Implementation of field sensor networks with Sun SPOT devices

Katsuhiro Naito†, Masaki Ehara‡, Kazuo Mori†, and Hideo Kobayashi†

†Department of Electrical and Electronic Engineering, Mie University
1577 Kurimamachiya, Tsu, Mie, 514-8507, Japan, {naito, kmori, koba}@elec.mie-u.ac.jp
‡School of Computer Science, Tokyo University of Technology
Katakuramachi 1404-1, Hachioji, Tokyo 192-0982, Japan, masaki@fpma.jp

ABSTRACT

An environmental observation system is a candidate application of sensor networks. A field sensor network for the environmental observation is also an effective system for green computing. In this paper, we propose a simple routing protocol and a frame structure for field sensor networks. Then we implement the proposed protocol on Sun SPOT devices, which are small wireless sensor devices produced by Sun Microsystems. The experimental sensor devices implement some sensors for measurements of temperature, humidity, and solid moisture. The proposed devices can observe environment periodically, and inform observed data information to a sink device by multi-hop communication technology. From the experimental trial, we show that the produced devices can construct the field sensor networks with high reliability for periodical observation.

Keywords: Field sensor networks, Environmental observation, Multi-hop routing, Sun SPOT

1 Introduction

The availability of micro-sensors and low-power wireless communications will enable deployment of distributed sensor networks [1], [2]. A field sensor network 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. Since transmission range of sensor devices is limited, multi-hop communication is used to convey observed information between sensor devices and a sink device. Moreover, low-power consumption is one of required functions to achieve long-lived networks [3].

Foremost purpose of sensor networks is development of long-lived sensor networks in spite of energy constraints of sensor devices [4]. Researches about power saving mechanisms are classified broadly into two categories. The first is at the Media Access Control (MAC) layer, where sensor devices turn off some circuits to reduce consumed power when they are not required for communication [5]–[7]. The sensor devices periodically wake up to communicate with neighbor devices in almost all researches. The MAC layer approach is the effective scheme to reduce power consumption for several sizes of sensor networks.

The second is at the network layer, where sensor devices find optimum routes for low-power consumption to convey observed information [8]–[10]. However, various types of control information should be transferred for finding routes minimizing power consumption. Moreover, complexity for route construction process will increase according to increasing of network sizes. Generally, devices for sensor networks have a small battery and small computational resources [11]. For these reasons, complex computational procedures will be difficult to implement for actual sensor network devices.

Among these researches, various performance has been evaluated with many sensor devices by computer simulations [12]. On the contrary, we focus on practical performance of sensor networks to achieve the specific application such as environmental observation systems. This is because evaluation of practical performance is important to achieve a reliable environmental measurement [13]. In the environmental measurement, periodical observation of temperature, humidity, solid moisture, etc. is required. Additionally, an autonomous-operation capability is also important to set up of sensor devices exteriorly.

In order to achieve an easy installation of sensor devices, wireless communication technology is an optimum method for exchanging data between sensor devices. As it is now, IEEE 802.11 [14] and IEEE 802.15.4 [15] are famous candidate standards for wireless sensor networks. IEEE 802.11 can achieve high transmission rates. Therefore, it is optimum to collect a large size of information such as pictures or movies. However, it is known that power consumption of IEEE 802.11 devices is especially high. So, it is difficult to achieve autonomous operations without a large scale generator such as large solar panels. In this paper, we intend a measurement of small size of information such as temperature, humidity, solid moisture, etc. Therefore, transmission rates of IEEE

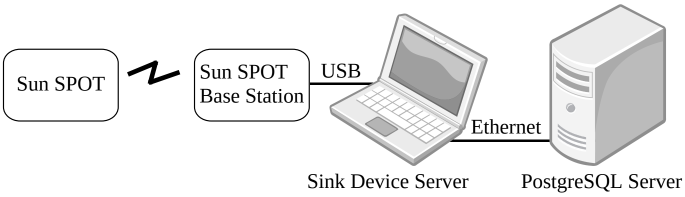

Figure 1: System model.

