Energy Efficient Routing Control for 6LoWPAN WSN with Power-supplied and Battery-powered Nodes

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***Abstract*— In smart home, smart taps will be important sensors that constitute a multi-hop home sensor network. Since a smart tap is connected to a household AC (Alternating Current) power, there is no need to consider batteries. Therefore, if power-supplied nodes like smart taps are selected as relay nodes, the network lifetime will be maximized. In this paper, we propose a novel route determination scheme that preferentially selects power-supplied nodes like smart taps as relay nodes in IPv6- implemented wireless sensor network for smart home. The proposed scheme is possible to prolong the network lifetime by distinguishing between power-supplied nodes and battery-powered nodes and selecting a power-supplied node as a relay node. We evaluated the performance of our proposed scheme by simulation and experimentation. Simulation and experimentation results show that our proposed scheme prolongs the network lifetime compared to the existing scheme. We also discussed the optimum parameter of the proposed scheme.**

***Index Terms*— Wireless sensor networks, 6LoWPAN, IPV6 Routing Protocol for Low power and Lossy Network, Home Energy Management System, TelosB**

I. INTRODUCTION

WITH the rapid growth of wireless communication technologies and advanced electrical appliances in homes and offices, smart home / smart office is expected to be realized. Smart home / smart office will provide a comfortable living through automation and optimization of the living environment, by environmental sensors (e.g., temperature, humidity, light, motion, etc.) with wireless communication capabilities and electrical appliances (e.g., lighting, air conditioning, etc.) that work together to build a network via wireless communication. In wireless sensor networks, maintaining high packet delivery ratio and prolonging network lifetime are even more important than achieving high throughput and low delay. This is because, each sensor node, which is battery-powered, sends data intermittently. Therefore, HEMS (Home Energy Management System) / BEMS (Building Energy Management System) is required as one of the smart home / smart office functions. In the HEMS / BEMS, smart taps with the power measurement and wireless communication capabilities aggregate the power consumption of each electrical appliance. By displaying the user's energy consumption to aware power savings, and controlling of electrical appliances based on aggregated data, HEMS / BEMS achieves power savings. In other words, a smart tap can be considered as one of the sensors that make up a home sensor network.

Because smart home / smart office is expected to work with other ICT (Information and Communication Technology) applications such as Internet and DLNA (Digital Living Network Alliance), sensor devices that constitute a home sensor network should be able to communicate by using IP. However, IEEE 802.15.4, that is a PHY / MAC protocol used in the sensor device, is not designed for IP, so it is difficult to implement the IP over IEEE 802.15.4 mainly because of the frame size difference between these two protocols. Therefore, IETF 6LoWPAN (IPv6 over Low power WPAN) working group has defined IPv6 networking for using IEEE 802.15.4 as lower layers [1].

The 6LoWPAN newly defines the Adaptation Layer to absorb the difference between IPv6 and IEEE 802.15.4. In addition, IETF ROLL (Routing Over Low power and Lossy Network) Working Group has proposed RPL (IPV6 Routing Protocol for Low power and Lossy Network) as a routing protocol that runs on 6LoWPAN [2]. RPL is available in a variety of environments by defining route selection rules, called OF (Objective Function) depending on the application [3]. For the purpose of ease of installation, environmental sensors in home sensor networks are desired to be battery-powered. Therefore, the challenge is to prolong the network lifetime of the sensor network in order to reduce maintenance costs.

On the other hand, there is no need to consider batteries on smart tap because it is connected to a household AC (Alternating Current) power. If power-supplied nodes like smart taps are selected as relay nodes, and battery-powered nodes like environmental sensors only transmit their own sensing data, the network lifetime will be maximized. In the current version,

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several OFs of RPL have been proposed. However, there have been no research results considering the existence of power-supplied nodes and employing them to prolong network lifetime as far as we know.

