Journal of information and
communication convergence engineering
http://jicce.org

J. Inf. Commun. Converg. Eng. 16(3): 135-141, Sep. 2018

Regular paper

An Adaptive Power-Controlled Routing Protocol for Energy-limited Wireless Sensor Networks

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Abstract

Wireless sensor networks (WSN) are composed of a large number of sensor nodes. Battery-powered sensor nodes have limited coverage; therefore, it is more efficient to transmit data via multi-hop communication. The network lifetime is a crucial issue in WSNs and the multi-hop routing protocol should be designed to prolong the network lifetime. Prolonging the network lifetime can be achieved by minimizing the power consumed by the nodes, as well as by balancing the power consumption among the nodes. A power imbalance can reduce the network lifetime even if several nodes have sufficient (battery) power. In this paper, we propose a routing protocol that prolongs the network lifetime by balancing the power consumption among the nodes. To improve the balance of power consumption and improve the network lifetime, the proposed routing scheme adaptively controls the transmission range using a power control according to the residual power in the nodes. We developed a routing simulator to evaluate the performance of the proposed routing protocol. The simulation results show that the proposed routing scheme increases power balancing and improves the network lifetime.

Index Terms: Adaptive power control, Energy harvesting, Network lifetime, Routing, Wireless sensor networks

I. INTRODUCTION

In recent times, there has been growing interest and application fields for sensor networks due to the development of various wireless services [1, 2]. Many issues, such as efficient power management, processing and storage ability, and reliability, have been actively studied in various fields for wireless sensor networks (WSNs) [3, 4]. In a wireless sensor network, the nodes configure the network in the absence of a dedicated base station or infrastructure. Since each node has a limited transmission range, nodes located at far distances cannot communicate with each other but must rely on multi-hop routing for data transmission. In multi-hop transmissions, the intermediate nodes located between the two nodes engaged in data transmission perform the role of a router that forwards packets to the next node according to the routing information.

An on-demand routing method is a typical routing protocol for ad-hoc networks such as WSN. This routing method is suitable for WSN where the network topology is continuously changing, since the nodes establish a routing path when data transfer is required. On-demand routing protocols include dynamic source routing (DSR) and ad-hoc on-demand distance vector routing (AODV). However, such routing protocols are inefficient in terms of power consumption, because they set a routing path based on the number of hops without regard to the power consumed in the transmissions. The sensor network is powered by batteries rather than by an external power supply; therefore, the available power is limited. Hence, if the battery is exhausted, the node will no longer be able to perform normal routing operations. As more nodes become depleted of power, the network loses

Received 16 July 2018, **Revised** 01 September 2018, **Accepted** 04 September 2018
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Open Access https://doi.org/10.6109/jicce.2018.16.3.135 print ISSN: 2234-8255 online ISSN: 2234-8883

functionality and reaches the end of its life. In particular, imbalance in power consumption among the nodes causes power imbalance problems in the network. Even if there are many nodes with sufficient power, power imbalance can cause the network to reach the end of its life rapidly [5]. To maximize the network lifetime, routing protocols should be designed to achieve balanced power consumption among the nodes.

Several routing protocols considering the residual power have been proposed to achieve efficient power consumption [6–8]. However, most of these routing protocols require a lot of overhead to get the power information of the neighboring nodes, thereby making the routing algorithm complicated. In this paper, we propose an adaptive power-controlled routing protocol. The proposed routing protocol controls the transmission power and range according the residual power of the nodes to reduce the power imbalance among them and extend the network lifetime.

The rest of this paper is organized as follows: in Section II, we present the relationship between the transmission power and radio range based on the residual power. In Section III, we propose an adaptive power-controlled routing protocol for WSN. In Section IV, we describe the simulation environment and present the results. Finally, we conclude the work in Section V.

II. TRANSMISSION POWER CONTROL

Since a wireless sensor network uses batteries that have limited power, the battery power of a node can easily be depleted and the function of the node stopped. If the number of dead nodes increases beyond a certain level, the entire network will run out of service. Therefore, the network lifetime can be increased by balancing the residual power of the nodes through transmission power control. In ad-hoc networks, most routing schemes are designed under the assumption that the transmission power and range of the nodes are equal. Fig. 1 shows such a scheme.

