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Urgency-Aware Adaptive Routing Protocol for Energy-Harvesting Wireless Sensor Networks

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Abstract

Energy-harvesting wireless sensor networks(EH-WSNs) can collect energy from the environment and overcome the technical limitations of existing power. Since the transmission distance in a wireless sensor network is limited, the data are delivered to the destination node through multi-hop routing. In EH-WSNs, the routing protocol should consider the power situations of nodes, which is determined by the remaining power and energy-harvesting rate. In addition, in applications such as environmental monitoring, when there are urgent data, the routing protocol should be able to transmit it stably and quickly. This paper proposes an adaptive routing protocol that satisfies different requirements of normal and urgent data. To extend network lifetime, the proposed routing protocol reduces power imbalance for normal data and also minimizes transmission latency by controlling the transmission power for urgent data. Simulation results show that the proposed adaptive routing can improve network lifetime by mitigating the power imbalance and greatly reduce the transmission delay of urgent data.

Keywords: *Adaptive routing, Energy harvesting, Urgency of data, Wireless sensor networks*

1. Introduction

In a wireless sensor network, sensor nodes installed in various environments sense various information. In many cases, a sensor network is used in an environment where external power cannot be provided, so this limited power problem is a very important technical constraint. To overcome this limitation, energy-harvesting technology has been applied to wireless sensor networks that can collect energy from the environment [1]-[2]. EH-WSNs overcome power limitations and extend network lifetime through their own energy-harvesting capabilities.

EH-WSNs mainly have the form of an ad-hoc network rather than a centralized type and use a multi-hop transmission method to transmit data to remote sink nodes because of the limitation of the transmission range of the node. Sensor nodes implanted in a wide area participate in multi-hop routing according to power

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conditions. The transmission delay and reliability are determined by the routing path. Therefore, the routing protocol that sets the path from the source node to the destination node is an important factor for network performance.

In EH-WSNs, nodes are equipped with energy-harvesting devices that collect various energy types such as ambient light, vibration, heat and wind, and energy storage devices that can store the collected energy. However, even in the energy-harvesting sensor network, the energy-harvesting rate is very low compared with the energy consumed and it is very large depending on the surrounding environment. It is thus not always possible to harvest and store enough energy. Therefore, the power problem is a very important constraint in the energy-harvesting sensor network, so power conditions such as residual power and the energy-harvesting rate in EH-WSN are important considerations when designing routing protocols. Many routing protocols have been proposed to extend network lifetime through efficient power usage in EH-WSN [3]-[5]. However, in most routing protocols, the overhead is greatly increased and routing protocols are complicated for sharing the power condition among nodes.

The routing protocol in most sensor networks is designed without considering the urgency of sensed data [6]. However, in applications such as environmental monitoring, there is a need for a routing protocol that can guarantee reliability while minimizing latency when urgent data are generated. For example, in urgent situations such as wildfire, it is necessary to select high-priority data and deliver it to the destination node as soon as possible [7]. Therefore, in case of urgent data, it is required to have a routing protocol that minimizes latency by reducing the number of hops. In this way, routing protocols must be adaptively changed according to the urgency of data.

This study designs an adaptive routing protocol for normal and urgent data based on the energy-harvesting rate, residual power, and data urgency. In the case of normal data, the routing path is composed of nodes with a relatively good energy situation to solve the power imbalance and extend network lifetime. The energy situation is determined by the remaining power of the nodes and the energy-harvesting rate. On the other hand, in case of urgent data, the routing path is selected with a view to minimizing transmission delay. To this end, a path that minimizes the number of hops is established by adjusting the transmission range through transmission power control.

The rest of this paper is organized as follows. Section II introduces the adaptive routing protocol that considers data urgency. Sections III and IV describe routing protocols for normal and urgent data, respectively. Simulation results are provided and discussed in Section V, and the conclusions are presented in Section VI.

