Energy Efficient and Secure Routing for WMSNs Using Directional Antenna

Mika Matsushima[1] and Ryo Katsuma[2]

[1]Osaka Prefecture University

[2] Osaka Prefecture University

ABSTRACT

Wireless multimedia sensor networks (WMSNs) can deliver multimedia data such as streaming video to multiple users by sensor nodes deployed in a field. The major problems of wireless sensor networks (WSNs) are radio eavesdropping and radio interference. Several studies have attempted to address these problems by limiting the reachable radio wave distance of each sensor node using directional antennas. We formulate a routing problem to dynamically create streaming-data transfer paths for WMSNs constructed by sensor nodes with directional antennas, and we propose a method to solve this problem by scheduling the condition (sleeping or active) and the antenna direction for each sensor node. When the video data stream is requested by multiple users, the proposed algorithm reduces the total energy consumption among relay nodes by merging transfer paths. Simulation results confirm that the proposed method can conserve the battery power of each node for a WSN with 198 nodes.

Keywords:- wireless multimedia sensor networks, directional antenna, routing, paths for streaming data

1. INTRODUCTION

Wireless sensor networks (WSNs) can collect a various type of information sensed by many sensor nodes deployed in a field of interest [1][2]. Various WSN applications such as agricultural monitoring, road traffic viewing by streaming video, and so on are expected because WSNs do not require electrical wirings or high cost infrastructures. WSNs that hundle multimedia data are called wireless multimedia sensor networks (WMSNs). Generally, agricultural monitoring is categorized as **collection type WSNs** that periodically collect and send environmental information sensed by sensor nodes to a sink node. On the other hand, **query type WSNs** deliver sensing data from a source sensor node to users who send queries, e.g., traffic viewing. Many WMSN applications are query type WSNs (**QWMSNs**). QWMSNs can improve the experience of people attending festivals. People are sometimes bored by waiting and searching for events or attractions at outdoor festivals. If QWMSNs are deployed on festival grounds to provide real-time streaming video of each event, dissatisfaction can be reduced by obtaining relevant information, such as the degree of crowdedness, and information about on-going events and shops. However, radio eavesdropping, radio interference, and lifetime extension problems exist with QWMSNs. In the radio eavesdropping problem, an eavesdropper listens to user communications. In the radio interference problem, when two or more radio waves are sent simultaneously, the receiver node cannot understand the message. Several studies have attempted to solve these problems using directional antennas [3]–[8]. A directional antenna can send radio waves in a specified direction. However, the requires setting up each antenna with the appropriate direction. In addition, many studies have attempted to extend network lifetime [9]–[11]. These studies aim to balance the energy consumption of each node by making disjoint paths in order to avoid exhausting sensor node batteries by extreme increases in the amounts of transmitted data. However, in QWMSNs, multiple users request the same streaming data. Thus, merging paths between one source and multiple users is required to reduce the amount of transmitted data. In this paper, we propose a method to create data paths between a source node and users who send queries to a source node for QWMSNs constructed by sensor nodes with directional antennas. In the proposed algorithm, when a user sends a query to a source node, the source node calculates a data path to the user and sends streaming data along the path. When another user sends a query to the same source node, the proposed algorithm reduces energy consumption by merging as many parts of these paths as possible. The proposed algorithm also determines antenna direction for each sensor node such that a transmitting sensor node does not involve the other nodes transmitting the streaming data. The remainder of this paper is organized as follows. In Section 2, we describe related work. Assumptions and the target problem formulation are described in Section 3. In Section 4, we propose an algorithm to dynamically create data paths that satisfy antenna direction conditions. We evaluate the proposed method in Section 5, and conclude the paper in Section 6.

