Radio-disjoint Multipath Routing with Dynamic Guard-band Shifting in Wireless Sensor Networks

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Abstract

A guard-band is used to prevent collision between paths in multipath routing protocols. However, problems such as traffic congestion, reduced lifetime, and void occurrence arise because existing protocols do not exploit the guard-band during packet transmission, but only transfer packets on the same path. To solve these problems, we propose radio-disjoint multipath routing that consists of guard-band shifting and balanced node selection. The proposed scheme transfers a packet on the constructed path and alternatively, into the guard-band area. In addition, the intermediate node is selected according to link quality and remaining energy, so all of the nodes involving packet transmission can be exploited equally. Through a performance evaluation, we demonstrate that the proposed scheme achieves a higher packet delivery ratio and prolongs the average network lifetime by at least 31% and up to approximately 99% compared with existing routing protocols, under the condition of a 90% link success ratio.

Keywords: Wireless sensor networks, Multipath routing, Guard-band shifting, Radio-disjoint, Network lifetime

1 Introduction

The multipath routing protocol is a routing strategy used to achieve various objectives such as balancing loads [1-2] and supporting quality of service (QoS) [3]. In particular, the multipath routing protocol could achieve the required packet delivery ratio by creating multiple paths from source to destination and simultaneously transmitting the packets on the constructed paths [4-5]. To construct the multipath, a source node exploits a path construction message to the destination. Under the message delivery process, the nodes that receive the construction message are designated as members of the path, and they participate in the packet transmission process. These schemes prevent a node from participating on different paths.

That is, they achieve a node-disjoint path construction to prevent a merger between different parts of the multipath [6-7]. However, the node-disjointed paths suffer from collision and interference between adjacent nodes that occur when they both attempt to transmit a packet at the same time. Collisions and interference among the nodes causes degradation of the packet delivery ratio. Eventually, this leads to performance degradation of the wireless sensor network (WSN). To solve the problem caused by collision and interference among the nodes, radio-disjoint multipath routing protocols that have a certain clearance called a guard-band [8] between the different paths have been proposed. In the radio-disjoint multipath, a source node calculates a criterion distance to leave space between the different paths. The source node considers the distance as a guard-band and transfers a path construction message to the destination through the nodes located outside of the guard-band. Through the path construction, the source node obtains a multipath for which the packet transmission of each path does not affect the other paths.

Although radio-disjoint multipath routing could prevent the problems of collision and interference among the paths, there would still be a problem. In the radio-disjoint multipath, a source node exploits the same paths while packet-transmitting to transmit a packet repeatedly. That is, as packets are delivered using only the node on the constructed paths, network nodes are exploited disproportionately. Therefore, this phenomenon leads to exhaustion of participating nodes even though the nodes located on the guard-band have enough energy. Eventually, this causes performance degradation by path failure, void occurrence, and so on. The problems are deepened in a low-density network in that the same node must be exploited at a high

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frequency for transmitting the packets.

To address these problems, we propose radio-disjoint multipath routing for balanced exploitation of network nodes by guard-band shifting. In the proposed scheme, a source node calculates paths that are spaced out with a certain clearance for packet transmitting, and forecasts the required number of paths based on link reliability. The clearance is called the guard-band, which is not utilized in the existing protocols. It would be exploited as alternates to the constructed paths. In other words, the odd-numbered packet-transmissions of the source node would be delivered over the constructed path and the even-numbered transmissions over the guard-band. Thus, the source node would calculate the start/end points of each path and the guard-band area. In addition, the intermediate node would select the next node according to the link success ratio, energy consumption, and remaining energy to use the nodes equally. Thus, the proposed scheme could solve the problems caused by a fixed guard-band alongside the advantages of existing radio-disjoint multipath routing. Through simulation, the proposed scheme was seen to improve the packet delivery ratio up to 25%. In addition, the network lifetime was prolonged by at least 33\% and up to 99% compared with existing routing protocols, assuming a 90% link success ratio.

The remainder of this paper is organized as follows. In Section 2, we describe existing radio-disjoint multipath routing for improving the packet delivery ratio, along with the exclusion of problems caused by collisions and interference. In Section 3, we explain the proposed radio-disjoint multipath routing with guard-band shifting for prolonging network lifetime and increasing reliability. The performance evaluation results are provided in Section 4. Finally, the proposed scheme is summarized and simulation results presented in Section 5.

2 Related Works

In this section, we briefly summarize the existing radio-disjoint multipath routing protocols.

EECA [9] constructs two radio-disjoint multipath routes with the aid of node position information. It also transfers each packet with minimum power usage due to a power control unit of the protocol. However, because it constructs only two paths, it is difficult to satisfy the required packet delivery ratio.

RGMR [10] constructs a sufficient number of paths to satisfy the required packet delivery ratio based on the predicted packet delivery ratio of a single path between source and destination. Thus, it should require enough nodes and space to construct a multipath. However, it requires high energy consumption because many paths are required to satisfy the required packet delivery ratio. In addition, because it should occupy a wide area to construct a radio-disjoint multipath, it may not be possible to construct a sufficient number of paths in a narrow network.

LDMR [11] achieves a packet delivery ratio based on a sufficient number of paths constructed by local decision. In addition, flexible path construction based on a local decision could better ensure stable packet delivery time compared to centralized multipath management, and could bypass voids on the routes. However, exploiting a number of paths to satisfy the required packet delivery ratio leads to high energy consumption, and LDMR requires more effort to limit energy consumption on the routes.

RD-GMR [12] has the capability of maximally avoiding interference among parts of the multipath. The main idea of RD-GMR is to transmit a packet through the multipath in non-interfering areas based on an interference-marking algorithm and a local control mechanism. The protocol can achieve high-reliability based on a constructed multipath divided into three parts: source area, intermediate area, and destination area. However, because it also constructs many paths to guarantee the packet delivery ratio, it requires too much energy, as with RGMR and LDMR.