This paper, which was previously presented in part at IEEE CCNC 2012 [4], proposes a novel route determination scheme that preferentially selects power-supplied nodes like smart taps as relay nodes in an IPv6-implemented wireless sensor network for smart home. The proposed scheme is possible to prolong the network lifetime by distinguishing between power-supplied nodes and battery-powered nodes and selecting a power-supplied node as a relay node under the same link conditions. The scheme proposed in [4] was evaluated by computer simulation under simple scenarios. In this paper, we evaluated the performance of our proposed scheme by simulation and experimentation. The simulation and experimentation results show that our proposed scheme prolongs the network lifetime compared to the existing schemes.

II. 6LOWPAN/RPL

A. 6LoWPAN

6LoWPAN is a protocol to communicate with IPv6 packets over IEEE 802.15.4 which is a PHY/MAC protocol for WSN. It has been discussed by the IETF 6LoWPAN Working Group and recommended as RFC4944. The main role of 6LowPAN is to define the Adaptation Layer to absorb the difference between IEEE 802.15.4 at the MAC layer and IPv6 at the network layer. For example, the maximum length of the IEEE 802.15.4 MAC frame is 127 octets, whereas the minimum MTU of IPv6 packet is 1280 octets. Thus, the packet, which is larger than 127 octets, is forwarded after the fragments at the link level by the Adaptation Layer. In addition, 25 octets MAC frame header and tailer, 40 octets IPv6 header and 8 octets UDP header are included in an IEEE 802.15.4 MAC frame. In other words, more than half of the frame length is occupied by these headers. Therefore, the Adaptation Layer appropriately compresses IPv6 and UDP headers.

B. RPL

RPL is a routing protocol for 6LowPAN developed by the IETF ROLL working group. RPL constructs a directed acyclic graph towards the sink node. This graph is called DODAG (Destination Oriented Directed Acyclic Graph). Each node transfers sensing data to the sink node along the DODAG. Figure 1 shows how the DODAG is constructed. First, the sink node sends the DIO (DODAG Information Object) message by link-local multicast as DODAG root. Nodes receiving the DIO determine their ranks according to Objective Function (OF), and then send DIO messages with their own ranks by link-local multicast. While propagating the DIO messages, each node determines the next hop to the sink node as a preferred parent from received DIO messages and its own ranks. Once DODAG is built, each node periodically sends a DIO message according to Trickle timer [7] which exponentially increases the period, and recalculates their ranks to maintain the DODAG. With representation of the network by DODAG and role of Trickle timer, RPL can reduce control packets to construct and to maintain the path. Therefore, RPL consumes less power than AODV and OLSR. OF is a set of rules used to construct DODAG (e.g., routing metrics and constraints on how to calculate the rank, and how to choose a parent). We can optionally define an OF according to the application, RPL nodes, however, must at least support the metric-less OF0 [8]. Routing metrics and constraints used in OF are defined by ROLL WG in \cite{draft-metrics}. By selecting the routing metrics and constraints depending on the purpose, RPL can be flexibly adapted to different environments. In addition, RPL also supports point-to-point communication [10]. There are two modes for point-to-point communication, storing mode or non-storing mode. In the storing mode, each node maintains a routing table to a destination node. In contrast, only DODAG root maintains routing table and performs source routing in the non-storing mode. We can choose one of these modes depending on the capabilities of the nodes. In both modes, the routing table is updated by information from the DAO (Destination Advertisement Object) messages sent upward DODAG. Figure 2 shows how the point-to-point communication at the storing mode and the non-storing mode is carried out. In the storing mode, if destination of the packet is not found in the routing table, the node forwards the packet to its parent node. When a node with information of the destination receives a packet, the node forwards packets to their destination. In the non-storing mode, all packets are sent to DODAG root at first. Then DODAG root sends the packets with routing information to their destination.

