Implementation of Energy Saving Mechanisms for Sensor Networks with SunSPOT Devices

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***Abstract*—A sensor network is a technique where many distributed sensor devices with a sensing system collect various information. In sensor networks, it is important to extend the lifetime of sensor devices with small batteries for long-term observation. In this paper, we propose an energy-efficient protocol for field sensor networks and implement the proposed protocol on SunSPOT devices which are small wireless sensor devices produced by Oracle. The developed devices can observe an environment periodically, and inform observed data information to a sink device by multi-hop communication technology. Additionally, the developed devices switch to sleep mode during a non-communication period to reduce consumed power. From the experimental trials, we show that the developed devices can extend the lifetime of sensor devices by reducing energy consumption.**

I. Introduction

Field sensing is one of candidate applications of distributed sensor networks. In field sensor networks, each sensor device observes environmental conditions periodically, and reports observed information to a sink device which is a special data collection device, by using multi-hop communication Moreover, long-lived networks are required in field sensor networks for the long term environmental observation. Researches about energy saving mechanisms for achieving long-lived networks are classified into two categories.

The first one is at the Media Access Control (MAC) layer [1][2]. In many sensor network applications, devices are in the idle state for a long time when no sensing event happens. For almost all devices, the energy consumption of receive mode is on the same order of size as the energy consumption of transmission mode. Additionally, most MAC protocols keep the receive mode even when devices need not receive messages. This problem is called the idle-listening problem. Given the fact that few messages are transmitted during the period, this procedure is the waste of energy. Therefore, sensor devices should turn off some circuits to reduce consumed energy at the MAC layer when they are not required for communication to solve the idle-listening problem. MAC protocols with sleep operation are classified into two types: Contention based and Scheduling based [3]. In the scheduling based protocol, the transmission timing of each sensor device is scheduled, thus sleep operation at a non-communication period can be effectively performed. However, because each sensor device performs transmission within decided time slot, time synchronization is required. In the Contention based protocol, each sensor device switches ON or OFF randomly, thus this protocol has scalability. This means that this protocol can easily adjust to the topology changes as some new nodes may join and others may die. However, because each sensor device cannot recognize transmission timing, sleep period is shorter than that of the scheduling based protocol. From these reasons, the MAC protocol which is matched two type protocols is required.

The second one is at the network layer, where sensor devices find optimum routes for low-energy consumption to convey observed information[4]. In field sensor networks, each sensor constructs routes to convey own observed information to a sink and there are many routes leading to a sink. Considering energy consumption, finding optimum routes is important in field sensor networks [5]. Therefore, sensor devices find routes minimizing energy consumption at the network layer. Several ways to find optimum routes are researched. In the conventional study, measuring RSSI, checking link quality, and checking hop count have been considered[6]-[8].

These mechanisms are the effective approach to reduce energy consumption. However, devices for sensor networks have only a small battery and small computational capability. Therefore, these mechanisms will be difficult to implement for actual sensor network devices. Additionally, among these researches, various performance has been evaluated with many sensor devices by computer simulations. On the contrary we have focused on practical performance of sensor networks to achieve the specific application such as the environmental observation [9].

In this paper, we propose an energy-efficient routing protocol for field sensor networks and implement the proposed protocol on SunSPOT devices [10][11]. Our proposed protocol is the cross-layer mechanism which is matched a routing protocol and a MAC protocol. We define an original frame format for packet transmission in order to reduce packet collision, and employ the sleep mode of sensor devices when they do not communicate with neighbor sensor devices. Additionally, each sensor device constructs routes to a sink device by exchanging routing information with neighbor sensor devices. This protocol reduces the number of route control packets, thus it is easy to implement in small devices. From the experimental results, we show that the proposed implementation can extend the lifetime of sensor networks for periodical environmental measurement.