2. RELATED WORKS

A sensor node with an omnidirectional antenna emits radio waves in a circular area. When the antenna transmits data to a node, the radio wave may reach another node. If that node is actively communicating, radio interference occurs. Existing studies have employed directional antennas to reduce radio interference by controlling reachable radio areas. An example of a directional antenna is the ESPAR antenna [4]. An ESPAR antenna is low cost, and it can be freely switched between omnidirectional and directional communication. Ishihara et al. proposed a synchronized method to change the direction of each sensor node for WSNs with ESPAR antennas [5]. In addition, Dai et al. proposed a method to increase throughput capacity and decrease delay by reducing the number of hops [7], and Razi et al. proposed a system model using directional antennas to reduce interference [8]. In addition, many studies have examined extending the lifetime of WSNs. If some sensor nodes exhaust their batteries, WSNs cannot operate even though the residual battery power of other sensor nodes is sufficient. To solve this problem, the LEACH and HEED routing protocols, which balance the energy consumption of each sensor node, have been proposed [9][10]. Li et al. proposed a method to create data paths that balance the residual battery power of each sensor node using the Multiple Input Multiple Output (MIMO) technique [11]. However, these existing studies only attempted to avoid data concentration on certain nodes for data collection WSNs. If users demand the same streaming data in QWMSNs, the increased energy consumption required to deliver such data to each user can be reduced by merging data paths. Therefore, a new method using this streaming data feature is required to balance the residual battery power of each node in QWMSNs. In this paper, we formulate a problem to extend the lifetime of QWMSNs. We propose an algorithm to merge multiple paths from a single source node to users for QWMSNs constructed with source and relay nodes with directional antennas.

3. PROBLEM FORMULATION

Here, we describe assumptions and formulate the target problem.

3.6 Assumptions

We target a QWMSN application that sends real-time streaming video data to users who want to know the state or degree of crowdedness of a certain location. The target QWMSNs are constructed with a source node and relay nodes. A source node with a wired power supply is placed at important event locations, and battery-powered relay nodes are deployed in the field at grid points of *a* [m]. A user sends its position and a query to a source node by flooding. A relay node that has received a query adds the data of its residual battery power and whether it is used in existing paths to the query, it and sends the query to other nodes. The source node that has received the query calculates a path to the user and sends the real-time streaming data. If the user stops watching the streaming video, the source node stops transmitting the data. Note that users do not move during reception of the streaming data. Each node equipped with a directional antenna emits a radio wave in a circular area of radius *b* [m] ($\sqrt{2}a < b < 2a$) or a circular sector of central argument θ [rad] ($0 < \theta < \pi$). The radio emission area of node *s* at time *t* is denoted by $s.range(t)$, which is determined by *b* and θ. When node *s* is not included in any paths at time *t*, $s.range(t) = \phi$. The initial battery power of each node is denoted by E_{init}. Note that battery power is never renewed.

3.7 Definitions for energy consumption

A sensor node consumes energy by sending and receiving data. Consumed power *trans(x, d)* required to transmit *x* [bit] data for *d* [m] is expressed by Formula (1).

$$trans(x,d) = E_{elec}x + \varepsilon_{amp}kd^2 \qquad (1)$$

Here, E_{elec} and ε_{amp} are constant values that represent the power required by information processing and the power for amplification, respectively. Consumed power *recep(x)* required to receive *x* [bit] data is expressed by Formula (2).

$$recep(x) = E_{elec}\,x \qquad (2)$$

A sensor node also consumes energy when idling in order to listen for hello messages sent by other nodes. Consumed power *listen(y)* required to listen for y [s] is expressed by Formula (3).

$$listen(y) = E_{listen}\,y \qquad (3)$$

3.8 Problem formulation

The inputs to the target problem are the target field, a source node, a set of relay nodes, the position of each node, the residual battery power of node *s* at time *t* $s.energy(t)$, the radio emission area of node *s* at time *t* $s.range(t)$, a set of users at time t, the position of each user, and the query of each user. The outputs are a data path schedule from the WSN start time t_s to WSN termination time t_e and a radio emission area schedule. The objective function is to maximize the amount of data that all users can receive. This is expressed by Formula (4).