802.15.4 are enough performance for this purpose. Moreover, we can utilize low-power consumption performance of IEEE 802.15.4 to achieve autonomous operations.

In this paper, we implement the field sensor network devices based on Sun SPOT [16], which is a small sensor device produced by Sun Microsystems. Implementation functions are classified into three parts. First part is access control mechanisms to wireless channel. In the proposed function, we define an original frame format for packet transmission in order to improve packet collision performance. Moreover, our proposed format is well-suited for reducing power consumption by turning off some circuits. Second part is routing mechanisms between sensor devices and a sink device. In the proposed protocol, each sensor device exchanges routing information with neighbor sensor devices. Then, it manages a route to its upstream sensor device and routes to some downstream sensor devices. Mechanisms of our protocol are especially simple. Therefore, it is easy for small sensor devices to implement the proposed protocol. Third function is environmental measurement mechanisms by using general sensors. In order to connect some general sensors, we produce a special sensor interface board connecting to the interface of Sun SPOT. With this sensor interface board, we can connect any general sensors to Sun SPOT devices by converting voltages from sensor output to input interfaces. From the experimental trial, we show that our implementation can construct the reliable field sensor networks for periodical environmental measurement.

2 System Model

Figure 1 shows the system model of the proposed system. Our system consists of many Sun SPOT devices, one Sun SPOT base station device with a sink device server and one database server. Therefore, we create two applications for the Sun SPOT devices and the Sun SPOT base station device respectively. In the proposed system, all Sun SPOT devices observe environment periodically by use of some sensors, and inform observed data information to the Sun SPOT base station device by multi-hop communication technology. The Sun SPOT base station device replies acknowledgement

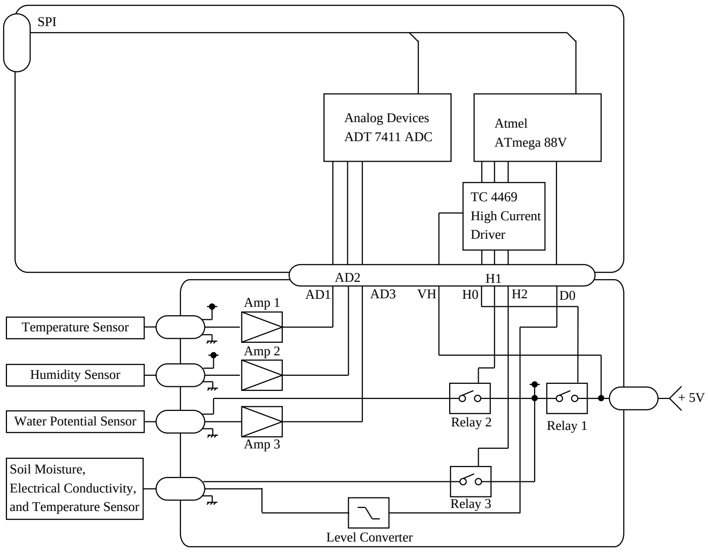

Figure 2: Interface board circuit.

Figure 3: Interface board connecting to Sun SPOT.

packets to Sun SPOT devices when it receives observed data information. Then, it registers the receive observed data information to the database server.

Figure 2 shows the overview of the sensor interface circuits. In order to connect some general sensors to Sun SPOT devices, we produce special interface boards connecting to the Sun SPOT eDemo board. Our sensor interface boards implement power management circuits for some circuits or sensor devices, voltage conversion circuits for adapting output voltage of sensors to input voltage of the eDemo board interface. Therefore, Sun SPOT devices can control power of whole sensor interface circuits and some parts of sensors.