II. System model

A. Hardware

In the assumed sensor networks, sensor devices operate with a battery and solar energy generation. All SunSPOT devices observe an environment periodically by using some sensors, and inform observed data information to the SunSPOT base station. Additionally, we produce an original interface board for SunSPOT to connect some sensors. Figure 1 shows the

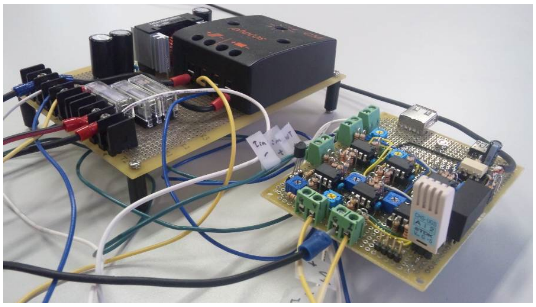

Fig. 1. SunSPOT with interface boards.

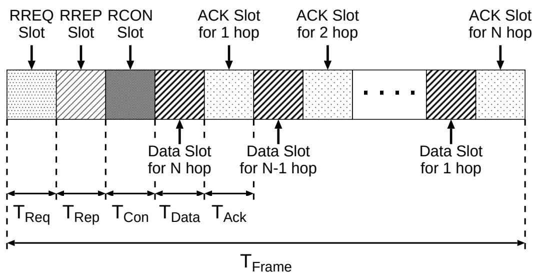

Fig. 2. Frame format.

interface board for SunSPOT. SunSPOT and the interface boards are operated with energy from a built-in battery of the sensor. SunSPOT devices can control energy of whole sensor circuits and some parts of sensors. Our proposed protocol focuses on the effectiveness of energy consumption by autonomous energy control of sensor devices.

B. Frame format

In the proposed protocol, we employ the special frame format in Fig. 2. Features of the frame format are dividing the frame into some time slots for desired purposes, and reducing collision probability. Here, because sensor devices support Carrier Sense Multiple Access(CSMA) mechanisms, they can transmit packets autonomously in each time slot. Additionally, in order to avoid the packet collision, each sensor device wait for a random backoff time before starting to send packets in each time slot. The purposes of each slot are described as follows.

- RREQ (Route REQuest) slot
  The RREQ slot is used for requesting a new route from sensor devices without available routes to the sink. In this slot, only RREQ packets, which are used for requesting a new route to neighbor devices, are transmitted by sensor devices.

- RREP (Route REPly) slot
  The RREP slot is used for replying hop count information to sensor devices that requested a new route. In this slot, only sensor devices with available routes can reply RREP packets.

- RCON (Route CONstruction) slot
  The RCON slot is used for route construction process between sensor devices. In this slot, three types of control messages are introduced to construct a route: First, RCREQ(Route Construction REQuest) packets are used for requesting a new route to a neighbor device if sensor devices do not have an available route to the sink device. Second, RCREP(Route Construction REPly) packets are used for replying to the downstream sensor device that transmitted RCREQ. Third, RCACK(Route Construction ACKnowledgement) are used for confirming the route construction to the upstream device.

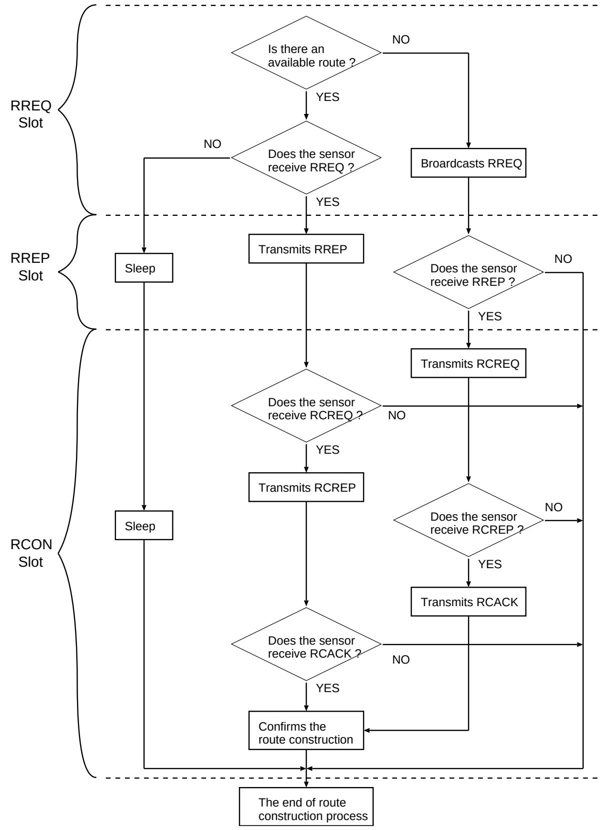

Fig. 3. Sleep operation in route construction process.