2. Adaptive routing according to data urgency

This paper proposes a routing protocol that can adaptively determine the routing path based on the urgency of data. To this end, a routing protocol is designed to support urgent data transmission based on AODV (Ad hoc On-demand Distance Vector) routing protocol [8]. In general, nodes transmit data to a destination node using the same routing protocol without considering the priority of the sensed data. However, most of the data periodically sensed in the sensor network, such as environmental monitoring, show a normal state, but urgent data, which rapidly change and rise above a certain level, or fall below a certain level, should be delivered to the destination node quickly with low latency. For urgent data, the most important requirement of routing design is to minimize hops and delay. On the other hand, in the case of normal data, routing protocols should be designed to use power efficiently, considering the energy-harvesting rate, and extend network lifetime by minimizing power imbalance among nodes.

The source node determines the urgency of data. To adaptively select the routing protocol, relay nodes

must know the urgency of packet data. Therefore, it is necessary to indicate the urgency of packet data during RREQ (Route Request) packet transmission. To do this, the priority field is added to the conventional RREQ packet as shown in Fig. 1. The priority field can be used to process data with various QoS (Quality of Service), but in this paper, the priority field has a value of 0 if data are a normal packet and a value of 1 for an urgent data packet.

type	Flags	Hop count	RREQ ID	Destination sequence number	Source address	Source sequence number	Priority

Figure 1. RREQ packet supporting data priority.

The nodes receiving the RREQ packet adaptively select the routing protocol according to their priority. If priority is 0, then the routing algorithm that considers the energy condition described in Section 3 will be selected. If priority is 1, the power-controlled routing described in Section 4 will be selected.

3. Energy balancing based routing protocol

In the case of normal data transmission, it is more important to use a power-efficient routing method that can extend network lifetime than transmission latency. Therefore, in this paper, the residual power and energy-harvesting rate are jointly considered when designing a routing protocol for normal data. Also, to extend network lifetime, the residual power of nodes should be balanced.

To this end, in this paper, the cost value of each routing path is newly defined using residual power, energy-harvesting rate, and variance of residual power. The power considering the energy-harvesting rate can be expressed as the expected residual energy $E_r(t+t_o)$, after the packet transmission period t_o, as shown in Eq. (1).

$$E_r(t+t_o) = E_r(t) - E_a + R_h(t)t_c \tag{1}$$

where t_c is charging time by energy harvesting and E_a is the energy consumed for data transmission by a node participating as a relay node and $R_h(t)$ is energy-harvesting rate. Since each node needs to know the power state of the routing path, as shown in Fig. 2, the RREQ packet transmits the average and variance of the remaining power of the nodes onto the path.

type	Flags	Hop count	RREQ ID	Destination sequence number	Source address	Source sequence number	Priority	Average residual energy $\overline{E}_{r,n}$	Energy variance $\sigma_{E,n}$

Figure 2. RREQ packet supporting routing for energy balancing.

In Fig. 2, $\overline{E}_{r,n}$ is the average residual energy of all nodes in the path to the current node *n* for the

estimated residual power obtained from Eq. (1). Energy variance $\sigma_{E,n}$ is the standard deviation of the expected residual energy of the nodes in the path. The nodes receiving the RREQ packet must update the average and standard deviation of the expected residual power in the path and send the RREQ packet again. When the *n*-th hop node receives the RREQ packet, it first updates the average residual energy using residual energy $E_{r,n}(t+t_0)$ as shown in Eq. (2).

$$\overline{E}_{r,n} = \left((n-1)\overline{E}_{r,n-1} + E_{r,n}(t+t_0)\right)/n \tag{2}$$

The average residual power in Eq. (2) represents the average remaining battery power in the next transmission period. This time, the standard deviation of the expected residual power of the nodes in the path needs to be updated to determine the balance of the expected residual power. To update the standard deviation, the following equation is used[9]:

$$\sigma_{E,n} = \left[\left((n-1)\sigma_{E,n-1}^2 + \left(E_{r,n} - \overline{E}_{r,n-1}\right)\left(E_{r,n} - \overline{E}_{r,n}\right)\right)/n\right]^{1/2} \tag{3}$$

The greater the expected average residual power, the better the energy-harvesting rate and energy state, so the likelihood of route selection should increase. On the other hand, if the standard deviation of power increases, the power difference of the nodes in the path is large and it acts as an important factor that can shorten network lifetime. Therefore, a path with a small standard deviation should be selected. In addition, even with the same power deviation, the lower the average residual power, the more serious the power imbalance problem. If nodes have sufficient power due to the high average remaining power, this may not be a big problem even if the power deviation among nodes increases. Therefore, for the path selection, the cost function for the *i*-th path is defined as the ratio of average residual power to the standard deviation, as shown in Eq. (4).