$$maximize\left(\sum_{k=1}^{N} w_k[t_0^k, t_1^k] \right) \quad (4)$$

Here, N is the number of queries, and t_0^k and t_1^k are the time of sending a query by user *k* and the time of finishing, respectively. $w_k[t_0^k, t_1^k]$ denotes the received data amount of user k. A user can receive the streaming data while the residual energy power of each node used by its path is not exhausted. This condition is expressed by Formula (5).

$$\forall t \in [t_0^k, t_1^k], \forall p \in P_u(t), p.energy(t) > 0 \quad (5)$$

Here, $P_u(t)$ is the set of nodes used by the path for user *u* at time *t*. To avoid radio interference and eavesdropping, we limit the radio emission area for each node so that nodes used by paths are not covered by the radio emission areas of other nodes. This constraint is expressed by Formula (6).

$$\forall t \in [t_0^k, t_1^k], \forall s \in R, \forall q \in Q(t,s), s \notin q.range(t) \quad (6)$$

Here, R is a set of nodes used by one or more paths, and $Q(t,s)$ is the set of all paths, with the exception of paths that include node *s* at time *t*.

4. ALGORITHM

Here, we present the algorithm proposed to solve the problems discussed in Section 3.

4.1 Outline

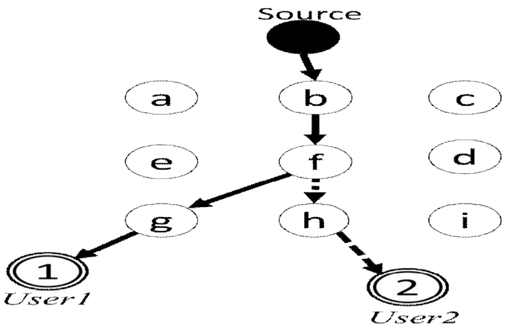


Figure 1. Paths for multiple users

When multiple users want to obtain streaming data generated by a single source node, the streaming data delivered to each user is the same. In order to reduce the number of relay nodes that join the paths, we attempt to merge the paths that deliver the streaming data to users. If a user sends a query to a source node that has not joined a path, the proposed algorithm initially constructs energy efficient paths by letting nodes with sufficient residual battery power relay the streaming data. When a user sends a query to a source node that has joined an existing path, the source node forces the paths to diverge. For example, nodes *a* to *i* are deployed on the field, as shown in Fig. (1), and the source node sends the streaming data to *User1*. The path between the source and *User1* is shown by arrows with solid lines. When *User2* sends a query to the source node, the streaming data that should be sent to *User2* is the same as that for *User1*. The new path that includes nodes *b* and *f* consumes less battery power than the disjoint paths. In the example shown in Fig. 1, the division point of the two paths is node *f*, and the link used by only *User2* is constructed after node *f* as the initial path construction. Each node emits the radio wave in a circular sector. The communicable range of the division point relay node must cover all destination nodes. The proposed algorithm calculates the antenna direction of each relay node emitting the radio wave and its central argument of the circular sector.

4.2 Proposed Algorithm

Here, we discuss in detail the proposed algorithm to construct dynamic data paths for delivering streaming data generated by source *s* to user *u* at time *t*.

Notation:

Let *P*, *Q*, and *R* denote sets of nodes. *P* denotes candidate nodes for the next hop, *Q* denotes the path, and *R* denotes non-candidate nodes.

Let *last(Q)* denote the latest element added to *Q*.

Let γ denote the radio emission area argument ($0 < \gamma < \frac{\pi}{2}$)

Let **unused node** denote a node that does not join any paths.

Let E_{ave} denote the average residual battery power among all nodes.

Algorithm:

Step 1. Set $P = \phi, Q = \{s\}, R = \phi$ and $p = s$.

Step 2. If *s* has joined an existing path, put unused nodes in the radio emission area of *p* (circular sector of radius $\sqrt{2}a$ and argument γ) into *P*.

Step 3. If $P \neq \phi$, go to Step 5; otherwise, go to Step 4.

Step 4. Put unused nodes ($\notin R$) whose residual battery power is greater than E_{ave} and whose position is within $\sqrt{2}a$ of *p* into *P*. If $P \neq \phi$, the algorithm fails and terminates.