- Data slot
  The data slot is used for data packet transmission of observed environmental information and forwarding of data packets from downstream sensor devices to an upstream a sensor device. To reduce packet corruptions, the data slot is divided into some sub-slots according to hop count from the sink devices. In order to achieve smooth forwarding of data packets from faraway sensor devices to the sink, the order of data sub-slot is set in a reverse order according to the number of hop counts.

- ACK(ACKnowledgement) slot
  The ACK slot is used for transmission of ACKs, which is a reply to incoming data, to sensor devices that transmit the data. The ACK slot is also divided into some sub-slots according to hop count from the sink devices. Contrary to data sub-slot, the order of ACK sub-slot is set in order according to the number of hop counts.

C. Sleep operation

SunSPOT has a sleep operation mode that can reduce consumed energy. In the proposed system, sensor devices switch to the sleep mode to reduce consumed energy when they do not perform communication.

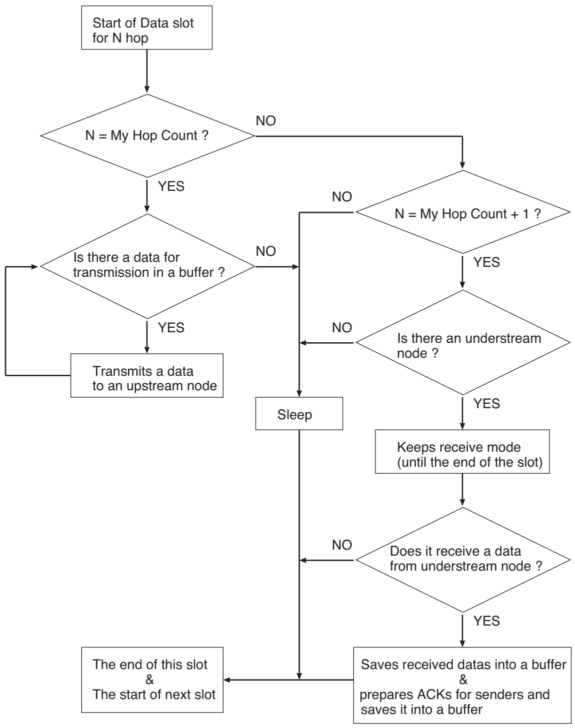

Fig. 4. Sleep operation in data transmission process

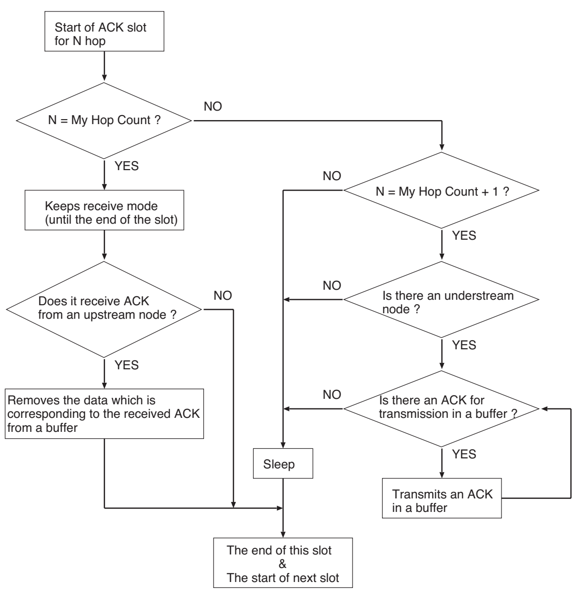

Fig. 5. Sleep operation in ACK transmission process

Figure 3 shows the flowchart of sleep operation for route construction process. In the RREQ slot, a sensor which has no available routes broadcasts a RREQ to neighbor sensor devices. Then, neighbor devices with an available route listen to the RREQ from the device. In the RREP slot, devices which have received the RREQ from the device in the RREQ slot transmit a RREP as a reply. In the RCON slot, a sensor device with no available route which have received the RREP in the RREP slot constructs a route by transmitting a RCREQ, a RCREP and a RCACK. Here, the device which does not receive a RREQ from neighbor devices does not request a route construction process. Therefore, remaining of listening to