IMCMRP [13] was proposed to minimize interference among the paths based on clustering. It identifies the cluster head nodes before constructing a multipath based on threshold residual energy and degree of node threshold interference. The intermediate node chooses the cluster heads according to a node's residual energy. When a node detects an event, the node transfer route request (RREQ) is sent to sink through the cluster heads and the sink node will return the route reply (RREP) to the node. After constructing multipaths, the source node transmits a packet to sink through the discovered paths. Although this achieves energy efficiency and reliability through the cluster head node, it has high reliance on the cluster head. Therefore, the energy consumption is concentrated on the nodes near the cluster head, which results in reduction of network life.

FD-AOMDV [14] sprints path discovery phase with a reduced amount of delay and constructs disjoint paths with minimized routing overheads. The source node transmits a path request (PREQ) message to the destination through all requiring paths. When the source node received a path reply (PREP) message from the destination, it activates the timer. After the timer expired, the source node sorts received PREP message in ascending order. After that, the source node selects disjoint paths among these paths. However, this scheme exploits only the same paths that were constructed in the above-mentioned process to transmit a packet to the destination. Thus, it could lead to exhaustion of the node on the paths, resulting in problems such as the occurrence of void area.

Table 1 summarizes key features with a comparison of the reliability, energy consumption, and network lifetime of the related work. RGMR and LDMR could satisfy the packet delivery ratio through a sufficient number of paths according to the required packet delivery ratio. However, because the other protocols exploit a limited number of paths, with them it is difficult to achieve the required packet delivery ratio. Because the energy consumption is heavily affected by the number of paths, RGMR and LDMR require more energy than the other protocols do. Finally, with respect to network lifetime, EECA would have longer network lifetime than other protocols because it constructs only two paths. On the other hand, RGMR and LDMR, which satisfy the required packet delivery ratio, have short network lifetime because there are many paths.

Table 1. Radio-disjoint multipath routing protocols

Routing protocols	Key features	Reliability	Energy consumption	Network lifetime
EECA	Two radio-disjoint multipath to improve reliability	Medium	Medium	Medium-Long
RGMR	High reliability based on various number of paths	High	High	Short
LDMR	High reliability based on various number of paths & void avoidance mechanism	High	High	Short
RD-GMR	Stricter prevention of interference between paths	Medium- High	Medium-High	Short-Medium
IMCMRP	Energy efficient and reliable multipath routing based on clustering	Medium	Low-Medium	Medium
FD-AOMDV	Minimizing routing overloads to find disjoint paths	Medium- High	Medium	Medium

3 Multipath Routing with Guard-band Shifting

In this section, we describe radio-disjoint multipath routing using guard-band shifting and balanced node selection. The proposed scheme can be largely categorized as predicting the required number of paths, calculating each anchor point of the paths, and packet transmitting with guard-band shifting.

In this paper, we assume that several conditions are satisfied for the fundamental routing in the proposed scheme. All node knows the location of the destination through location service protocol [15] and its own position by internal GPS or other localization protocol [16]. Through the beaconing, they realize the information about their one-hop neighbor nodes.

3.1 Required Number of Paths Prediction Process

In this section, we describe the required number of paths prediction process. Algorithm 1 describes the pseudo code for the required number of paths prediction process at the source node. The process proceeds as follows: (1) predict the packet delivery ratio of a single path, (2) decide whether additional paths are required, and (3) if required, calculate the number of paths.

Algorithm 1. Bifurcation decision process at an intermediate node i

P_{req}: a required packet delivery ratio
P_{exp}: an expected packet delivery ratio
P_i: a packet transmission success ratio to node i
k_i: the number of neighbors of node i
$P_{(k,\ n)}$: link reliability when n of k neighbors is selected by opportunistic routing
N_{hop}: a number of hop count from itself to the destination
n: the number of paths (default = 1)
Dist(a, b): a distance between node a and b
r: transmission radius
function BIFURCATION_DICISION
  $N_{hop} = \lceil Dist(i,dst)./r \rceil$
  $P_{(k,\ 1)} = 1-(1-P_1)\times(1-P_2)\times\cdots\times(1-P_k)$
  $P_{\exp} = (P_{(k,l)})^{N_{hop}}$
  if $P_{exp} > P_{req}$ **then**
    return n
  end if
  while $P_{exp} < P_{req}$ **do**
    $n = n + 1$
    $P_{exp} = (P_{(k,n)})^{N_{hop}}$
  end while
  return n
end function

First, the source node can measure the average link reliability of each other neighbor node through beacon message exchange before data transmission. The average link reliability is calculated through the average link quality of all of the neighbors. The link quality is calculated through the number of beacon messages received from each neighbor node over some time. For example, if the transmission cycle of a beacon message is one second and a source node s receives 80 beacon messages for 100 seconds from a neighbor node i, the link quality P_i is 80%. In the same way, the source node could obtain the link quality of all of the neighbors. The average link reliability P_{link} could be computed as follows:

$$P_{link} = \frac{1}{n(A)} \sum_{i=1}^{n(A)} P_i, A = \{x \mid x = \text{neighbor nodes of source}\} \quad \textbf{(1)}$$

where the equation 1, A is the set of neighbor nodes of a source node and n(A) is the number of elements in set A. Here, P_i is the link quality of the i-th neighbor in set A.

Step 1 (line 10-12): Based on the measurements, the source node can obtain the average link reliability P_{link}. Let r be the radius of the radio range and Dist(a, b) be the distance from a to b. First, the source node could calculate the expected number of hop counts from source to destination N_{hop} as $\lceil Dist(src, dst)./r \rceil$ (line 10). Using the probability P_{link} and the expected number of hop counts N_{hop}, the source node can predict the expected packet delivery ratio of a single path P_{exp} given by $(P_{(k,l)})^{N_{hop}}$ (line 12).

Step 2 (lines 13-15): After predicting the packet delivery ratio of a single path, the source node compares P_{exp} with the required packet delivery ratio P_{req}. If P_{exp} is greater than P_{req}, the source node decides that an additional path is not required and returns n. (lines 13-15).

Step 3 (line 16-20): However, if P_{exp} is less than P_{req} in step 2, the source node realizes that additional paths are required to satisfy P_{req} (line 16). The source node increases n by 1 and recalculates P_{exp} through $(P_{(k,n)})^{N_{hop}}$ (lines 17-18). When the source node finds the number of paths required to satisfy the condition that P_{exp} is greater than P_{req}, the source node returns the required number of paths n (line 20).