The sensor interface boards connect to the interface connector of the eDemo board, which is the standard interface board of Sun SPOT as Fig. 3. The interface connector of the eDemo board supplies power for external devices. Therefore,

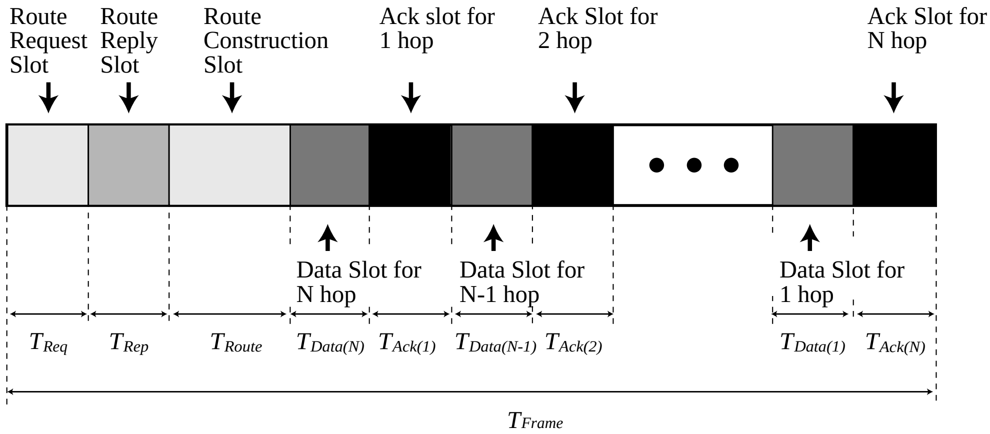

Figure 4: Frame format.

the sensor interface boards can operate by this power supply from the eDemo board if consumed power is small. Additionally, our interface boards implement a DC connector for external power supply. Then, general sensor devices can connect to our boards.

3 Media access control

Sun SPOT devices support some routing protocols such as Ad hoc On demand Distance Vector (AODV) [17]. However, cross layer approaches between a data-link layer and a network layer are important in order to achieve reliable sensor networks. In this paper, we implement original mechanisms about media access control and routing function.

In the actual wireless communication, wireless channel status changes frequently. Therefore, some signals from sensor devices may interfere with each communication. As a result, collision avoidance mechanisms for interference problems are important in sensor networks.

In the proposed system, we employ the special frame format in Fig. 4. Features of the frame format are dividing the frame into some time slots for desired purposes, and reducing collision probability. The frame format is assumed to repeat in intervals of T_{Frame}. T_{Frame} consists of the route request slot T_{Req}, the route reply slot T_{Rep}, the route construction slot T_{Route}, the data transmission slot for n hops from the sink device $T_{Data(n)}$, and the acknowledge transmission slot for n hops. Where n is a number of hop count from sink devices and N is an assumed maximum hop count. Sensor devices support Carrier Sense Multiple Access(CSMA) mechanisms. Therefore, they can transmit packets autonomously in each time slot. Moreover, our proposed format is well-suited for reducing power consumption because nodes can decide to turn off circuits by checking the route request slot and hop count information. The purposes of each slot are described as follows.

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

- Route reply slot
  The route reply slot is used for replying hop count information to sensor devices that request a new route. Only sensor devices with available routes can reply route reply (RREP) control packets in this slot.

- Route construction slot
  The route construction slot is used for route construction process between sensor devices. In the route construction process, three types of control messages are introduced to construct a route; a route construction request (RCREQ) control packet, a route construction reply (RCREP) control packet, and a route construction acknowledgement (RCACK) control packet.

- Data transmission slot
  The data transmission slot is used for data packet transmission of observed environmental information and forwarding of data packets from downstream sensor devices to upstream sensor devices. The data slot is divided into some sub-slots according to a number of hops n from the sink device. Therefore, neighbor sensor devices with a different hop count transmit data packets at different sub-slot timing. As a result, we can reduce packet corruptions due to data packet forwarding.