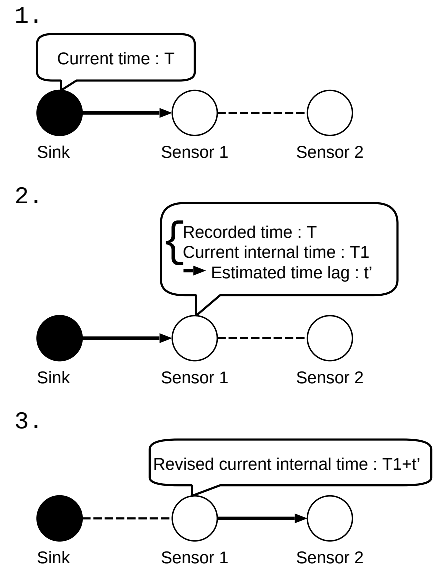

Fig. 6. Synchronous processing

a channel causes waste of energy. Then, they remain sleeping until the end of route construction process period.

In the proposed frame format, the data and the ACK slots are divided into some sub-slots according to the number of hop counts, and each sensor transmits and receives packets in the sub-slots where the sensor is allowed to perform transmission. Each sensor sleeps in data or ACK slots where downstream devices and itself do not perform communication. In addition to those mentioned above, there are some cases where the sensor can sleep. We describe this in the following explanation.

Figure 4 shows the flowchart of sleep operation in the data slot. In the data slot of own hop count, sensors transmit data, which are monitored by itself or transmitted by downstream devices, to an upstream device. Then the sensors sleep in the slot if they do not have new data to transmit in the buffer.

In the proposed transmission, the upstream device transmits an ACK to the downstream devices as a reply when they receive data from downstream devices. Therefore, sensors keep the data in buffer until they receive an ACK from the upstream device.

Here, sensor devices without downstream devices sleep in the slot because they need not listen to a channel.

Figure 5 shows the flowchart of sleep operation in the ACK slot. In the ACK slot for own hop count, sensors receive an ACK and remove the transmitted data from the buffer. In the ACK slot for own downstream devices, the sensors transmit an ACK when they receive data from downstream devices. Here, sensors without downstream devices sleep in the slot because they do not have any ACKs to transmit to the downstream devices.

D. Synchronous processing

Our protocol assumes the situation where each sensor device recognizes transmission timing by using an internal time-clock. In order to achieve frame operation, it is required that internal time in each device is synchronized. However, in actual devices, the internal time of each sensor device is not synchronized and the time lag between devices increases with the passage of time. In order to solve this problem, we employ synchronous processing.

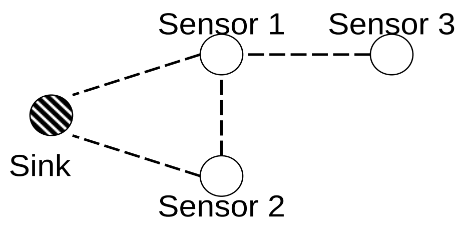

Fig. 7. Assumed device location.