In this case, all the nodes in the transmission path participate in data transmission using the same transmission power regardless of the residual power of the node. A node with low residual power can easily reach the end of its life. This leads to a reduction in the network lifetime. Therefore, if the nodes in the routing path have different residual powers, the power can be balanced by adjusting the transmit power of the nodes, as shown in Fig. 2.

Using the log-normal propagation model, the received power P_r can be obtained by the following equation [9]:

$$P_r(d) = P_t - PL(d_0) - 10\alpha \log_{10} \frac{d}{d_0}, \qquad (1)$$

where d is the distance between the transmit and receive nodes, P_t is the transmit power, and a is the path loss exponent that ranges approximately between 2 and 4 depending on the wireless environment. $PL(d_0)$ denotes the path loss at a reference distance, d_0. From Eq. (1), it can be seen that when the transmission distance is doubled, a transmission power of 4–16 times the original transmission power is required according to the path loss exponent. As the transmission distance increases, very high transmission powers will be required to receive data transmissions at the receiver node. Since the difference in power consumption caused by controlling the transmission range is very large, it is necessary to set an appropriate transmission region according to the residual power of the nodes.

III. POWER-CONTROLLED ROUTING

The proposed routing algorithm is based on AODV routing protocol. First, the nodes are divided into three groups: high-power, normal, and low-power nodes, according to their residual powers. As Fig. 3(a) shows, if all the nodes are normal nodes, the routing path is set in the same manner as the conventional AODV routing. As Fig. 3(b) shows, when there are high-power nodes, the transmission power and distance

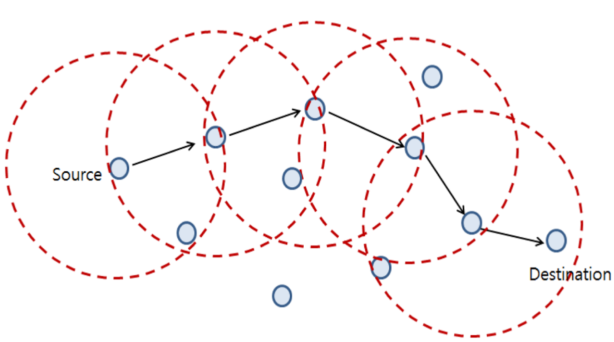

Fig. 1. Routing path with equal transmission range for the nodes.

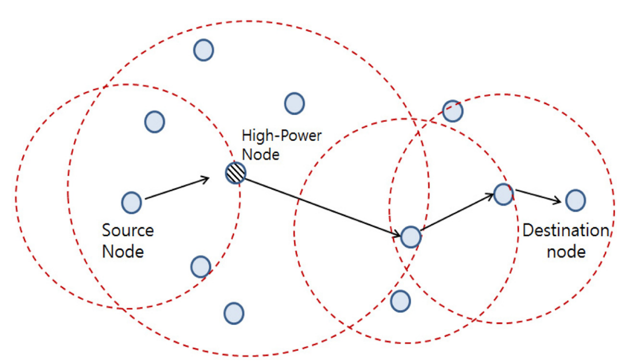

Fig. 2. Routing path with different transmission ranges for the nodes.

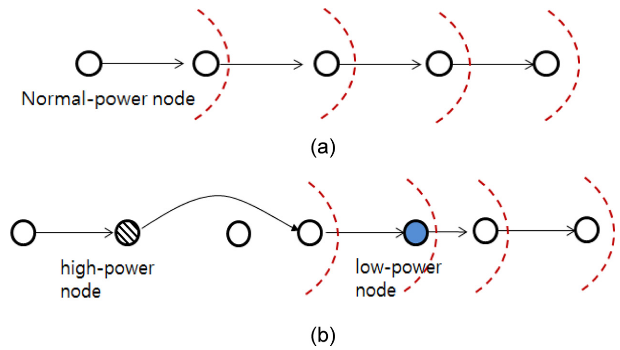

Fig. 3. Routing example according to remaining power in the presence of (a) normal-power nodes, (b) high-power and low-power nodes.

are both increased. Therefore, the power consumption of the high-power nodes is increased; however, the overall hops on the routing path can be reduced, thereby reducing the power consumption of the other nodes. Finally, if there is a low-power node on the path, the transmission power is reduced, thereby reducing the transmission range and, consequently, the power consumption of the low-power node is reduced. In this case, although the number of hops may be increased, the power control according to the residual power makes it possible to use the power of the nodes evenly, thereby increasing the lifetime of the network.