$$\text{cost}_{n,i} = \frac{\sigma_{E,n,i}}{\overline{E}_{r,n,i}} \tag{4}$$

The nodes receiving the RREQ packet read the average energy and energy variance from the RREQ packet to calculate the cost value, select the path with the lowest cost value, and discard other paths. In the conventional AODV, the route is selected based on the number of hops. However, in this power-based routing protocol, the destination node can select a path having good residual power and a high power balance among nodes even if the number of hops increases.

4. Power-controlled routing for urgent data

It is of crucial importance that urgent data are delivered to the destination node with minimum latency rather than power efficiency. In this paper, depending on the urgency of the data, the transmitted power is controlled so that the transmission range can be changed. In urgent data transmission, the node controls the transmitted power and the transmission range of the packet according to the residual power to ensure that all the residual power of the node can be used as much as possible and ensure that the urgent data can be routed with the minimum number of hops. Fig. 3 shows the extension of the transmission range for urgent data. When transmitting urgent data, the number of hops to the destination node can be reduced as much as

possible by extending the transmission range according to residual power.

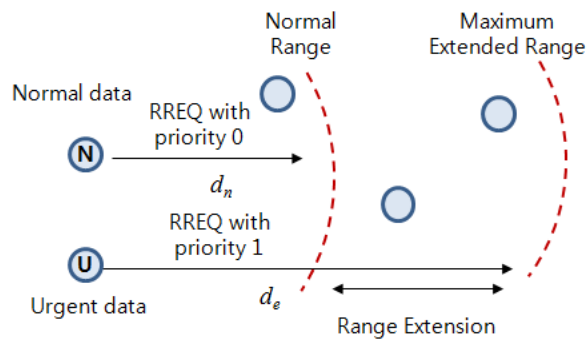

Figure 3. Example of range extension for urgent data.

Using the log-normal model, which is a representative propagation model, the relation between transmitted power P_t, received power P_r, and distance d between the transmitter and receiver can be obtained.

$$P_t(d) = P_t - L(d_0) - 10\alpha \log_{10}\left(\frac{d}{d_0}\right) \tag{5}$$

where α is the path loss exponent, which is approximately 2–4 depending on the environment, and $L(d_0)$ is the path loss at reference distance d_0. According to Eq. (5), the transmission power of urgent data with extended range d_e is as follows:

$$P(d_e) = P(d_n)\left(\frac{d_e}{d_n}\right)^{\alpha}, \tag{6}$$

Where d_n is a transmission range of normal data. As shown in Eq. (6), since the transmission power increases exponentially with increasing transmission distance, the transmission power of urgent data should be limited to $P_{t,\max}$. In this paper, the extended transmission range is limited to $d_n < d_e \le 2d_n$. Hence, $P_{t,\max} = P(d_n)2^{\alpha}$. The node with urgent data controls the transmission range from d_n to the maximum transmission range $d_{e,\max}$ by controlling transmission power. If the node has normal data, the power-based routing protocol proposed in Section 3 is used. By giving priority to urgent data, nodes route to the destination node with a minimal hop, controlling the transmission range according to residual power.

Fig. 4 is an example of setting the routing path with the minimum number of hops by adjusting the transmission range in case of urgent data. Unlike normal data transmission, urgent data should select a path that minimizes latency rather than increases power efficiency. Therefore, instead of using the cost function defined in Section 3, the path with minimum hops should be selected, as shown in Fig. 4. In case of urgent data, RREP (Route Response) packet should be transmitted to reach the maximum transmission range to

cover the extended transmission range.