3.2 Anchor Point Calculation Process

After calculating the number of paths, a source node calculates the anchor points to enter/exit each path based on the following information: (1) required number of paths n, (2) radius of the radio range r, and (3) rotation angle of source and destination θ.

Figure 1 shows that the location of the anchor points of each path. Each path consists of a main and sub path and each path is as far as $2r$ to avoid collision between the paths. To calculate the anchor points of each path, the source node draws a reference line. If the number of path n is even, the source node creates n/2 paths above the reference line and n/2 paths below the reference line (Figure 1 shows an example of two paths). If the number of paths n is odd, the source node creates one path near the reference line, and then (n-1)/2 paths above the reference line and (n-1)/2 paths below the reference line. We describe the formula for obtaining the enter/exit coordinates for the paths between source and destination with rotation angle θ as follows.

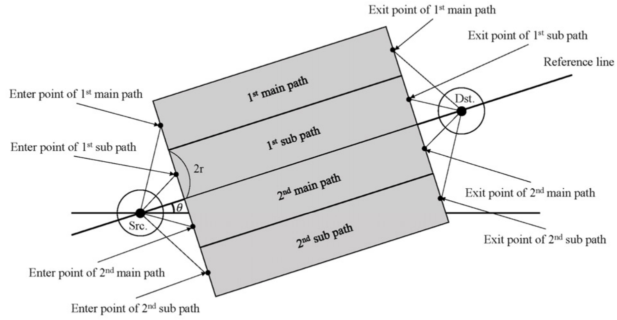

Figure 1. An example of calculating the enter and exit points for each path

In case of the enter point of main path is

$$\begin{bmatrix} x_{i-th\ main\ enter} \\ y_{i-th\ main\ enter} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 2r \\ 2n-4i+3 \end{bmatrix} + \begin{bmatrix} x_{src} \\ y_{src} \end{bmatrix} \quad \textbf{(2)}$$

In case of the enter point of sub path is

$$\begin{bmatrix} x_{i-th\ sub\ enter} \\ y_{i-th\ sub\ enter} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 2r \\ 2n-4i+1 \end{bmatrix} + \begin{bmatrix} x_{scr} \\ y_{scr} \end{bmatrix} \quad \textbf{(3)}$$

In case of the exit point of main path is

$$\begin{bmatrix} x_{i-th\ main\ exit} \\ y_{i-th\ main\ exit} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} -2r \\ 2n-4i+3 \end{bmatrix} + \begin{bmatrix} x_{dst} \\ y_{dst} \end{bmatrix} \quad \textbf{(4)}$$

In case of the exit point of sub path is

$$\begin{bmatrix} x_{i-th\ sub\ exit} \\ y_{i-th\ sub\ exit} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} -2r \\ 2n-4i+1 \end{bmatrix} + \begin{bmatrix} x_{dst} \\ y_{dst} \end{bmatrix} \quad \textbf{(5)}$$

where equations 2, 3, 4, and 5, $(x, y)_{i\text{-}th\ main\_enter}$ and $(x,y)_{i\text{-}th\ sub\_enter}$ mean the enter points of i-th main and sub path. The terms $(x, y)_{i\text{-}th\ main\ exit}$ and $(x,y)_{i\text{-}th\ sub\ exit}$ mean the exit points of the i-th main and sub path. The terms (x_{src}, y_{src}) and (x_{dst}, y_{dst}) are the coordinates of source node and destination, respectively. Based on the equations, the source node could acquire the coordinate pairs to transmit packets with guard-band shifting.

3.3 Packet Transmission Process with Guard-band Shifting

After calculating the coordinate pair of each path, the source node transmits the packet to the destination through multiple paths with guard-band shifting. That is, the source node exploits the main path and sub path alternately to avoid collisions between paths. The main path of the constructed path is exploited to use odd-numbered packet transmissions of the source node and the sub paths become the guard-band. Similarly, the sub path of the constructed path is exploited to use even-numbered packet transmissions of the source node and the main paths becomes the guard-band. Exploiting the main and sub path alternately between each packet transmission and exploiting of the remaining paths as guard-bands in this way, is called guard-band shifting.

Figure 2 shows that an example of odd-numbered packet transmission through the multipath. Because it is an odd-numbered packet transmission, the source delivers the packets to the enter points of each main path and the sub paths become the guard-band. The node located on the enter points selects the next node according to link quality and remaining energy. For example with Figure 2, the node *i* would choose one of the neighbor nodes: node *A*, *B*, *C*, and *D*. Assuming their link quality, remaining energy, and energy consumption for packet transmission is adequate, as in the following Table 2:

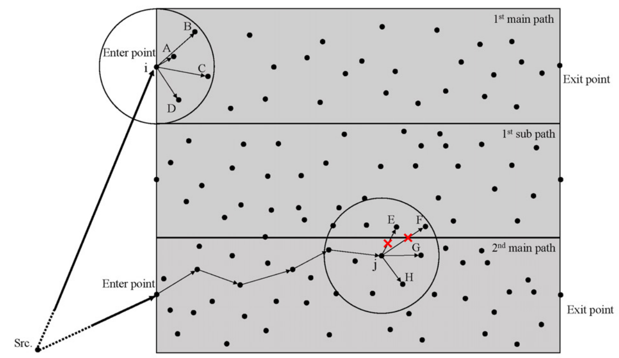

Figure 2. An example of transmitting a packet through the multipath

Table 2. An example of the node selection process

	Node A	Node B	Node C	Node D
Link quality	100%	80%	50%	75%
Energy consumption	60 mJ	80 mJ	100 mJ	75 mJ
Estimated transmission energy consumption	60 mJ	100mJ	200 mJ	100 mJ
Remaining energy	3000 mJ	3000 mJ	3000 mJ	3000 mJ
The number of possible packet transfers	50	30	15	30

Step 1. The node *i* could obtain the estimated transmission energy consumption E_{est} according to energy consumption *E* and link quality *P* using the following equation 6. The equation 6 is induced by the sums of infinite geometric series.

$$E_{est} = \frac{E}{1-(1-P)} \tag{6}$$

Based on equation 6, the estimated transmission energy consumption considering the retransmission of node *A* is 60 mJ. Similarly, the estimated transmission energy consumption of node *B*, *C* and *D* is 100 mJ, 200 mJ, and 100 mJ.