- Acknowledgement transmission slot
  The acknowledgement transmission slot is used for acknowledgement packet transmission and forwarding of acknowledgement packets from upstream sensor devices to downstream sensor devices. The acknowledgement slot is divided into some sub-slots according to a number of hops n from the sink device like as the data transmission slot.

4 Routing control

In the field sensor networks assumed in this paper, sensor devices are installed in widespread area. Therefore, multi-hop communication technology is used for transmission between a sink device and sensor devices. In this paper, we propose a simple routing protocol for field sensor networks. This is because limited resource of sensor devices makes difficult to implement complex routing schemes. In the proposed routing protocol, each sensor device exchanges its own hop count information, and constructs a route to an upstream device and manages its downstream devices.

4.1 Routing control packets

In the proposed protocol, following routing-control packets are used for route construction processes.

- Route request
  Route request (RREQ) control 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. They include only identification about a type of routing control packets.

- Route reply
  Route reply (RREP) control packets are used for informing own hop count information if sensor devices with available routes receive the route request control packets. A sensor device, which receives route reply control packets, can select an upstream device with a minimum hop count number. The route reply control packets include an identification about a type of routing control packets and hop count information of the own sensor device.

- Route construction request
  Route construction request (RCREQ) control packets are used for requesting route construction to an upstream sensor device if sensor devices can receive the route reply control packets. They include an identification about a type of routing control packets and a physical address of the upstream sensor device.

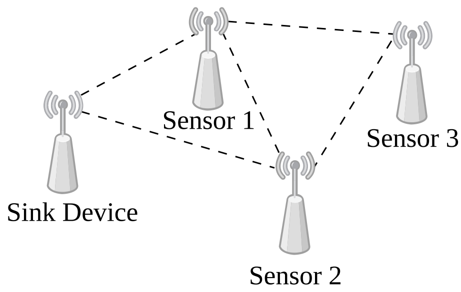

Figure 5: Assumed device location

- Route construction reply
  Route construction reply (RCREP) control packets are used for replying to the downstream sensor device that transmits the route construction request control packet. They include an identification about a type of routing control packets and a physical address of the downstream sensor device.

- Route construction acknowledgement
  Route construction acknowledgement (RCACK) control packets are used for confirming the route construction to the upstream sensor device. They include an identification about a type of routing control packets and a physical address of the upstream sensor device.

5 Example operations

In this section, we describe example operations of route construction processes and data transmission processes. In this example, we assume the sensor device location in Fig. 5. In this location, the first and the second sensor devices are located near the sink device, and the third sensor device is located near the first and the second sensor devices. Therefore, the first and the second sensor device can communicate with the sink device, the third sensor device, and each other. The third sensor device can communicate with the first and the second sensor devices.

5.1 Route construction process

Figure 6 shows an example of packet transmission in route construction processes with the device location in Fig. 5. In this figure, broadcast packets are indicated as narrow solid-arrow lines, unicast packets for destination devices are indicated as thick solid-arrow lines, unicast packets for neighbor devices are indicated as dot-arrow lines.

In the proposed protocol, devices without available routes broadcast a RREQ control packet to neighbor sensor devices. In the example, all sensor devices broadcast RREQ control packets at the route request slot.

Then, devices with available routes reply a RREP control packet to sensor devices which transmitted the RREQ control packet. In the example, the sink device is an only device with available routes. Therefore, the sink device replies RREP control packets to the first sensor device and the second sensor device. On the contrary, the first sensor device and the second sensor device do not reply a RREP control packet to the third sensor device because they do not have available routes to the sink device at this moment.

In the proposed protocol, sensor devices select neighbor sensor devices with the minimum hop count as their own upstream device. Additionally, sensor devices which transmit a RREP control packet first is selected as an upstream device if the hop count is same value. In the example, the first sensor device transmits a RCREQ control packet to the sink device to start route construction processes. The sink device replies a RCREP control packet to the first sensor device in order to confirm that its own device is selected as the upstream device. Finally, the first sensor device replies a RCACK control packet to the sink device to complete the route construction processes. The second sensor device performs to construct a route like as the first sensor device.