A. Redefined RREQ and RREP

In this paper, we modify the Route Request (RREQ) packet to control the transmission power. As Fig. 4 shows, a Radio Range (RR) field is added to the existing RREQ message field. RR field can have values 0, 1, and 2 according to the transmission power of the RREQ packet.

As shown in Fig. 5, when RR = 0, the RREQ packet is transmitted with normal power. When RR = 1, the RREQ packet is transmitted at a power lower than the normal power to reduce the transmission area. When RR = 2, the RREQ packet is transmitted at a high power so that it has a wider transmission area than a normal RREQ packet. By adding the RR field in the RREQ packet, the receiver node can obtain the transmission power and range of the RREQ packet.

For power-controlled routing, the RREP packet is also

Type	Flags	Reserved	Hop Count
RREQ ID			
Destination Address			
Destination sequence number			
Source Address			
Source Sequence Number			
Radio Range (RR)			

Fig. 4. Modified RREQ message for power-controlled routing.

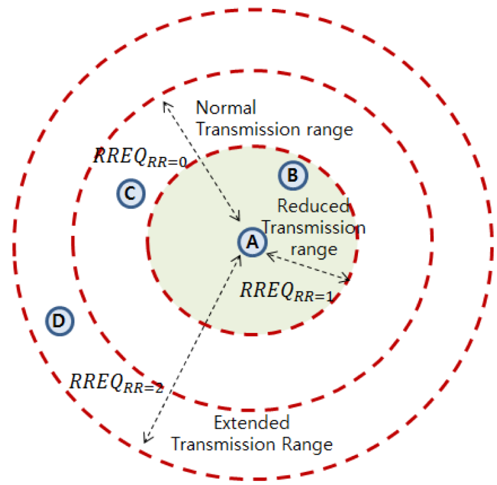

Fig. 5. Modified RREQ packet and its transmission range.

Type	Flags	Reserved	Hop Count
Destination Address			
Destination sequence number			
Source Address			
Source Sequence Number			
Node Range (NR)			

Fig. 6. Modified RREP message for power-controlled routing.

modified by adding a Node Range (NR) field in conventional RREP packets, as shown in Fig. 6. NR is set to 1 if the node to which the RREP is to be transmitted is in the reduced range, to 0 if in the normal range, and to 2 if in the extended range.

B. Routing for High-Power Nodes

When the RREQ is flooded in the proposed power-controlled routing protocol, high-power nodes transmit packets with high power; therefore, nodes far away from high-power nodes are more likely to be selected as relay nodes, as shown in Fig. 7. However, since relay nodes at a distance from the high power nodes do not know the distance to the high power nodes, normal-power RREP packets will be transmitted, i.e., the remote high-power nodes may not receive the RREP packets. Therefore, a high-power node must inform the neighbor node that it is a high-power node. This problem can be solved using the modified RREQ packet in Fig. 4. Since the modified RREQ includes information about the RR, the node receiving the RREQ can recognize that the transmitting node is a high-power node.

In the proposed power-controlled routing protocol, high-power nodes transmit $RREQ_{RR=0}$ packets with normal power and $RREQ_{RR=2}$ packets with high power, as shown in Fig. 8. Node C receives $RREQ_{RR=2}$ and knows that the current trans-

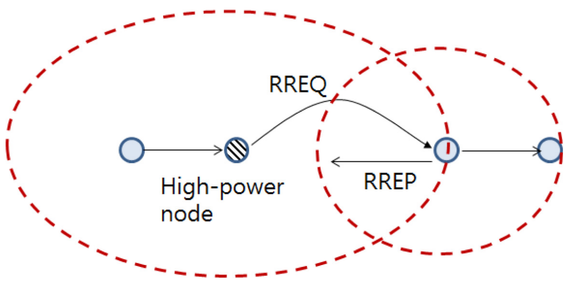

Fig. 7. The problem of RREQ-RREP exchange for long distances.