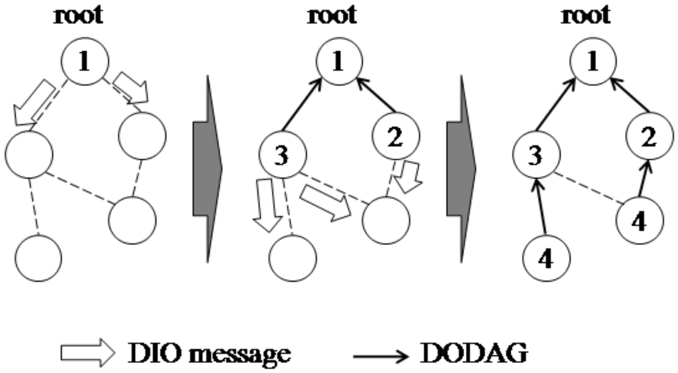


Fig. 1. DODAG construction

C. Implementation of 6LoWPAN/RPL

In the current version, 6LoWPAN and RPL, which are designed for sensor networks, have been implemented on a number of operating systems, e.g., Tiny OS [11] and Contiki OS [12]. 6LoWPAN and RPL implementations on Tiny OS are named BLIP and Tiny RPL, and those on Contiki OS are named uIPv6 and Contiki RPL, respectively [13]. Both of Tiny RPL and Contiki RPL implement OF0 and Minimum Rank Objective Function with Hysteresis (MRHOF) as Objective Function.

MRHOF uses the link ETX (Expected Transmission Count) as a routing metric. In MRHOF, nodes calculate the increase of ranks from a parent by link ETX with the parent, and select the node that minimizes its own ranks as a preferred parent node. Selecting a preferred parent and calculating own rank of a node *n* are simply represented as Eqs. (1) and (2).

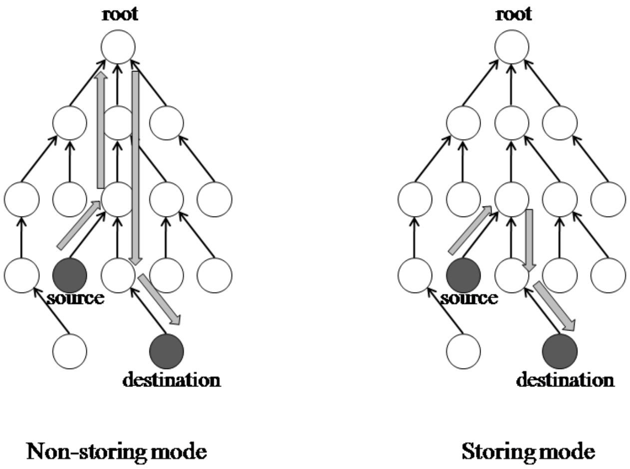
$$p_{pref}(n) = p \in P_n \mid \min[rank(n,p)], \tag{1}$$

$$rank(n,p) = rank(p, p_{pref}(p)) + ETX(n,p). \tag{2}$$

In Eq. (1), P_n denotes the set of candidate parents of the node *n*. In Eq. (2), *ETX (n, p)* is the link ETX between the node n and the candidate parent *p*. Link ETX is calculated by exponentially weighted moving average (EWMA) of the ETX value obtained from the link layer. ETX for a certain time *t* is calculated by

$$ETX(t) = \alpha ETX(t-1) + (1-\alpha)X, \tag{3}$$

where *X* is the number of transmissions, and α is a smoothing factor.



Non-storing mode **Storing mode**

Fig. 2. Point-to-point communication

III. PROPOSED SCHEME

This paper assumes an IPv6-implemented wireless sensor network for smart home as an application. In this network, environmental sensors, such as temperature, humidity, light and human presence sensors, and smart taps that measure the power consumption of each appliance transmit the sensing data of each node to the sink node. For easy installation, environmental sensors should be battery-powered. Therefore, they have to save power consumption as much as possible to extend the operating time. Meanwhile, as smart taps are connected to a household AC power, there is no need to consider the remaining power of batteries. When we implement RPL with MRHOF in these sensor nodes, for example, the DODAG shown in Figure 3 is built. In DODAG in Figure 3, the preferred parents are selected regardless of whether battery- powered or power-supplied. Battery-powered nodes selected as preferred parents increase power consumption by relaying data. As a result, the network lifetime will be shortened. Therefore, we propose the OF to select smart taps as the preferred parent node. The easiest way to select the power-supplied node as a preferred parent is to give the power-supplied node the higher rank than the rank of the battery-powered node under the same link conditions. In the proposed method, we extend Eq. (2) to Eqs. (3) and (4).