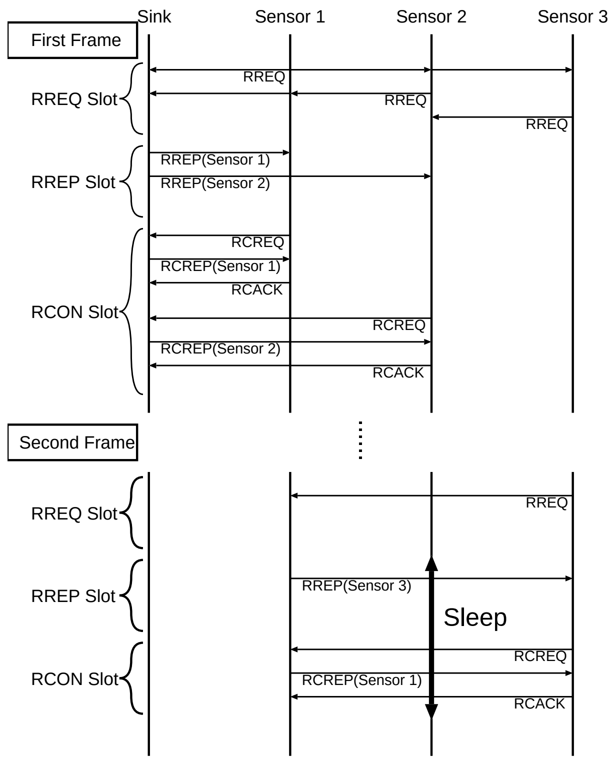

Fig. 8. Example of route construction process and sleep operation.

In this processing, each sensor device recognizes the internal time of the sink as base time and attempts to synchronize with that. This processing is executed regularly in the second half of the RREQ slot. Figure 6 shows the process of proposed synchronous processing. The process of this operation is described as follows.

1) The sink transmits the message-packet which contains current time information to downstream devices.
2) The sensor devices which receive the message-packet estimate the time-lag between itself and the sender by comparing the internal time and the time in the message-packet. Additionally, the sensor devices revise the internal time by using the estimated value and it performs timing control with the revised internal time.
3) In the next frame interval, the sensor devises which have revised internal time transmit the message-packet with current time to downstream devices. By continuing the above-mentioned process until the message-packet arrives to end devices, all sensor devices attempt to synchronize the internal time with the time of the sink.

III. Example operations

We describe example operations of route construction processes and data transmission processes. In this example, we assume the location of the sensor devices in Fig. 7. In this location, Sensor 1 can communicate with the sink, Sensor 2, and Sensor 3. The Sensor 2 can communicate with the sink and the Sensor 1. The Sensor 3 can communicate only with the Sensor 1.

A. Route construction process

Figure 8 shows an example of packet transmission in route construction process with the device location in Fig. 7. In this figure, arrow lines indicate packet transmission by unicast or broadcast. At the RREQ slot, Sensor 1, 2 and 3 which have no available route broadcast the RREQs to neighbor sensor devices. Then, the sink is an only device with an available route in this example. Therefore, the sink transmits the RREPs to Sensor 1 and 2 which transmitted the RREQs in the RREP slot. On the contrary, Sensor 1 does not transmit the RREP to Sensor 3 because they do not have available routes to the sink at this moment. In the proposed system, sensor devices select neighbor sensor devices with the minimum hop count as their own upstream device, and the sensor device that transmits the RREP first is selected if the hop count has the same value. Therefore, Sensor 1 transmits the RCREQ to the sink to start route construction processes. The sink replies the RCREP to Sensor 1 in order to confirm that its own device is selected as the upstream device. Finally, Sensor 1 transmits the RCACK to the sink to complete the route construction. Sensor 2 performs to construct a route as Sensor 1.

In the proposed frame format, routing control slots are allocated at the beginning of frame interval. Therefore, sensor devices which locate far from the sink construct a route at coming frame intervals. As a results, Sensor 3 transmits the RREQ again at the next frame interval. Sensor 1 transmits the RREP to Sensor 3 because it has the available route. In the RCON slot, Sensor 3 constructs a route with Sensor 1. On the contrary, Sensor 2 which has the available route dose not receive a RREQ from neighbor devices. Therefore, Sensor 2 sleeps in the RREP slot and the RCON slot because it is not required for transmission of route control messages.

B. Data transmission process

Figure 9 shows an example of packet transmission in data transmission processes with the device location in Fig. 7. In this figure, arrow lines indicate packet transmission by unicast. In proposed protocol, the data and ACK slots are divided into some sub-slots according to hop counts. Figure 9 assumes that the maximum hop count is set to two.