Step 5. Let $q \in P$ denote the unused node nearest to *u* that satisfies Formula (6). Put *q* into *Q*. Set $P = \phi$. If *q* cannot be found, put *p* into *R*, $p = last(Q)$, and return to Step 2.

Step 6. If $q = u$, *Q* is the output and the algorithm terminates; otherwise, put *p* into *R*, $p = q$, and return to Step 2.

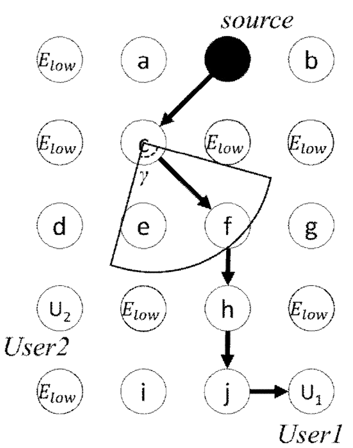


Figure 2.
Use the existing path

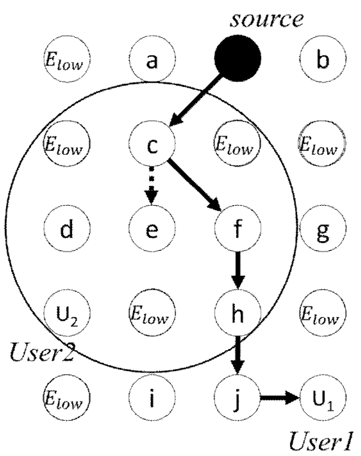


Figure 3.
Diverge from existing path

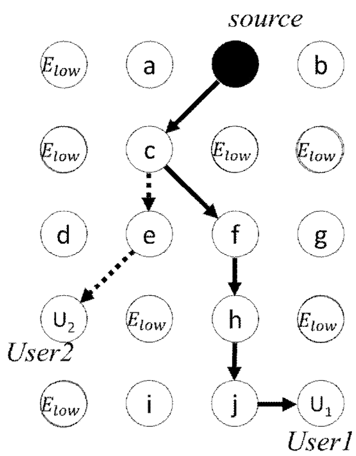


Figure 4.
Complete the path construction

We show an example in Fig. 2, including a source node, relay nodes, and users. A node with lower residual battery power than E_{ave} is shown as E_{low}. An existing path to user u_1 is drawn with solid line arrows. When user u_2 sends a query to the source node, the source begins calculation. First, unused node *c* is selected by Step 2 and Step 4 because *c* is nearest to u_2 and has already joined the existing path. Unused nodes covered by *c*'s circular sector of central argument γ covering *f* are candidates for the next hop. In this case, *e* nearest to unused node u_2 is selected. In Fig. 3, *e* becomes the division point and has the candidates for the next hop $P = \{d, f, u_2, h\}$ according to Step 3. Finally, u_2 is selected as *e*'s next hop by Step 4. Then, the path for User2 is determined, as shown in Fig. 4, and the algorithm terminates.

4.3 Deciding the direction of radio emission

When a node sends the data, it must satisfy Formula (6). In this section, we describe the method for determining the radio emission direction for each node. Let *F* denote a set of next hop destinations of node *p*. The argument $\alpha_{(p,f)}$ made by p and $f \in F$ is expressed by Formula (7).

$$\alpha_{(p,f)} = \arcsin(\frac{f.y - p.y}{\sqrt{(f.x - p.x)^2 + (f.y - p.y)^2}}) \qquad (7)$$

Here, $p.x$ and $p.y$ are the x and y coordinates of *p*, respectively.To satisfy Formula (6), the radio emission area argument γ is expressed by Formula (8).

$$\forall f \in F, \begin{cases} \max(\alpha_{(p,f)}) - \min(\alpha_{(p,f)}) & (\beta < \pi) \\ \max(\alpha_{(p,f)}) - (\min(\alpha_{(p,f)}) - 2\pi) & (otherwise) \end{cases} \quad (8)$$

Here, $\forall f \in F, \max(\alpha_{(p,f)})$ and $\min(\alpha_{(p,f)})$ denote the maximum and minimum argument made by p and $f \in F$, respectively. β represents $\max(\alpha_{(p,f)}) - \min(\alpha_{(p,f)})$.