$$rank(n,p) = rank(p, p_{pref}(p)) + ETX(n,p) + C(n) \tag{4}$$

$$C(n) = \begin{cases} 0 & n \text{ is power} - \text{supplied node} \\ 1 & n \text{ is battery - powered node} \end{cases} \tag{5}$$

If a DODAG under the same conditions as shown in Figure 3 is constructed by using our proposed method as *c = 2*, the DODAG depicted in Figure 4 is constructed. In DODAG in Figure 4, all of battery-powered nodes are leaf nodes and do not relay data. Therefore, the network lifetime will be maximized.

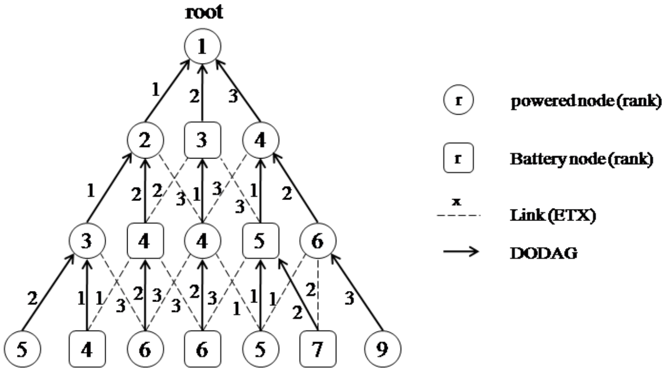


Fig. 3. Example of DODAG constructed by MRHOF

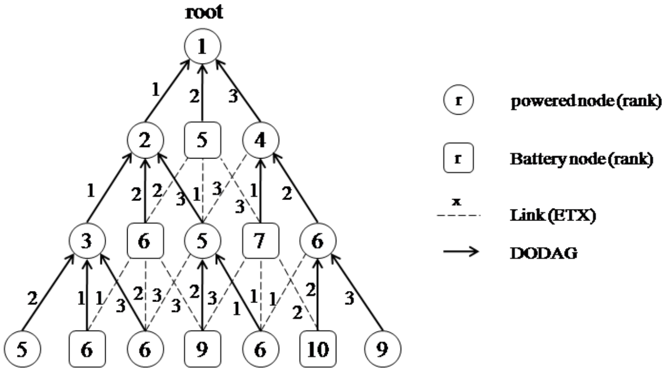


Fig. 4. Example of DODAG constructed by proposed method

IV. SIMULATION EVALUATION

In the previous work [6], we just evaluated basic performances. In [6], we assumed random topology and no frame loss. In this paper, we assume topology in regular pattern, and Unit Disk Graph Medium Distance Loss. Figure 5 shows the simulation topology. 25 sensor devises are deployed in a 5x5-rectangular pattern. The distance between neighboring nodes is 2.0 m. Node 1 is a sink node, Node 2, Node 3, Node 4, Node 6, Node 7, Node 8, and Node 9 are power-supplied nodes, and the other nodes are battery-powered nodes. Table I shows simulation parameters. Values in energy consumption are default values of Cooja. Battery capacity corresponds to 1/800 times the capacity of an alkaline battery. Transmitted signal attenuates with distance. A node on the transmission range receives a frame successfully with the RX success ratio.