Step 2. The node *i* calculates the number of possible packet transfers *N* through calculated estimated transmission energy consumption E_{est} and remaining energy E_{remain} as in the following equation 7.

$$N = \frac{E_{remain}}{E_{est}} \tag{7}$$

According to equation 7, node *A* can transmit a packet 50 times, and *B*, *C*, and *D* can transmit a packet 30, 15 and 30 times, respectively. The node *i* selects a neighbor node in proportion to the number of possible packet transfers, and transfers the packet to the node. In this example, node *i* selects node *A*, *B*, *C*, and *D* at a ratio of 10:6:3:6, respectively, to deliver the packets.

In the case that node *j* is located near the guard-band, node *E*, *F*, *G* and *H* might be candidates to transmit a packet of node *j* However, node *j* would know that node *E* and *F* are located in the sub path used as the guard-band based on the transmission radius *r* and linear equation between enter point and exit point. Because the guard-band area is exploited to prevent collisions between paths, node *j* considers only node *G* and *H* in the node selection process. Thus, node *j* could determine the transmission ratio according to the number of possible packet transfers of node *G* and *H* by the same process as in node *i*.

3.4 Avoid Handling Process with Area Shifting

A void area could occur for a variety of reasons such as the discharge of a network node, or a batch of nodes. Because a void area causes problems like path failures, a solution is essential to ensure the transmission quality of the sensor network. Thus, we describe a void-handling process by which to bypass a void area.

Figure 3 shows an overview of the proposed void handling process. In Figure 3, the node *i* is a stuck node that encounters a void area. The stuck node *i* transmits a packet to model the void area by the right/left hand rule [17]. Through the right/left hand rule, the stuck node could obtain the coordinates of boundary nodes around the void area, and figures out its approximate size. In Figure 3, we assume that the size of the void is equals 2*r* x 3*r*. To bypass the void, the node *i* calculates a bypass point *j*, which is as far away from the node as the height of the void area 2*r*, and then notifies its former nodes that the node *j* is an alternative node of itself to bypass the void area. In addition, the node *i* transmits a notification packet including the information of endpoint *m* which is as far away from the node *j* as the width of the void area 3*r*. As some transmission areas are shifted, the node *j* also calculates a bypass point *k* and notifies its former nodes that the node *k* is an alternative node of itself to bypass the void area.

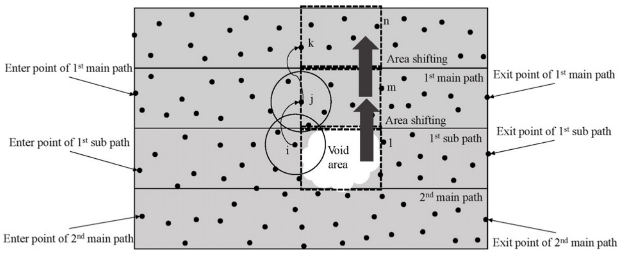

Figure 3. Overview of the void handling process with area shifting

After the area shifting process, the existing 1st main path is modified to "enter point →former nodes of node j →node k v node n → rear nodes of node m → exit point". Likewise, the existing 1st sub path is modified to "enter point →former nodes of node i → node j →node m →rear nodes of node l → exit point".

Algorithm 2. Pseudocode for avoiding a void at a stuck node s

This algorithm would start when an intermediate node encounters a void
1. h: a height of the modeled void
2. w: a width of the modeled void
3. θ: an angle between source node s and reference line
4. $(x, y)_{shifted\_enter}$: start point of shifted area
5. $(x, y)_{shifted\_exit}$: exit point of shifted area
6. P_{det}: a packet to detect voids by right/left hand rule
7. P_{notify}: a packet to notify the bypass node to former nodes
8. $P_{shifting}$: a packet to notify the area shifting to bypass node
9. **function** AREA_SHIFTING
10. Send_Void_Detection_Msg(P_{det})
11. Modeling the shape of void
12. Calculates h and w of modeled void
13. **if** $0 < \theta < \pi </2$ **then**
14. ▹ void located above the reference line
15. Calculates $(x, y)_{shifted\_enter}$, $(x, y)_{shifted\_exit}$
16. **else**
17. ▹ void located belo the reference line
18. Calculates $(x, y)_{shifted\_enter}$, $(x, y)_{shifted\_exit}$
19. **end if**
20. Send_Notification_Msg(P_{notify})
21. Send_Shifting_Notification_Msg($P_{shifting}$)
22. **end function**

Algorithm 2 describes the pseudo code for bypassing the void at a stuck node s. The algorithm is largely divided into three steps: (1) modeling the void, (2) calculating a bypass point for area shifting, and (3) notification of information to related nodes.

Step 1 (line 10-12). The stuck node s transmits the message to model the void by the right/left hand rule (line 8). Each node that receives the message, records its location information in the message and then forwards the message. The stuck node s would receive a message including the coordinates of nodes located around the void. Based on this information, node s obtains the approximate size of void h x w (line 12).

Step 2 (line 13-19). To reduce the effect of the area shifting, area shifting is performed upwards if a void area occurs above the reference line (line 13), otherwise, area shifting is performed downwards (line 16). Thus, the stuck node s sets the direction of area shifting according to the angle of the reference line from itself, and calculates coordinates for area shifting according to the size of the void area (line 15 and 18).

Step 3 (line 20-21). After calculating the coordinates of bypass points, the stuck node s notifies former nodes the points to the area shifting and bypass points (line 20). The former nodes would realize the area shifting and transmit the packet to a bypass point. Node s transmits a packet to a node located on the bypass point to notify it of the area shifting (line 21). If necessary, the node that receives the packet about bypassing performs the same area shifting.

4 Performance Evaluation

In this section, we describe the simulation results for the EECA, LDMR, IMCMRP, and proposed scheme. EECA is the most representative radio-disjoint multipath routing protocol that constructs two paths and transmits data on the paths. LDMR constructs several paths depending on the required packet delivery ratio. IMCMRP elects the cluster head nodes to minimize interference and constructs multipaths based on the cluster.