To cover all elements of *F* by *p*, the radio emission direction of p is determined by Formula (9).

$$\forall f \in F, \begin{cases} \dfrac{\max(\alpha_{(p,f)}) - \min(\alpha_{(p,f)})}{2} & (\beta < \pi) \\ \dfrac{\max(\alpha_{(p,f)}) - (\min(\alpha_{(p,f)}) - 2\pi)}{2} + \pi & (otherwise) \end{cases} \quad (9)$$

5. EVALUATION

We performed simulation experiments to evaluate the proposed method. We investigated the delivery rate for streaming and the average node residual battery power by varying the number of queries.

5.1 Settings

In our simulation, the field size is set to 500 [m] × 300 [m] in reference to Maishima Arena, Osaka, Japan. The reachable radio distance is set to 40 [m]. The initial battery power for each node is set to 32400 [J]. These settings were determined by reference to the literature [12]–[13]. According to the reachable radio distance and field size, the relay nodes are deployed as grid points at 28.29 [m]. A source node is deployed at the north center position of these grid points. Therefore, we use 197 relay nodes and one source node. The duration of the event is set to 12 h. The number of queries is 30 to 150. Note that queries are generated randomly. We measured the number of constructed paths (each user can obtain) and the residual battery power of each node after the event finished (i.e., after 12 h).

Comparative method

Here, we compare the proposed method with a greedy method. A greedy method does not consider the residual battery power of each node and selects the node nearest to the user as the next hop node. Note that the other parts of the greedy algorithm are the same as the proposed algorithm. The details of the greedy method algorithm are as follows.

Step 1. Set $P = \phi, Q = \{s\}, R = \phi$ and $p = s$.

Step 2. If *s* has joined the existing path, put unused nodes in the radio emission area of *p* (circular sector of radius $\sqrt{2}a$ and argument γ) into *P*.

Step 3. If $P \neq \phi$, go to Step 5; otherwise, proceed to Step 4.

Step 4. Put unused nodes ($\notin R$) whose positions are within $\sqrt{2}a$ of p into P. If $P \neq \phi$, the algorithm fails and terminates.

Step 5. Let $q \in P$ denote the unused node that is nearest to *u* and satisfies Formula (6). Put *q* into *Q*. Set $P = \phi$. If *q* cannot be found, put *p* into *R*, $p = last(Q)$, and return to Step 2.

Step 6. If $q = u$, *Q* is the output and the algorithm terminates; otherwise, put *p* into *R*, $p = q$, and return to Step 2.

5.2 Simulation result

We confirmed that both methods constructed paths for queries. However, a difference in residual battery power of each node was observed. Figure 5 shows the average residual battery power of all nodes. We confirmed that the proposed algorithm outperforms the greedy algorithm in terms of residual battery power. Figure 5 shows the average of residual battery amount for all nodes. We confirmed that our algorithm is better than the greedy algorithm. Figure 5 also shows that this difference tends to increase with an increased number of queries because the proposed algorithm has an energy efficiency mechanism (Step 4).

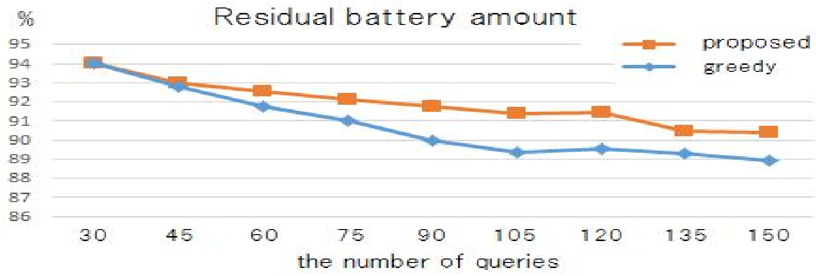


Figure 5. Residual battery power after 12 h

6. CONCLUSION

In this paper, we have formulated a problem to construct dynamic data paths for data streaming. To address this problem, we have proposed an algorithm to dynamically determine the next hop of each node and the radio emission direction. The proposed algorithm uses nodes with residual battery power that is sufficient for data paths. Simulation results confirmed that the proposed method is more efficient than a greedy method that does not avoid using nodes with low residual battery power for a 500 [m] × 300 [m] field, 198 nodes, and 150 queries.