In the simulation, the network lifetime and packet delivery ratio are evaluated. The network lifetime is defined as the time from network initialization to the first node failure due to battery depletion.. The packet delivery ratio is defined as the ratio of the number of received packets to that of transmitted packets.

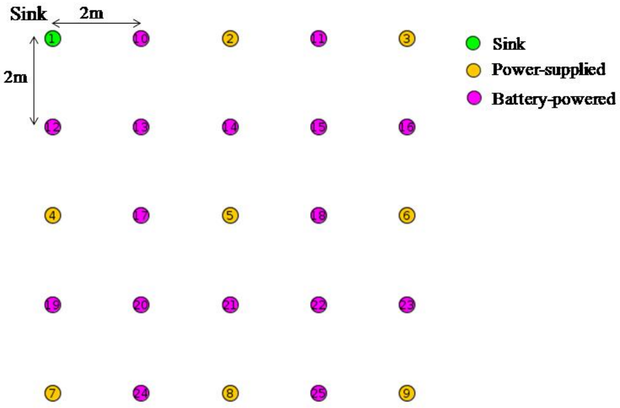


Fig. 5. Simulation topology

TABLE I
Simulation Parameters

Parameter		**Parameter Value**
Simulator		Cooja
Device model		Tmote Sky (MSP430+CC2420)
Radio medium		Unit Disk Graph Medium (UDGM) : Distance Loss
Rx success ratio		0.1, 0.4, 0.7
Radio range	Transmit	5 m
	Interference	10 m
Data size		24 Byte
Sensing interval		15 s
Energy consumption	Low Power Mode (LPM)	0.1635 mW
	CPU	5.4 mW
	Listen	60.0 mW
	Transmit	53.1 mW
Battery capacity		2.5 mAh

A. Network Lifetime

Figure 6 shows the network lifetime. $c=0$ corresponds to the conventional scheme (MRHOF). The network lifetime of the proposed scheme is about 1.5 times longer than MRHOF, when RX success ratio = 0.4 and 0.7. On the other hand, the network lifetime of the proposed scheme is almost the same as that of MRHOF, when RX success ratio = 0.1. The increase of retransmissions causes high energy consumption when the RX success ratio is low. Using $c\,(\geq 1)$ leads to selecting power-supplied node as a parent node. Thus the proposed scheme with $c=1$ is sufficient for prolonging network lifetime.

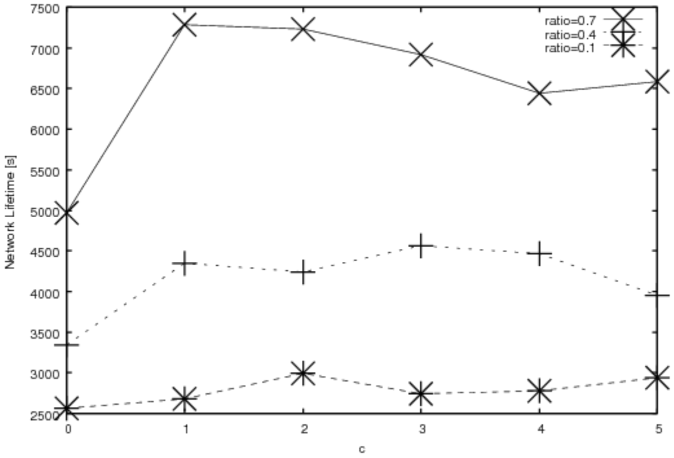


Fig. 6. Network lifetime (Simulation)

B. Packet Delivery Ratio

Figure 7 shows the packet delivery ratio of the proposed scheme and MRHOF. $c=0$ corresponds to MRHOF. The packet delivery ratio of the proposed scheme is almost the same as that of MRHOF when RX success ratio = 0.4 and 0.7. The packet delivery ratio achieves nearly 1.0. On the other hand, the packet delivery ratio of the proposed scheme degrades as c increases when RX success ratio is small. It is because power-supplied nodes in with bad communication environment are sometimes selected as parent nodes.