In Section 4.1, we analyse a time complexity to confirm that a node has a capability to perform the proposed scheme. In Section 4.2, we describe the simulation environment and evaluation factors. The simulation results according to the number of nodes are explained in Section 4.3. The simulation results according to network traffic are described in Section 4.4. In Section 4.5, we provide the simulation results according to the number of sources. Finally, the packet delivery ratio versus size of void area is provided in Section 4.6.

Table 3. Time complexity of the proposed scheme and other protocols

Routing protocol	Time complexity
EECA	$O(N)$
LDMR	$O(N \times P)$
IMCMRP	$O(N)$
Proposed Scheme	$O(N)$

4.1 Time Complexity Analysis

In this section, to verify the capability of the node to perform the proposed scheme, we describe the time complexity analysis results. Table 3 summarizes the time complexity of the proposed scheme and other protocols. The proposed scheme has two loops: (1) a loop that has a running time proportional to the number of neighbor nodes (N) to calculate the required number of paths and (2) a loop that has a running time depending upon the node selection process in packet transmission process (N). Therefore, the complexities of the loops are equal to $2O(N)$. In addition, since the running time of anchor point calculation process and void handling process would be terminated within a fixed time, their time complexities are $O(1)$ and $O(1)$, respectively. As a result, the time complexity of the proposed scheme could be expressed as $2O(N) + 2O(1)$. Therefore, the overall time complexity of the proposed scheme is $O(N)$. Compared to the other protocols, EECA has a running time proportional to the number of neighbor nodes (N) to select the suitable nodes to construct radio-disjoint multipaths. Thus, the time complexity of EECA is $O(N)$. LDMR has two loops: (1) a loop that has a running time proportional to the number of neighbor nodes (N) to calculate the required number of paths and (2) a loop that has a running time according to finding the start and exit point of each paths (P). Thus, the complexities of LDMR could be expressed as $O(N \times P)$. IMCMRP also has two loops: (1) a loop for neighbor identification that has a running time proportional to the number of neighbor nodes (N) and (2) a loop that has a running time proportional to the number of neighbor nodes (N) to cluster head node selection. Therefore, the time complexity of IMCMRP is $O(N)$.

4.2 Simulation Environment Setting

We simulated and analyzed the proposed scheme and other protocols on an NS-3 simulator. Table 4 describes the detailed setup of our simulation. The nodes were placed in a 1000m×1000m terrain. Some nodes (100) were placed in the form of a grid and the remaining 900 were randomly placed. The transmission and receiving power consumption of a node was 24.92 and 19.72 mJ per byte, respectively.

The parameters are default values for performance evaluations, and simulation results which to be described in this chapter, are the results of changes to some parameters such as the number of the source nodes. Through the simulation, we estimated the network lifetime and packet delivery ratio in terms of the number of nodes, network traffic, and the number of sources. In particular, the network life time can be defined according to [18], and in this paper, performance evaluation was performed in two aspects: lifetime based on the number of alive nodes and based on connectivity. In addition, the packet delivery ratio

Table 4. Time complexity of the proposed scheme and other protocols

Parameter	Value(s)
Routing protocol	EECA, LDMR, IMCMRP, Proposed scheme,
Terrain	(1000 m, 1000 m)
End-to-end distance	700 m
Node	1000 Nodes, Uniform & Random placement
Transmission range	100 m
MAC protocol	802.15.4 MAC
MAC layer	CSMA /CA
Bandwidth	250 Kb/s
Payload size	32 bytes
Energy consumption (Tx)	24.92 mJ per 1 byte
Energy consumption (Rx)	19.72 mJ per 1 byte
Required packet delivery ratio	95%
Average link reliability	90%

versus size of void is presented to measure the effect of voids. The simulations were performed 30 times, and the graph provided represents the average simulation results. The evaluation factors and terms are summarized as follows:

- **Network lifetime based on the number of alive nodes** is defined as the time at which the first node is discharged.
- **Network lifetime based on connectivity** is defined as the time that arbitrary two nodes cannot exchange the data for each other. That is, it means that the network partition occurred.
- **Packet delivery ratio** is defined as the ratio of the number of data arriving at the destination to the number of data generated by the source node.
- **Number of nodes** is defined as the number of nodes placed in the terrain.
- **Network traffic** is defined as the number of packets sent per second.
- **Number of source** is defined as the number of nodes that generate the packet.
- **Size of void** is defined as the width of the void area.

4.3 Simulation Results according to Number of Nodes

In this section, we present the performance evaluation results while increasing the number of nodes with link reliability of 90%. In this simulation, the packets that failed during the transmission process did not retransmit to confirm the change in the packet delivery ratio.

Figure 4 shows the packet delivery ratio relative to the number of nodes. When the number of nodes is 500 or more, LDMR, IMCMRP, and the proposed scheme can satisfy the required packet delivery ratio by constructing a sufficient number of paths. However, when the number of nodes is less than 500, they cannot satisfy the required packet delivery ratio due to the lack of network nodes needed to construct enough paths.

EECA shows a consistently lower packet delivery ratio compared with the other protocols, regardless of the number of nodes. This is because EECA constructs only two paths, so fewer nodes participate than in other protocols.

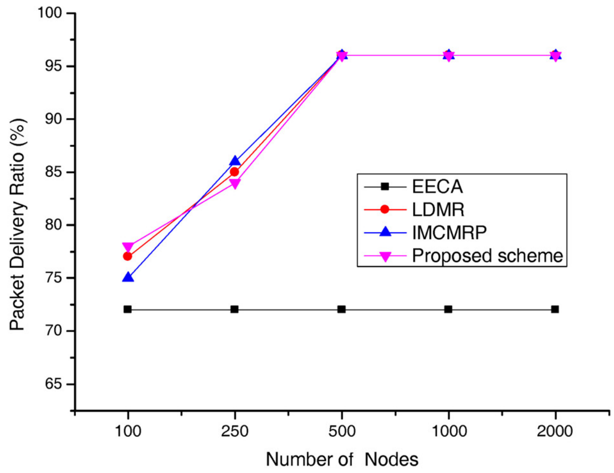

Figure 4. Packet delivery ratio related to the number of nodes

Figure 5 shows the network lifetime based on the number of alive nodes versus the number of nodes. When the number of nodes is 250 or more, LDMR and the proposed scheme have longer network lifetimes than EECA and IMCMRP do. This is because there are more candidate nodes available for packet transmission in LDMR and the proposed scheme. In particular, because the proposed scheme selects the next node more equally according to link quality and remaining energy, it offers a longer network lifetime than with LDMR. However, when the number of nodes is less than 250, LDMR and the proposed scheme show shorter network lifetimes than with EECA and IMCMRP.