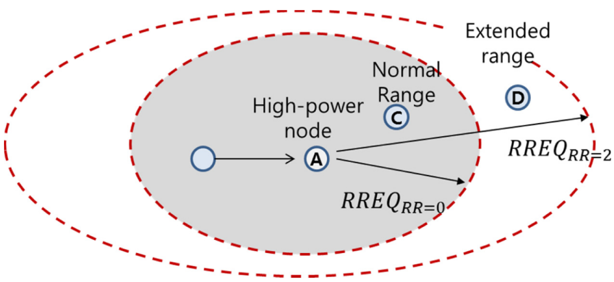

Fig. 8. RREQ transmission for high-power nodes.

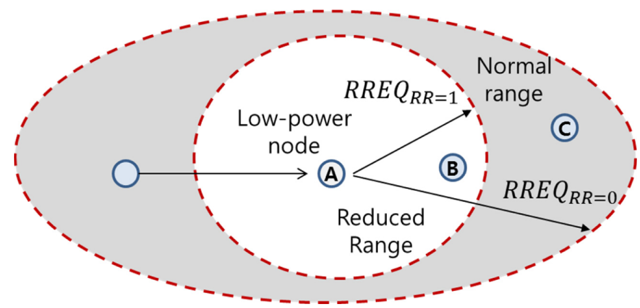

Fig. 9. RREQ packet transmission for low-power nodes.

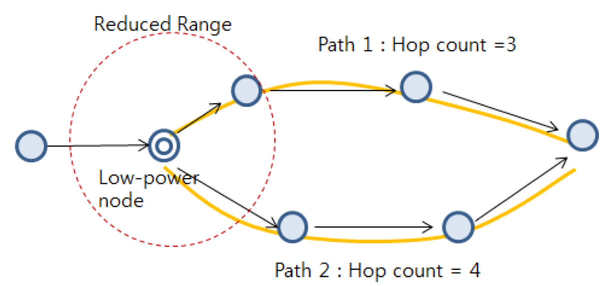

Fig. 10. Routing path with a low-power node.

mit node is a high-power node. However, since it also receives $RREQ_{RR=0}$, the node knows that it is in the normal region. So, node C tries to complete the path by transmitting a normal-power RREP in the conventional method. Conversely, node D does not receive $RREQ_{RR=0}$ but only receives $RREQ_{RR=2}$, and knows that the transmit node is a high-power node and that node D is in the extended region. Therefore, when the RREQ flooding is completed and the RREP transmitted, node D, belonging to the extended area, transmits a high-power RREP packet to be able to reach node A.

C. Routing for Low-Power Nodes

If the residual power of a node is lower than the reference value and it is classified as a low-power node, it is necessary to reduce the power consumption by reducing the transmission range. In this paper, by reducing the transmission power of the RREQ, relay nodes are found within a smaller transmission area, so that data can be transmitted with less power. However, in this case, as the transmission range decreases, the problem that a relay node does not exist within the transmission range may occur.

Therefore, similar to the routing of high-power nodes, if a node A is a low-power node, it transmits two packets $RREQ_{RR=0}$ and $RREQ_{RR=1}$, as shown in Fig. 9. At this time, $RREQ_{RR=0}$ is a packet transmitted with normal power and has a normal transmission range. On the other hand, $RREQ_{RR=1}$ reduces the transmission region by reducing the transmit power.

In Fig. 9, node C receives only $RREQ_{RR=0}$, but node B receives both $RREQ_{RR=0}$ and $RREQ_{RR=1}$. The reason for sending $RREQ_{RR=0}$ at normal power is that routing should be achieved through the node in the normal transmission region when there is no relay node in the low-power region. In addition, the nodes receiving RREQ can determine the transmission region they belong to. After receiving the RREQ, nodes B and C flood the RREQ through the network according to the conventional AODV scheme.