References

[1] I. F. Akyildiz, Weilian Su, Y. Sankarasubramaniam, E. Cayirci, "A survey on sensor networks," Journal of IEEE Communications Magazine, Vol. 40, Issue 8, pp. 102-114, 2002.

[2] Marko Pesko, Mitja Stular, Matevz Vucnik, Miha Smolnikar, and Miha Mohorcic, "Bluetooth-Based Mobile Gateway for Wireless Sensor Network," International Workshop on Sensing Technologies in Agriculture, Forestry and Environment, 2011.

[3] Hong-Ning Dai, Qiu Wang, Dong Li, and Raymond Chi-Wing Wong, "On Eavesdropping Attacks in Wireless Sensor Networks with Directional Antennas," Hindawi International Journal of Distributed Sensor Networks Volume 2013 (2013), Article ID 760834, 2013.

[4] Haruo Kawakami and Takashi Ohira, "Electrically Steerable Passive Array Radiator (ESPAR) Antennas," IEEE Antennas and Propagation Magazine, Vol. 47, Issue 2, pp. 43–50, 2005.

[5] Susumu Ishihara, Takashi Osawa and Tokuya Inagaki, "Power saving hierarchical sensor network architecture with synchronized directivity switching," IPSJ SIG Technical Report 2010-UBI-25(54), pp. 1-6, 2010.

[6] Hong-Ning Dai, Kam-Wing Ng, and Min-You Wu, "Channel Allocation in Wireless Networks with Directional Antennas," Journal of Sensor and Actuator Networks, No. 2, pp. 213-234, 2013.

[7] Hong-Ning Dai, "Throughput and Delay in Wireless Sensor Networks using Directional Antennas," 5th International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), pp. 421-426, 2009.

[8] Razi, A. and Abedi, A, "Interference reduction in Wireless Passive Sensor Networks using directional antennas," Wireless Workshop (FBW), 2011.

[9] W. R. Heinzelman, A. Chandrakasan and H. Balakrishnan, "Energy-Efiicient Communication Protocol for Wireless Microsensor Networks," the 33rd Hawaii International Conference on System Sciences, pp. 1-10, 2000.

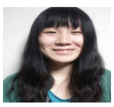
[10] O. Younis and S.Fahmy, "HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks," IEEE Trans. on Mobile Computing, Vol. 3, No. 4, pp. 366–379, 2004.

[11] Jianpo Li, Xue Jiang, and I-Tai Lu, "Energy Balance Routing Algorithm Based on Virtual MIMO Scheme for Wireless Sensor Networks," Hindawi Journal of Sensors, Vol. 2014, Article ID 589249, 2014.

[12] Ram Ramanathan, "On the performance of ad hoc networks with beamforming antennas," ACM International Symposium on Mobile Ad Hoc Networking and Computing (Mobihoc), pp. 95–105, 2001.

[13] M. Sichitiu and R. Dutta, "Benefits of multiple battery levels for the lifetime of large wireless sensor networks," NETWORKING, pp. 1440–1444, 2005.

AUTHOR



Mika Matsushima received a bachelor's degree in science from Osaka Prefecture University in 2014. She is currently a first year Masters student at Osaka Prefecture University.

Ryo Katsuma received a bachelor's degree in education from Kyoto University of Education in 2006. He also received master's and doctoral degrees in engineering from the Nara Institute of Science and Technology. He is currently an assistant professor at Osaka Prefecture University. His research field of interest is ad-hoc networks.