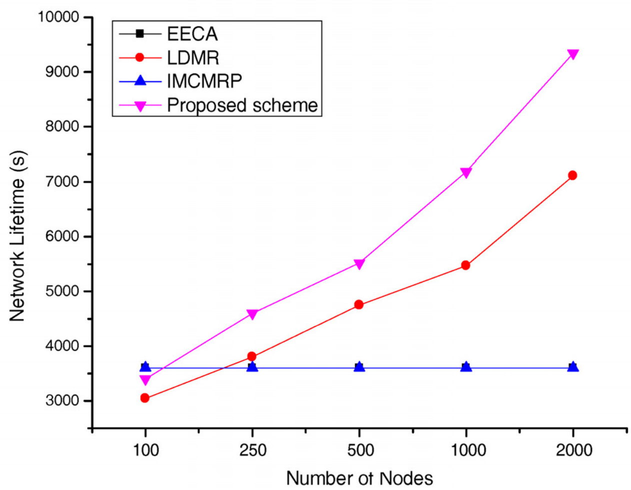

Figure 5. Network lifetime based on the number of alive nodes related to the number of nodes

This is because the same node around the source is overused to construct multiple paths. In the case of EECA, the packet is transferred only over the constructed path, and in the case of IMCMRP, the packet is delivered through the cluster head node, so these two protocols have nodes that are intensively exploited to transmit the packets. Therefore, because the nodes are discharged first regardless of the number of nodes, they have a shorter network lifetime than with other protocols.

Figure 6 shows the network lifetime based on connectivity versus the number of nodes. Network lifetime of all protocols except the proposed scheme does not increase significantly compared with Figure 5. It is because the node that participated on the path already consumed similar energy with the first failed node. In particular, the smaller the number of nodes, the network lifetime is similar to Figure 5. That is, when a node failure occurred in a low-density network, the network partitioning would be accelerated because there are no nodes that replace the discharged node. Conversely, when the number of nodes becomes higher, the proposed scheme shows a significant increase in network lifetime than other protocols because it exploits the nodes equally in the data transfer process based on various factors. However, as other protocols use the same path repeatedly, the network lifetime only increases slightly for similar reasons as when the number of nodes is smaller.

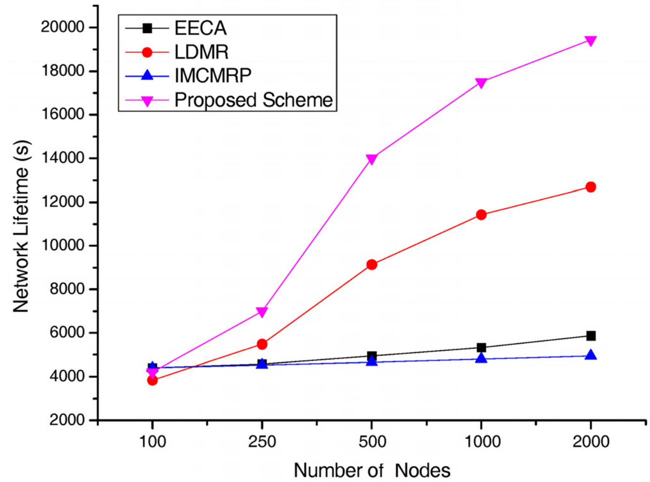

Figure 6. Network lifetime based on connectivity relative to the number of nodes

4.4 Simulation Results According to Network Traffic

In this section, we demonstrate the effect of network traffic on the packet delivery ratio and network lifetime. In this simulation, the packets that failed during the transmission process are retransmitted to investigate the effect of network traffic.

Figure 7 shows the packet delivery ratio versus the network traffic. Until five packet transmissions per second, all of the protocols except EECA can achieve the required packet delivery ratio. However, in the case of more than ten transmissions per second, the packet delivery ratio decreases. In the case of LDMR, the packet is delivered at a certain interval to avoid collisions in the packet transmission process from the source node to the enter point of each path. As a result, because the nodes near the source node suffer from the bottleneck problem, some packets are omitted. In the case of IMCMRP, a packet is kept until the cluster head node receives the ACK message. Thus, a buffer overflow of the cluster head node might occur and this leads to packet omissions under the condition of high network traffic. Finally, the proposed scheme also shows reduction of the packet delivery ratio because of the omission of packets due to conflicts and interference occurring near the source node. However, because the path in which a packet is transmitted is different in each transmission due to guard-band shifting, the proposed scheme has fewer omissions compared with the other protocols.

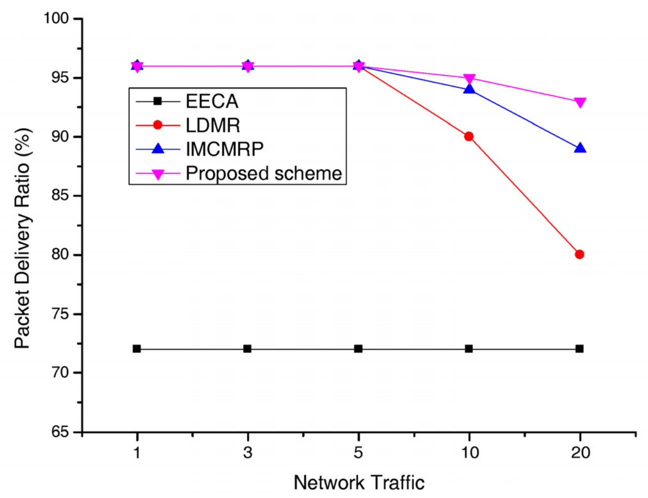

Figure 7. Packet delivery ratio relative to network traffic

Figure 8 shows the network lifetime based on the number of alive nodes versus the network traffic. All of the protocols show shorter network lifetimes when network traffic is increasing. In the cases of EECA and IMCMRP, which exploit the same path for each transmission, it could be seen that the network lifetime is extremely short. LDMR and the proposed scheme also have a short network lifetime, however, they have a relatively long lifetime because the nodes are selected evenly compared with previous protocols. In particular, the proposed scheme exploits all the nodes present in the path between source and destination evenly based on guard-band shifting, so the network lifetime is longer than with LDMR, which maintains radio-disjoint by never using the guard-band area.