Relay node B is closer to the low-power node A; however, the routing path containing node B may have more hops than the routing path containing node C because the distance between nodes A and C is shorter. Therefore, it is possible that the path containing node C is chosen as the routing path. To solve this problem, the node receiving $RREQ_{RR=1}$ knows that it belongs to the low-power area and decreases the number of hops by one. In other words, by subtracting the number of relay nodes in the reduced range from the total number of hops, the possibility of selecting the route containing the near-end node B is increased.

Fig. 10 shows an example of a routing path that includes low-power nodes. Although both paths have the same number of hops, path 1 includes a node in the reduced range and the number of hops is reduced to three; path 1 is therefore selected as a final routing path and the low-power node can reduce its transmit power.

Although a routing path is established, node A does not know whether the next node is in the reduced range or not and cannot determine the transmit power. To solve this problem, the modified RREP packet in Fig. 6 is used. After the RREQ packet is flooded to the destination node, the RREP is transmitted through the routing path. When the RREP is transmitted, the NR in the RREP is equal to 0 if the next hop node is in the normal region, and equal to 1 if the node is in the reduced region. Using the value of the NR in the RREP, node A can determine the transmit power at the time of the data transmission.

IV. SIMULATION AND RESULTS

In this paper, we developed a routing simulator to evaluate the performance of the proposed routing protocol. Fig. 11 shows the initial screen of the routing simulator.

The entire network consists of 121 nodes, arranged in a grid structure. The battery capacity was set to 25 J for fast simulation, and the path loss exponent was set to 2. Table 1 shows the network parameters used for the simulation [10].

The nodes are divided into low-power nodes, normal-power nodes, and high-power nodes according to their residual powers, with the transmission distance of normal power nodes set to 250 m. In mod1, the transmission distance of the low-power nodes, normal-power nodes, and high-power nodes have a ratio of 1:2:4, whereas in mod2, the ratio is 1.5:2:3.

Fig. 12 shows the standard deviation of the residual power after 5k packets are transmitted. In the conventional AODV scheme, the standard deviation of the residual power of the nodes is greater than that of the proposed power-controlled routing algorithm, indicating that the conventional AODV routing has a greater imbalance in power consumption among nodes than the proposed power-controlled routing algorithm. Conversely, in the proposed power-controlled routing protocol, the standard deviation of the residual power is greatly reduced. The standard deviation also depends on the threshold power α for the low-power nodes and the threshold power β for high-power nodes. The standard deviation at α = 25% and β = 75% is smaller than standard deviation at α = 15% and β = 85%.

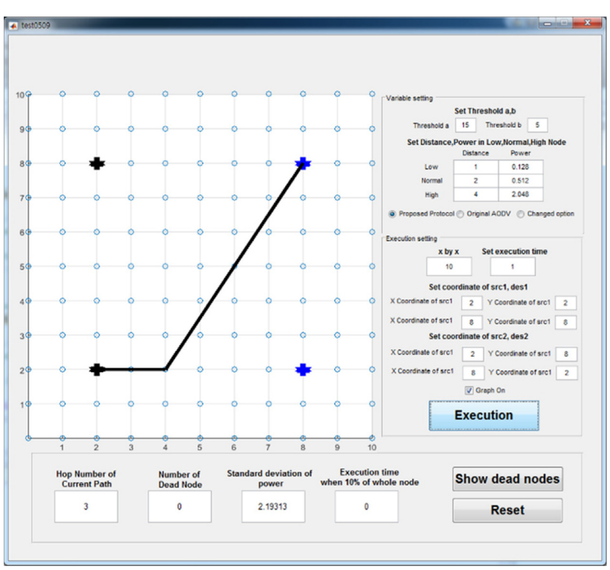

Fig. 11. Initial screen of the routing simulator.

Fig. 13 shows the percentage of dead nodes due to the complete discharge. In the conventional AODV scheme, the number of dead nodes increases rapidly from the beginning of the packet transmission. On the other hand, in the proposed scheme, when the number of packets to be transmitted is small, the number of dead nodes is very small, but gradually increases as the number of packets increases. The number of nodes that have reached the end of their lives is directly related to the lifetime of the network and is a very important performance indicator. Consequently, it can be seen that the use of the power-controlled routing protocol can greatly improve the network lifetime.