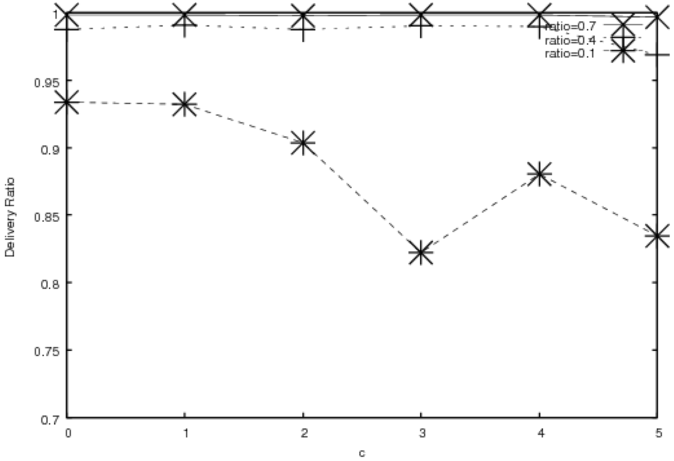


Fig. 7. Packet delivery ratio (Simulation)

C. Evaluation Index

When c is large, sensor nodes are prone to select a power-supplied node as the parent node. Using large c should increase the network lifetime. In lossy network, however, a link with bad communication environment may be selected by using large c. That causes the degradation of delivery ratio. For evaluating both packet delivery ratio and network lifetime, we use the other evaluation index as a cost function. Figure 8 shows the evaluation index of the proposed scheme. *Evaluation_Index* is defined as

$$Evaluation\_Index(c) = \frac{Lifetime(c)}{Lifetime\_MRHOF} \times Delivery\_ratio(c), \quad (6)$$

where *Lifetime(c)* is the lifetime for each *c*, *Lifetime_MRHOF* is the lifetime of MRHOF, *Delivery_Ratio* is the delivery ratio for each *c*, and *Lifetime(c)/Lifetime_MRHOF* is the improvement rate of lifetime. From Fig. 8, we found that there is an optimum *c*, which achieves high evaluation index. When RX success ratio = 0.1 and 0.7, the optimum $c = 2$. When RX success ratio = 0.4, the optimum $c = 3$.

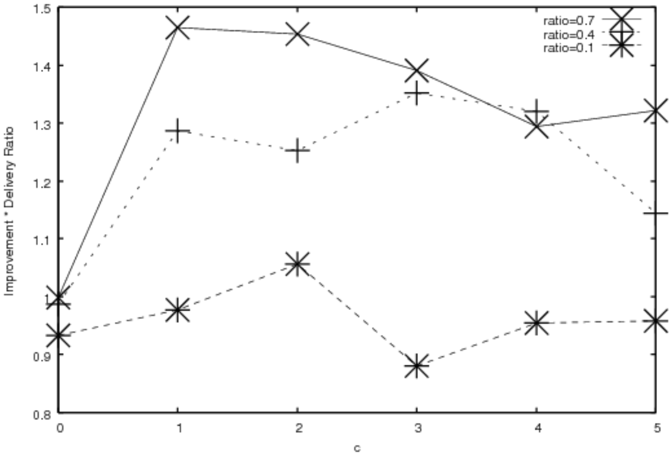


Fig. 8. Lifetime improvement ratio × packet delivery ratio versus *c* (Simulation)

V. EXPERIMENTAL EVALUATION

In order to verify the effectiveness of the proposed method, we evaluated the performance by the experimentation. In this experimentation, we use TelosB [14] as sensor devises. MSP430 and chipcon-CC2420 are implemented in TelosB as a processor and wireless-communication module, respectively. Figure 9 shows a TelosB sensor devise. Figure 10 shows the indoor experimentation topology.