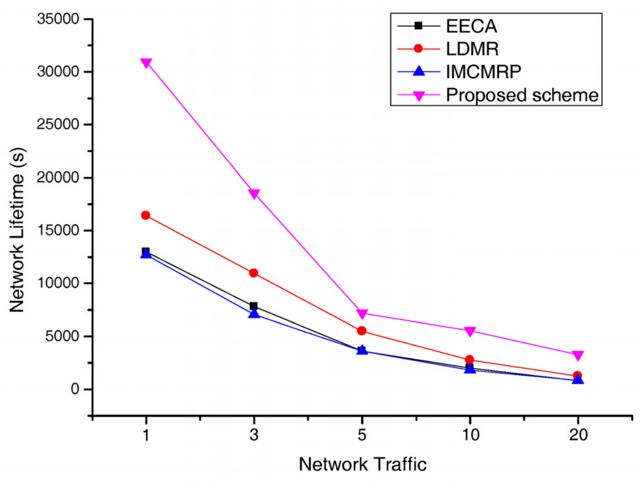

Figure 8. Network lifetime based on the number of alive nodes relative to network traffic

Figure 9 shows the network lifetime based on connectivity versus the network traffic. As the increase of the network traffic provides overload on the node on the path, it accelerates node discharge. In addition, after the discharging of the first node, the load would be provided to other nodes around the discharging node. That is, the failure of the nodes accelerated from the point of the first node failure, and the path which contains the nodes would be lead to the network partitioning. Thus, the protocols exploiting only the constructed path and nearby nodes quickly shorten the network lifetime. However, in the case of the proposed scheme, although the node might be failed quickly in some low-density area, the network lifetime is longer than other protocols because the proposed scheme exploits the node on the path equally. That is, since nodes are exploited evenly through the guard-band shifting, the proposed scheme has a longer network lifetime.

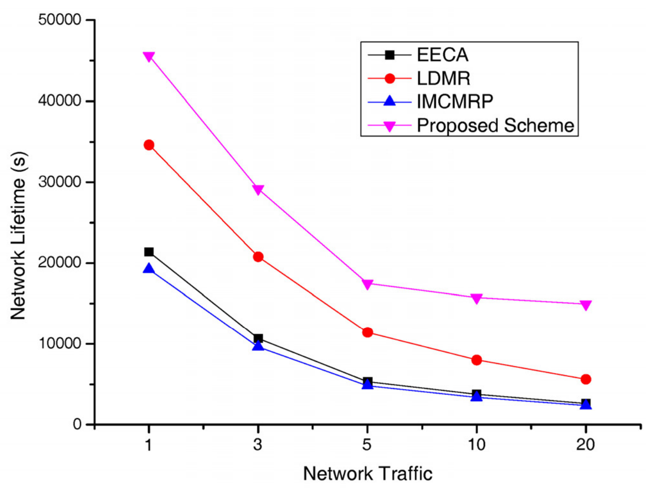

Figure 9. Network lifetime based on connectivity relative to network traffic

4.5 Simulation Results according to Number of Sources

In this section, we provide the simulation results while increasing the number of source nodes.

Figure 10 shows the packet delivery ratio versus the number of source nodes. All protocols show reduced packet delivery ratios as the number of source nodes increases. With EECA, the packet delivery ratio decreases due to the overlay of each path; however, the packet delivery ratio drop is smaller than with other protocols because each source node constructs only two paths. With LDMR, because many multipaths are constructed to improve the packet delivery ratio, many paths would be overlaid (compared to those of EECA) and conflicts and interference occur. Therefore, the packet delivery ratio drop is larger than with other protocols. Similarly, many paths overlap with the proposed scheme to satisfy the required packet delivery ratio, as with LDMR. However, the packet delivery ratio drop is relatively small because of even intermediate node selection based on guard-band shifting. Finally, with IMCMRP, there are significantly fewer conflicts and interference compared with the other protocols because packets are transferred through the cluster head node. However, due to the focusing of packets in the cluster head node, this one has a shorter network lifetime than with the other schemes.

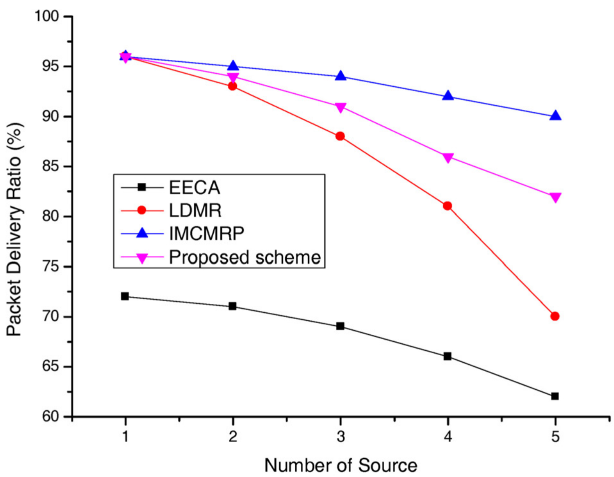

Figure 10. Packet delivery ratio relative to the number of sources

Figure 11 shows network lifetime based on the number of alive nodes versus the number of source nodes. Similar to the packet delivery ratio, the network lifetime also appears to decrease as the number of source nodes increases. For EECA, because each source node constructs only two paths, it can be seen that the network-lifetime-drop according to the number of source nodes is relatively small. In the case of LDMR and the proposed scheme, as multiple source nodes construct multiple multipaths, the network lifetime rapidly decreases. However, the proposed scheme has a relatively long network lifetime because it selects the intermediate nodes evenly through guard-band shifting. In the case of IMCMRP, because all packets transmitted from each source are delegated to the cluster head node, massive energy consumption by the cluster head node occurs, which leads to drastic reduction of the network lifetime.