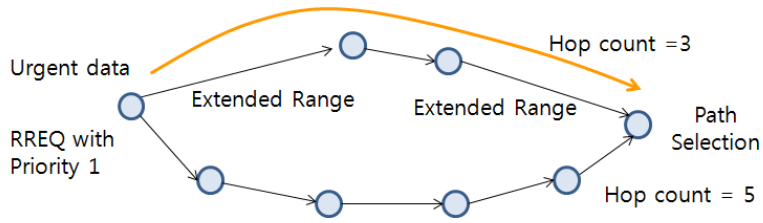

Figure 4. Example of routing based on the number of hops for urgent data

5. Simulation and performance evaluation

In this paper, the performance of the proposed adaptive routing protocol is analyzed via simulation. For the simulation, the network is composed of 100 nodes arranged in a grid. It is assumed that the average value of the energy-harvesting rate is 1–5 mW and that it follows Gaussian probability distribution. The network parameters for the simulation are shown in Table 1 [10].

Table 1. Networking parameters for simulation

Parameter	Value
Data packet	128 byte
Bandwidth	250 kbps
Tx power	83.7 mW
Rx power	72.6 mW
Path loss exponent	2.5
Transmission range	100 m
Max. extended transmission range	200 m
$E_{r,min}$	0.7 mJ

In this simulation, assuming that the sensing data is divided only into normal and urgent data and medium access control conversion is possible without delay, this paper analyzed the MAC protocol performance in normal and urgent data, respectively.

Figs. 5 and 6 show the variance of residual power and probability of power depletion at a node according to the average energy-harvesting rate. Three types of routing are compared. The first one is the conventional AODV, whereas the second one is the routing protocol that considers only the average expected residual power of nodes. The last one is the routing protocol using the cost function considering both the average and variance of residual power. As shown in Fig. 5, in the proposed routing protocol, the variance of residual power of nodes is the lowest. It can be seen that power imbalance is lowest in the proposed routing protocol. Even considering only the average of expected residual power, the power balance is improved compared with the conventional AODV. This is because the proposed method selects the path with the smallest cost function, increasing the residual power and lowering the standard deviation. As shown in Fig. 6, reducing the power imbalance reduces the probability of running out of residual power. In other words, by improving the power balance of nodes it is possible to reduce the power depletion of nodes and increase network lifetime.

Fig. 7 shows the average number of hops on a routing path according to the energy-harvesting rate. In the proposed routing protocol, the average number of hops for normal data increases slightly compared with the

conventional AODV. However, in case of urgent data, the hop count is greatly reduced. This is because different MAC schemes are adaptively applied according to the urgency of data. That is, power efficient routing is used for normal data, so there is no reduction in the number of hops, but for urgent data, power consumption is sacrificed to minimize transmission delay and the number of hops is reduced. Fig. 8 shows the probability of power depletion of nodes according to the incidence of urgent data. The routing protocol proposed in this paper consumes more power to send urgent data, so the probability of power depletion of a node increases as the incidence of urgent data increases. However, when the incidence rate of urgent data is less than 0.06, it has a lower probability of power depletion than the conventional AODV, which enables more stable data transmission than it is the case with the existing AODV.