At first, we describe packet transmission. At data slot for 2 hop devices, Sensor 3 with two hops transmits the data packet to Sensor 1. Sensor 1 recognizes that it should forward the data packet from Sensor 3 because the route construction between two devices was completed at the RCON slot. Therefore, Sensor 1 saves the received data into its own data-buffer. Then, Sensor 1 and 2 transmit their data to the sink at data slot for 1 hop devices. Additionally, Sensor 1 transmits the received data from Sensor 3 to the sink. In the proposed protocol, ACKs are transmitted from the sensor or sink to the downstream device to confirm the successful data transmission from sensors. Therefore, the sink transmits two ACK to sensors with one hop

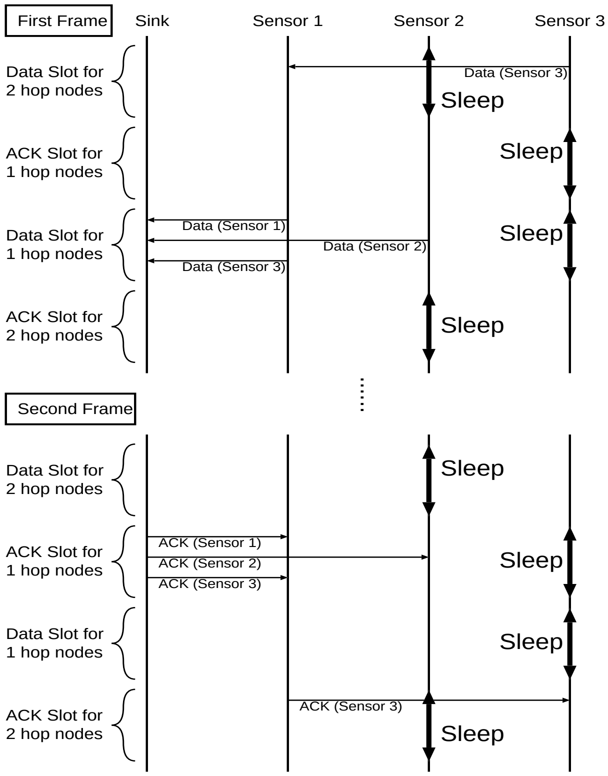

Fig. 9. Example of data transmission process and sleep operation.

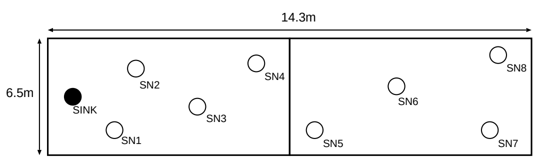

Fig. 10. Location of sensor devices.

at ACK slot for 1 hop devices. Sensor 1 and Sensor 2 recognize that transmission of own data is completed successfully. Then, Sensor 1 transmits ACK to Sensor 3 to confirm the successful data transmission from Sensor 3 to its own at ACK slot for 2 hop devices.

Here, in the proposed data transmission, each sensor device retransmits the same data packet until it receives an ACK packet, thus the data arrival ratio of our protocol is 100%. Additionally, because of framework, the transmission delay may be caused. But, it is not a very serious problem because this delay is kept below a few frames and the target of our protocol is the network which realizes 100% data-arriving.

Here, all sensors sleep in data and ACK slot except for the slots in Fig. 9 if the maximum hop count is larger than two. Additionally, Sensor 2 has no downstream device, thus it sleeps in data and ACK slot for 2 hop devices where it is required for communication with downstream device with 2 hop count. On the other hand, Sensor 3 is 2 hop from the sink, thus it sleeps in data and ACK slot for 1 hop devices.

IV. Experimental results

In order to evaluate the performance of the proposed protocol, we perform experimental trials with SunSPOT devices. In the experiment, each sensor device observes own battery voltage every five minutes interval. Then, it transmits the observed data to the sink device and retransmits again if ACK is not received. Eight sensor devices and a sink device are installed in the laboratory as Fig. 10. In this evaluation, in order to focus on energy consumption of the sensor devices, each sensor device has no battery supply. Table I shows the detailed parameters.

TABLE I
Experimental parameters.

