher lifetime rates than *Original Greedy Forwarding* and *PRR×Distance Greedy Forwarding* at node density 200. This improvement is due to our candidate node-selection scheme and node-scheduling scheme. Other schemes do not consider the residual energy of nodes. Additionally, they do not use node scheduling in geographic routing.

3. Relative Retransmission Rate

We count number of retransmissions to measure energy-efficiency. Relative retransmission rate of *PBLE* (R_{PBLE}) shows similar relative retransmission rate compared to *PRR×Distance Greedy Forwarding* (Fig. 8). On average, *PBLE* achieves a 76.59% lower relative retransmission rate than does *Original Greedy Forwarding*. Specifically, *PBLE* achieves 88.12% lower relative retransmission rate than does *Original Greedy Forwarding* at node density 200.

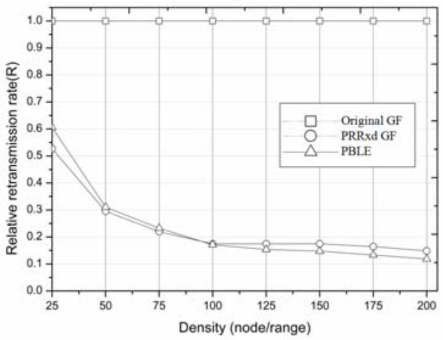

Fig. 8.Relative retransmission rate at different densities.

V.Conclusion

Energy-efficient transmission is an important and fundamental issue in real wireless sensor networks. Previous existing routing methods had problems in real WSNs. In this study, we propose a new geographic forwarding method, *PBLE*. *PBLE* uses *EPV* that considers the asymmetry of wireless links and calculates the *Energy_level*, PRR and local information of the node. *PBLE* improves data transmission compared to previous schemes. *PBLE* achieves higher performance in terms of *Energy_level* and considers the asymmetric environment from an increased network lifetime. In addition, the node-scheduling method contributes to prolong the network lifetime. That is, we achieve superior results to previous schemes in delivery rate, lifetime rate and relative retransmission rate for various WSN environments.

In the future, we will extend our study by applying it to a Multi-Hoping Wireless sensor network. We will improve *PBLE* for mobile sensors with wireless links.

References

[1] D. C. Streere, A. Baptista, D. McNamee, C. Pu, and J. Walpole, “Research Challenges in Environmental Observation and Forecasting Systems,” *in Proc. of 6th Int. Conf. on Mobile Computing and Networking*, Boston, 2000, p.299.

[2] L. Schwiebert, S. K. S. Gupta, and J. Weinmann, “Research Challenges in Wireless Networks of Biomedical Sensors,” *in Proc. 7th Int. Conf. on Mobile Computing and Networking*, Rome, 2001, pp.151-165.

[3] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," *Computer Networks*, vol.38, no.4, pp. 393-422, 2002.

[4] J. Zhao, and R. Govindan, “Understanding Packet Delivery Performance in Dense Wireless Sensor Networks,” *in Proc. 1st Int. Conf. on Embedded Networked Sensor Systems*, Los Angeles, 2003, pp.1-13.

[5] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker, “Complex behavior at scale: An experimental study of low-power wireless sensor networks,” *Technical Report*, vol. 02, no.13, 2002.

[6] D.S.J. De Couto, D. Aguayo, J. Bicket, and R. Morris, “A High-Throughput Path Metric for Multi-Hop Wireless Routing,” *Wireless Networks*, vol.11, issue.4, pp.419-434, 2005.

[7] J. Kamimura, N. Wakamiya, and M. Murata, “Energy-Efficient Clustering Method for Data Gathering in Sensor Networks,” *IEIC Technical Report*, vol.103, no.691, pp.31-36, 2004.

[8] B. Karp and H.T. Kung, “GPSR: Greedy Perimeter Stateless Routing for Wireless Networks,” *in Proc. of 6th Int. Conf. on Mobile Computing and Networking*, Boston, 2000, pp.243-254.

[9] K. Seada, M. Zuniga, A. Helmy, and B. Krishnamachari, “Energy-Efficient Forwarding Strategies for Geographic Routing in Lossy Wireless Sensor Networks,” *in Proc. of 2nd Int. Conf. on Embedded Networked Sensor Systems*, Baltimore, 2004, pp.108-121.

[10] M. Zamalloa, K. Seada, B. Krishnamachari, and A. Helmy, “Efficient Geographic Routing over Lossy Links in Wireless Sensor Networks,” *ACM Transactions on Sensor Networks*, vol.4, no.3, 2008.

[11] E. Park, D. Bae, and H. Choo, “Energy Efficient Geographic Routing for Prolonging Network Lifetime in Wireless Sensor Networks,” *in Proc. of Int. Conf. on Computational Science and Its Applications*, Fukuoka, 2010, pp.285-288.

[12] A. Woo, T. Tong, and D. Culler, “Taming the Underlying Issues for Reliable Multihop Routing in Sensor Networks,” *in Proc. of 1st Int. Conf. on Embedded Networked Sensor Systems*, Los Angeles, 2003, pp.14-27.

[13] V. Shnayder, M. Hempstead, B. Chen, G. W. Allen, and M. Welsh, “Simulating the Power Consumption of Large-Scale Sensor Network Applications,” *in Proc. of 2nd Int. Conf. on Embedded Networked Sensor Systems*, Baltimore, 2004, pp.188-200.

[14] M. Zuniga, and B. Krishnamachari, “Analyzing the Transitional Region in Low Power Wireless Links,” *in Proc. of IEEE Int. Conf. on Sensors and Ad Hoc Communications and Networks*, Santa Clara, 2004, pp.517-526.

[15] M. Z. Zamalloa, and B. Krishnamachari, “An Analysis of Unreliability and Asymmetry in Low-power Wireless Links,” *ACM Transactions on Sensor Networks*, vol.6, no.2, 2007.

[16] CC1000 Data Sheet. Texas Instruments Incorporated: Dallas, TX, USA, 2007.

[17] M. Mamun, T. Hasan-AI-Mahmud, S. Debnath, and M. Islam, “Analyzing the Low Power Wireless Links for Wireless Sensor Networks,” *Journal of Telecommunications*, vol.1, issue.1, pp.123-127, 2010.

[18] B. Leong, S. Mitra, and B. Liskov, “Path Vector Face Routing: Geographic Routing with Local Face Information,” *in 13th Proc. of IEEE Int. Conf. on Network Protocols*, Boston, 2005, pp.147-158.

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