20 sensor devises are deployed in a 4x5-rectangular pattern. The distance between neighboring nodes is 1.5 m. Node 1 is a sink node, Node 2, Node 3, Node 4, Node 5, and Node 6 are power-supplied nodes, and the other nodes are battery-powered nodes. There are 31 transmission-power levels in a TelosB-sensor node, as shown in Table II. In this experimentation, the transmission-power level is 4. In the experimentation, the network lifetime and packet delivery ratio are evaluated.

Fig. 9. Sensor device

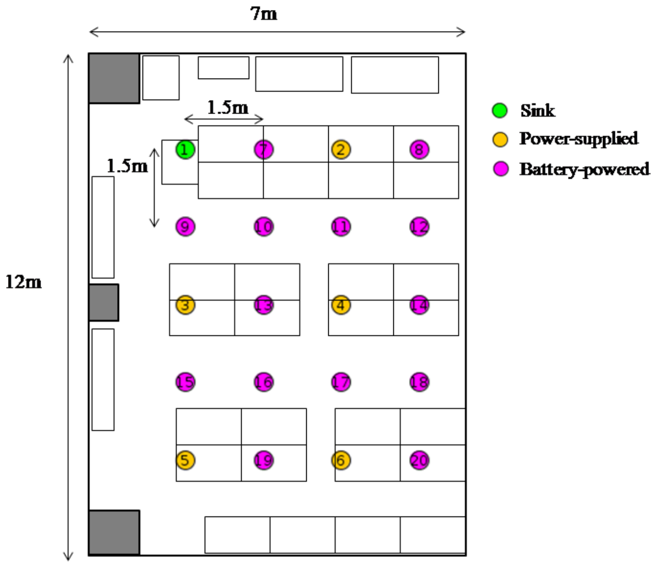


Fig. 10. Experimentation topology

Table II
Transmission-power Levels in a TelosB Sensor Node

Value	Level
1	Lowest
31	Highest

A. Network Lifetime

Figure 11 shows the network lifetime of the proposed scheme and the conventional scheme (MRHOF). It can be seen that the effect of prolonging the network lifetime is small when c is small, because the rank of battery-powered nodes does not increase sufficiently. In the experimental environment, the difference of ETX for each link is large. Thus, using large c leads to selecting power-supplied node as a parent node. However, in case that c is too large, power-supplied node, which has low link quality, can also be selected. That causes the increase in retransmissions. Thus, there is an optimum *c* in the proposed scheme. The network lifetime was the longest at *c = 4*. The network lifetime of the proposed scheme is about 1.5 times longer than MRHOF.

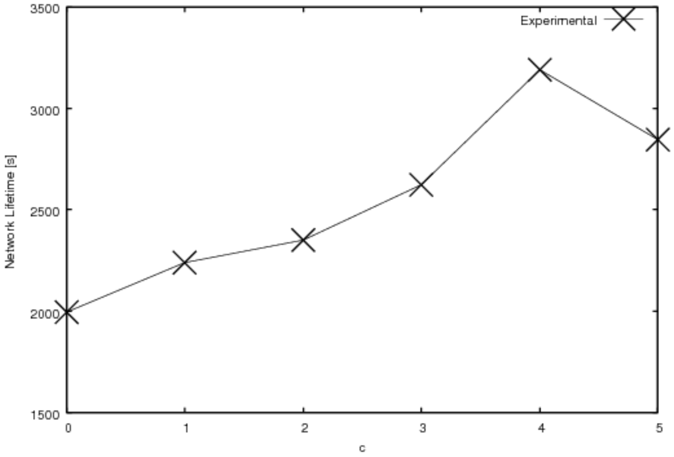
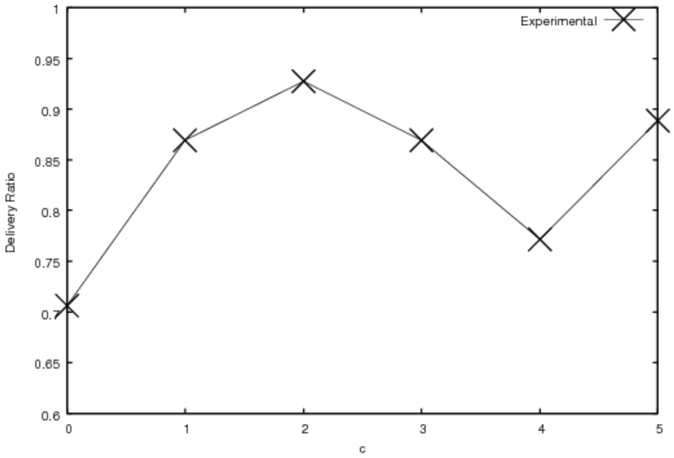