Sensor device	SunSPOT
Number of devices	8
Monitor interval	5 [minute]
Monitor period	5 [hour]
T_{Frame}	60 [second]
T_{Req}	1 [second]
T_{Rep}	3.5 [second]
T_{Con}	5.5 [second]
T_{Data}	2.5 [second]
T_{Ack}	2.5 [second]
Maximum hops N	10
Transmission power	-10 [dB]
Size of data packet	140 [Byte]
Size of ACK packet	122 [Byte]

Figure 11 shows average amount of time-revision of sensor devices. From the results, we can find that the amount of time-revision increases with the passage of time. The internal time of each sensor device is almost synchronized at the beginning. However, the time-lag between devices increases with the passage of time. Therefore, sensor devices have to perform a big revision of the internal time.

Figure 12 shows the amount of average hop count of each sensor device. From the results, we can find that the hop count from the sink device is not stable. The reason for this is that each sensor device reconstructs the constructed route in case it receives RREQ from its own upstream device or it retransmits data packets many times. Therefore, if the sensor device reconstructs a new route with the other device, the hop count may be changed.

Figure 13 shows the amount of battery voltage drop of each sensor device. Additionally, figure 14 shows transition of battery voltage of sensor devices. This value means the amount of the dropped battery voltage by each sensor device through the 5-hour experiment. From the results, each sensor device with sleep operation can reduce the amount of battery voltage drop about a half of that of devices without sleep operation. The reason for this is that sensor devices with sleep operation sleep while they are not required for communication, and can reduce wasteful energy consumption.

Figure 15 shows the normalized number of transmitted data packets per number of observations. This value means the number of required data packet retransmission for informing one observed data. From the results, each sensor retransmits some data packets even if they are located near the sink device. This is caused by the noise from some computers and IEEE 802.11 devices that operate in the room. Therefore, some data packets or ACKs are lost due to the interference. As a results, the number of retransmission increases. Additionally, if many sensor devices transmit packets toward a single device, it is possible that some packets are lost because of a congested traffic and interaction. From the results, we can find that the results in the case with or without sleep operation show similar performance. Here, the same transmission protocol is used

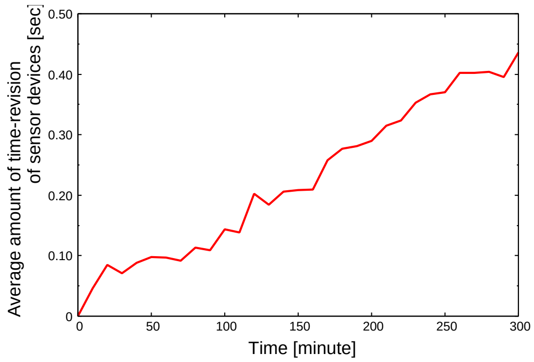

Fig. 11. Average amount of time-revision

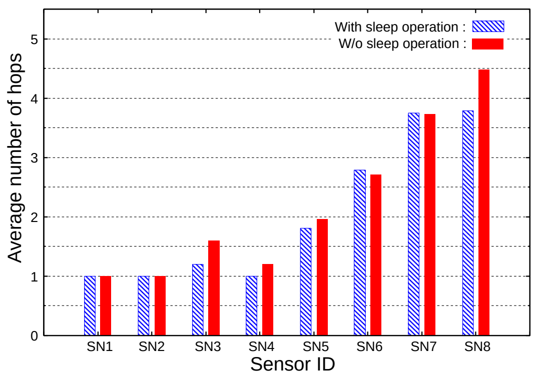

Fig. 12. Average hop count

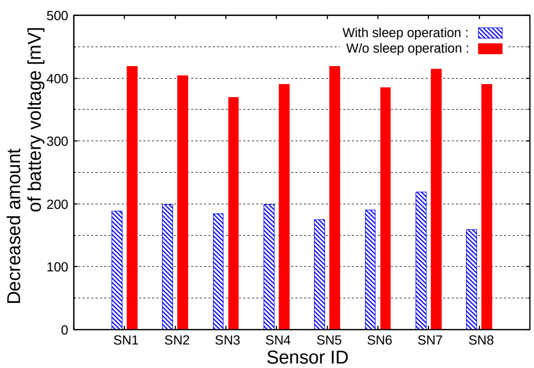

Fig. 13. Energy consumption

in the two cases and the difference between two cases is only sleep operation at non-communication period. Therefore, this result means that the transmission performance is kept even if the proposed sleep operation is employed and the performance is changed because of the effect from surrounding environment.