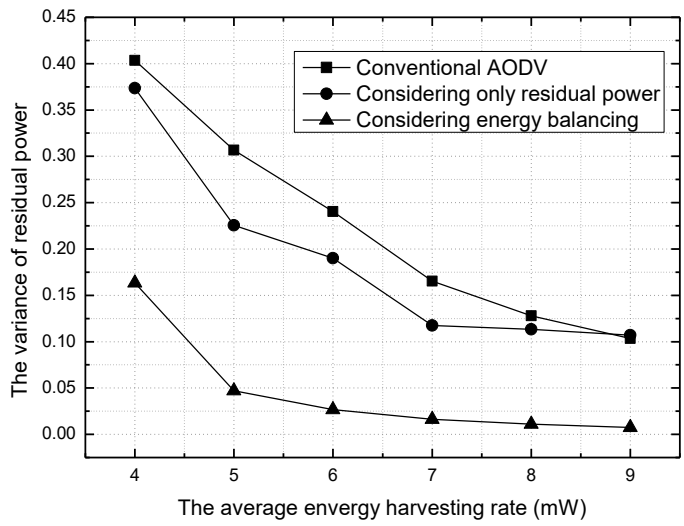

Figure 5. Variance of residual power according to energy-harvesting rate

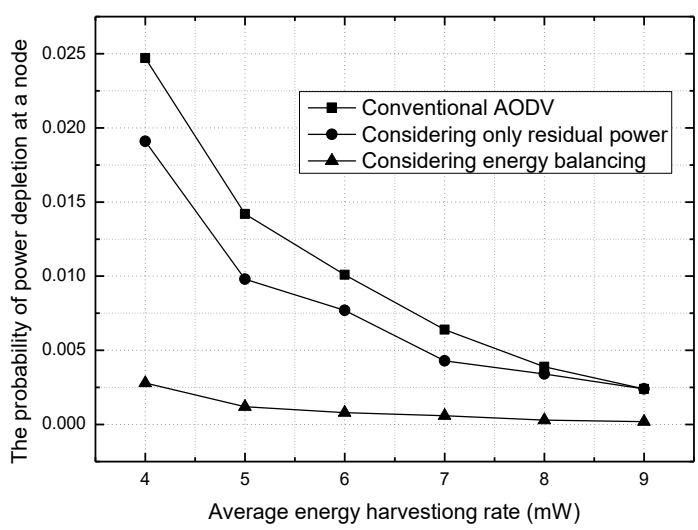

Figure 6. Probability of power depletion according to average harvesting rate

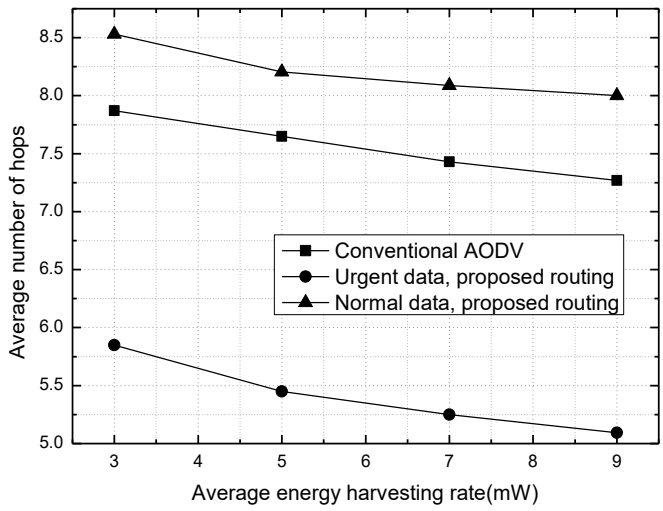

Figure 7. Average number of hops according to average energy-harvesting rate

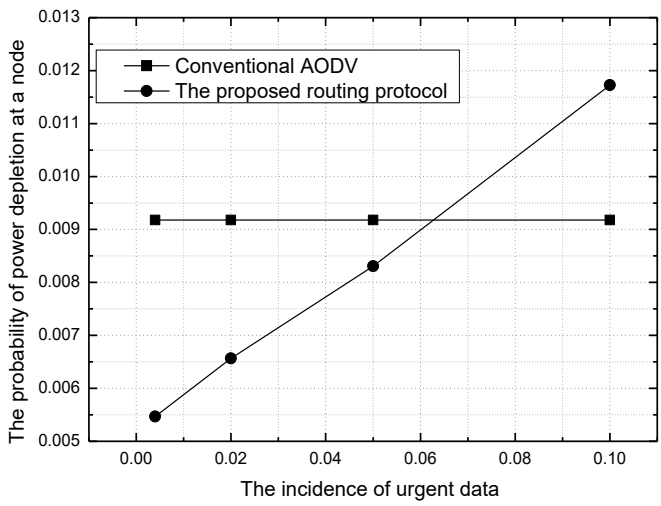

Figure 8. Probability of power depletion according to incidence of urgent data

6. Conclusions

This paper designed an adaptive EH-WSN routing protocol that can support both normal and urgent data considering the priority of data. In the transmission of normal data, the path is set by using the cost function considering the average expected residual power and deviation value. Through this, the power imbalance problem among nodes is resolved, lowering the probability of power depletion of nodes and extending network lifetime. In the transmission of urgent data, the transmission range is variably adjusted through power control to greatly reduce the number of hops to the destination node, thereby minimizing latency. In the wireless sensor network where normal and urgent data are mixed, the routing protocol can be adaptively applied according to the priority of data. The overall network performance can be improved by efficient power usage and latency minimization

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