Fig. 11. Network lifetime (Experimentation)

B. *Packet Delivery Ratio*

Figure 12 shows the packet delivery ratio of the proposed scheme and MRHOF. The packet delivery ratio of the proposed scheme is better than that of MRHOF. Thus, the proposed scheme can maintain more stable route than MRHOF. In the experimental environment, ETX is sometimes unstable. MRHOF, which selects a preferred parent based on only ETX, often reconstructs the DODAG. This causes the increase in the number of packets, which do not arrive in the sink node. On the other hand, the proposed scheme decides a preferred parent based on not only ETX but also *c*. Thus the proposed scheme reconstructs DODAG much less than MRHOF.



Fig, 12. Packet delivery ratio (Experimentation)

C. *Evaluation Index*

When *c* is large, sensor nodes are prone to select a power-supplied node as the parent node. Using large *c* should increase the network lifetime. In a lossy network, however, a link with poor communication environment may be selected by using large *c*. That causes the degradation of delivery ratio. Thus, as well as simulation, we show the evaluation index, which is expressed as Eq. (6). Figure 13 shows the evaluation index of the proposed scheme. Compared with the simulation, the network lifetime increases drastically by using large *c*. Thus, the evaluation index also increases as *c* is large. In the experimentation, the optimum *c* is 5.

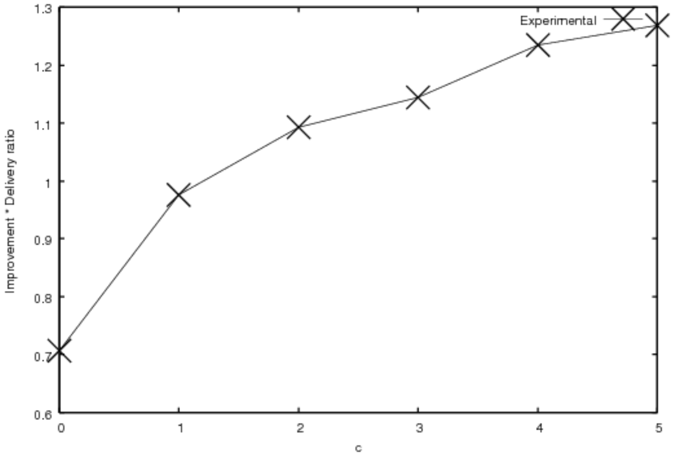


Fig. 13. Lifetime improvement ratio × packet delivery ratio versus *c*

VI. CONCLUSION

In this paper, we propose the OF in the RPL to increase network lifetime in an IPv6-implemented wireless sensor network for a smart home. Our proposed method selects power-supplied nodes such as smart taps as preferred parents under the same link conditions by adding constant value, *c*, to the ranks of the battery-powered nodes. Additionally, we compared our proposed method with MRHOF by simulation and experimentation. In the experimentation, we use TelosB as sensor devises. We showed the increase in the network lifetime, the delivery ratio, and the evaluation index, taking into account the improvement of lifetime and the delivery ratio. We also showed the optimum parameter, *c*, for simulation and experimentation.

As a next step of research, we should consider more useful routing metrics, which can cope with sudden communication-environment degradation, and the method to find optimum value of *c* theoretically.

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