V. Conclusion

In this paper, we have proposed an energy-effective protocol for field sensor networks and evaluated practical performance by using SunSPOT. Our protocol is easy for small sensor devices to implemented. From the experimental trials, we could find that the proposed protocol can reduce energy consumption and extend the lifetime of the sensor devices. Our future work is the proposal of a load-balanced routing protocol for avoiding traffic concentration.

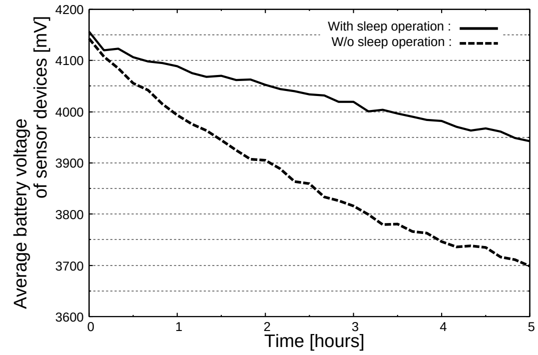

Fig. 14. Transition of average battery voltage of sensor devices

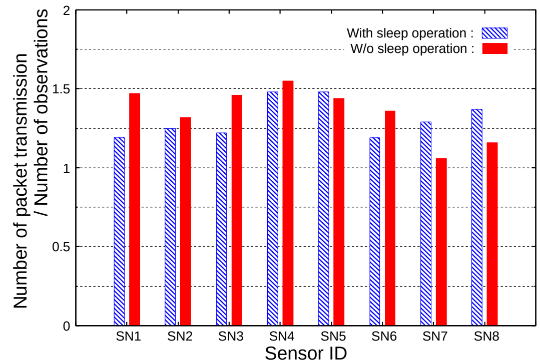

Fig. 15. Number of transmitted packets per data packets

Acknowledgment

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References

[1] W.Ye, J. Heidemann and D.Estrin, "An Energy-Efficient MAC protocol for Wireless Sensor Networks," IEEE INFOCOM 2004, pp.1567-1576, Jun. 2002.
[2] S. Ramakrishnan, H. Huang, M. Balakrishnan, and J. Mullen, "Impact of sleep in a wireless sensor MAC protocol," VTC2004-Fall. 2004 IEEE 60th Vehicular Technology Conference, vol. 7, pp. 4621–4624, Sept. 2004.
[3] R. Yaday, S. Varma and N. Malaviya, "A survey of MAC protocols for Wireless Networks," UbiCC journal, vol.4, no.3, Aug. 2009.
[4] Q. Cao, T. He, L. Fang, T. Abdelzaher, J. Stankovic and S. Son, "Efficiency Centric Communication Model for Wireless Sensor Networks," IEEE INFOCOM 2006, pp.1-12, Apr. 2006.
[5] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," IEEE Wireless Communications, pp. 6-28, Dec.2004.
[6] R. C. Shah and J. M. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," IEEE WCNC 2002, pp.350 - 355, Mar. 2002.
[7] Jyh-Cherng Shieh, Tzu-Yun Lai, Cheng-Long Chuang, En-Cheng Yang, Kuo-Chi Liao, Jyh-Rong Tasy, Wu-Huan Hsu, Joe-Air Jiang, "Study of routing path reliability for static outdoor wireless sensor network in ecological monitoring," ISMAB, April 2010.
[8] C. Schurgers and M. B. Srivastava, "Energy efficient routing in wireless sensor networks," MILCOM Proc. Communications for Network-Centric Operations: Creating the Information Force, pp. 357-361, 2001.
[9] R. Cardell-Oliver, K. Smettem, M. Kranz, K. Mayer, "Field testing a wireless sensor network for reactive environmental monitoring," Intelligent Sensors, Sensor Networks and Information Processing Conference 2004, pp. 7 - 12, Dec. 2004.
[10] K. Naito, M. Ehara, K.Mori and H. Kobayashi, "Implementation of field sensor networks with SunSPOT devices," IPSJ ICMU 2010, Apr. 2010.
[11] URL:http://www.sunspotworld.com