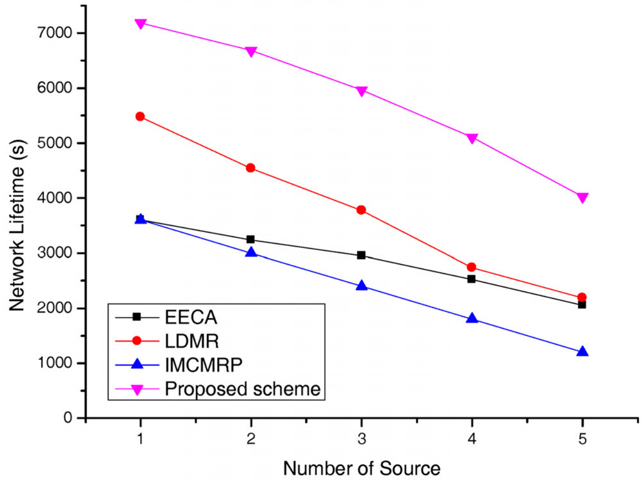

Figure 11. Network lifetime based on the number of alive nodes relative to the number of sources

Figure 12 shows network life time based on connectivity relative to the number of sources. The increase in the number of source nodes leads to the quickly exhausting energy of the node for some overlapped paths, as with earlier mentioned traffic in Section 4.4. Thus, the time of first node failure in the overlapped paths is rapidly pulled, and it leads to rapid exhaustion of the nearby node. Since the protocols except the proposed scheme transmit the packet through the same path until the path is broken, the moment of the network partitioning would be rapidly approached after the first node failure. However, in case of the proposed scheme, the network partitioning is later than other protocols because the candidate nodes would be exploited as evenly as possible as in the overlapped paths.

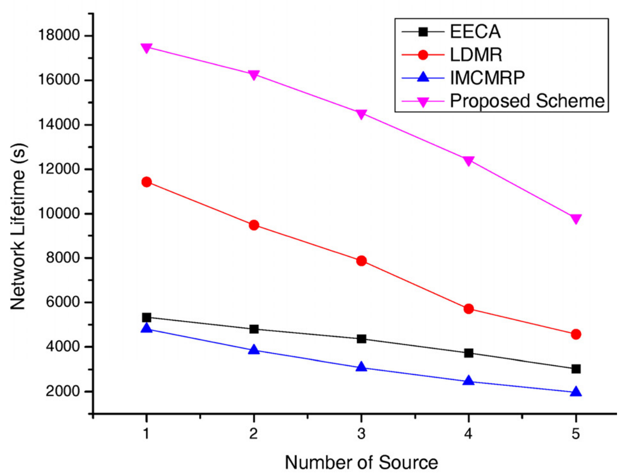

Figure 12. Network lifetime based on connectivity relative to the number of sources

4.6 Packet Delivery Ratio versus Size of Void Area

In this section, we demonstrate the packet delivery ratio versus the size of the void area through Figure 13. Overall, the void area can be seen to be having an adverse effect on all protocols. Many control messages and much time are required to bypass void areas. In addition, a large network is required to bypass a smaller void for radio-disjoint. Therefore, as the size of the void area grows, more time should be spent in the process of bypassing it. This leads not only to omission of packets, but also to the inability to construct a sufficient number of paths. As a result, increase in the void area drops the packet delivery ratio sharply. With ICMRP, as the multiple paths from the cluster head to the destination merge due to the void area, the packet delivery ratio decreases. However, a relatively higher packet delivery ratio could be provided by retransmission supported by the cluster head node. Because the proposed scheme exploits the area shifting mechanism, it could construct the path to bypass a void in less time than LDMR could. In addition, the proposed scheme is free from constraints on the size of the network because the shifting mechanism requires less extent to bypass a void. However, with EECA, the packet delivery ratio is not affected because it bypasses the void area to create paths.

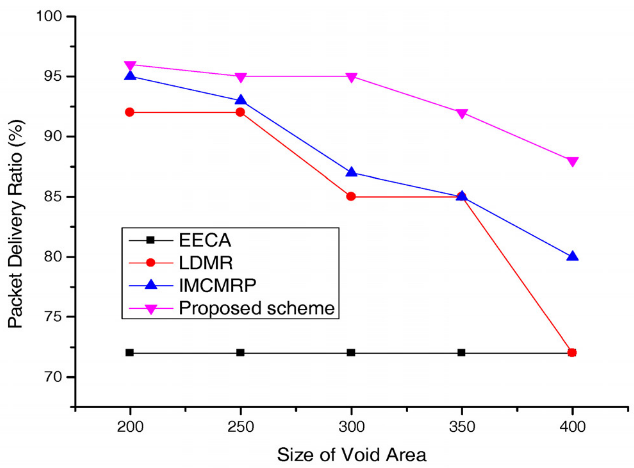

Figure 13. Packet delivery ratio relative to the size of voids

5 Conclusions

Many radio-disjoint multipath routing protocols have been proposed to prevent path failure by collision and interference. However, existing studies have not considered exploiting the guard-band area while transmitting packets. Thus, they suffer from many problems such as traffic congestion and shortened lifetime. Therefore, we propose energy-balanced multipath routing based on guard-band shifting. The proposed scheme transfers the packets on the constructed main path and guard-band area as alternative sub paths. Moreover, because the intermediate nodes are selected according to link quality, energy consumption, and energy remaining, the proposed scheme could utilize the network nodes more equally compared with existing studies. Thus, the proposed scheme prevents traffic congestion and shortening of lifetime that occur because only the same paths are used intensively. Through simulation, it was determined that the proposed scheme would improve the packet delivery ratio up to 25%. In addition, the network lifetime would be prolonged by at least 33% and up to 99% compared with existing routing protocols with a 90% link success ratio.

Acknowledgements

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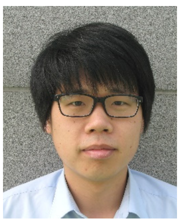
Biographies



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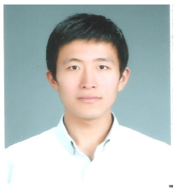

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