Fig. 14 shows the standard deviation of the residual power according to the threshold of the high-power nodes at a = 25%. If the threshold is too low, the number of dead nodes increases. When the threshold β is near 75%, the network lifetime is maximized.

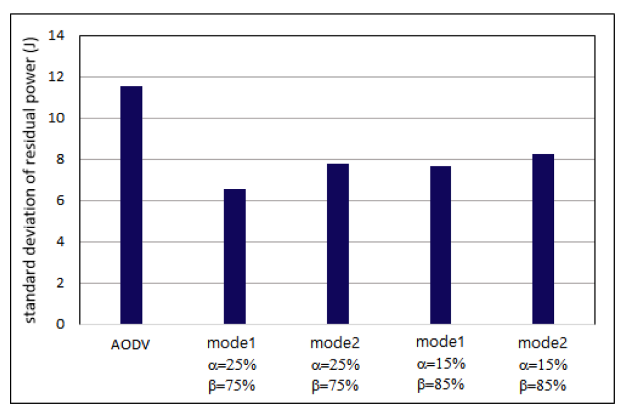

Fig. 12. Standard deviation of the residual power.

Table 1. Networking parameters for the simulation

Parameter	Value
Network size (km^2)	2.5 × 2.5
No. of nodes	121
Transmission range (m)	250
Bandwidth (kbps)	250
Tx power (mW)	31.2
Rx power (mW)	22.2
Packet size (byte)	28

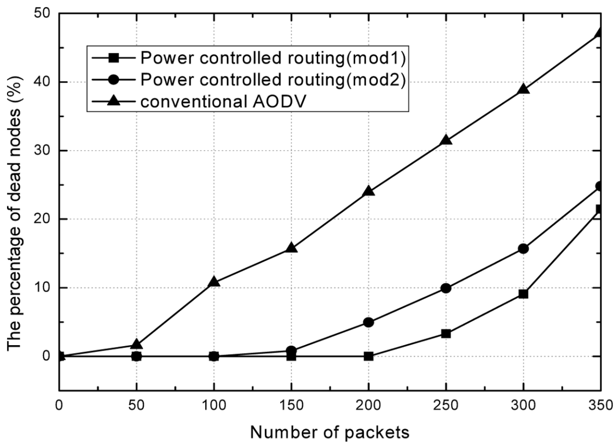

Fig. 13. The percentage of dead nodes according to the number of packets.

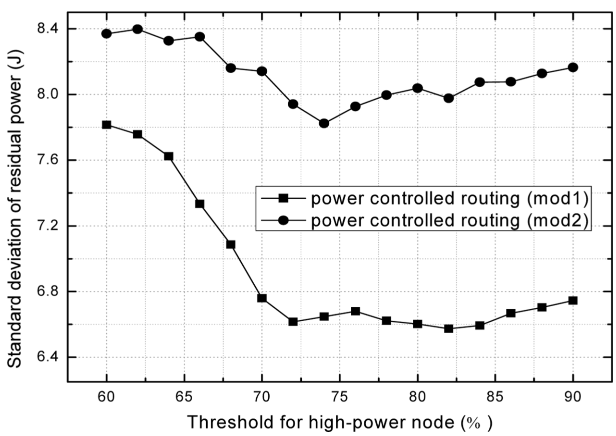

Fig. 14. Standard deviation of residual power according to the threshold of high-power nodes.

V. CONCLUSION

In this paper, we proposed an adaptive power-controlled routing protocol that can increase the network lifetime by solving the problem of the power imbalance among nodes. The transmitted power is controlled according to the residual power of the nodes. For this adaptive power control, each node is classified as a high-power, normal-power, or low-power node depending on its residual power. The transmission powers are allocated according to the power group. For a distributed WSN, the content and transmission method for signaling packets are newly modified in this paper so that the status of battery power in a node can be ascertained, and the power-controlled routing can be enabled. The performance of the proposed power-controlled routing protocol was simulated and compared with the conventional routing protocol. The results showed that the imbalance in residual powers was greatly reduced and the network lifetime was improved.

ACKNOWLEDGMENTS

This research was supported by KOREATECH Education and Research Promotion Program (2018).

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