In the proposed frame format, slots about route control are allocated at a beginning of frame interval. Therefore, sensor devices, which locate far from the sink device, construct a route at coming frame intervals. In the example, the third sensor device transmits a RREQ control packet again at next frame interval. The first sensor device and the second sensor device reply a RREP control packet to the third sensor device because they have available routes. The third sensor device starts to construct a route to the first sensor device because the first sensor device transmits the RREP control packet first and the hop count values of the first and the second sensor devices are same.

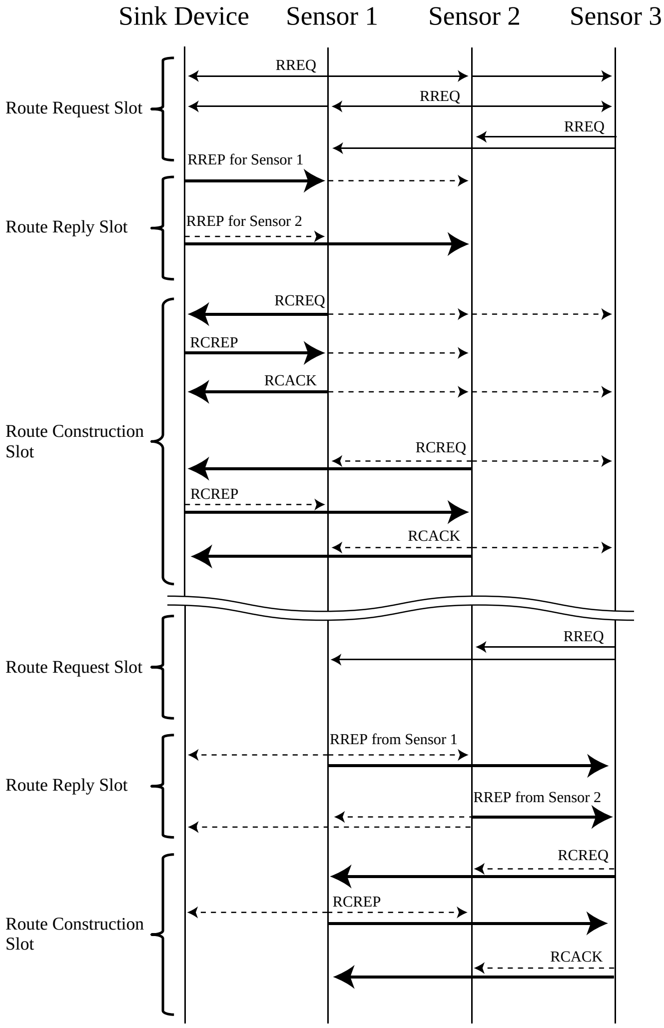

Figure 6: Example of route construction process

5.2 Data transmission process

Figure 7 shows an example of packet transmission in data transmission processes with the device location in Fig. 5. In this figure, broadcast packets are indicated as narrow solid-arrow lines, unicast packets for destination devices are indicated as thick solid-arrow lines, unicast packets for neighbor devices are indicated as dot-arrow lines.

In the proposed frame format, slots about data transmission are allocated after the slots about the route construction. The data and acknowledgement slots are divided into some sub-slots according to the number of hop counts. Figure 7 assumes that maximum hop count is set to two. In order to achieve smooth forwarding of data packets from faraway sensor devices to the sink device, the order of data sub-slot is set reverse order according to the number of hop counts. On the contrary, the order of acknowledgement sub-slot is set in order according to the number of hop counts because acknowledgement packets are forwarded from the sink device to sensor devices.

In the example, the third sensor device with two hops transmits the data packet to the first sensor device. The first sensor device recognizes that it should forward the data packet from the third sensor device because the route construction between the first sensor device and the third sensor device was completed at the route construction slot. Therefore, the first sensor device saves the received data packet into its own data-packet buffer.

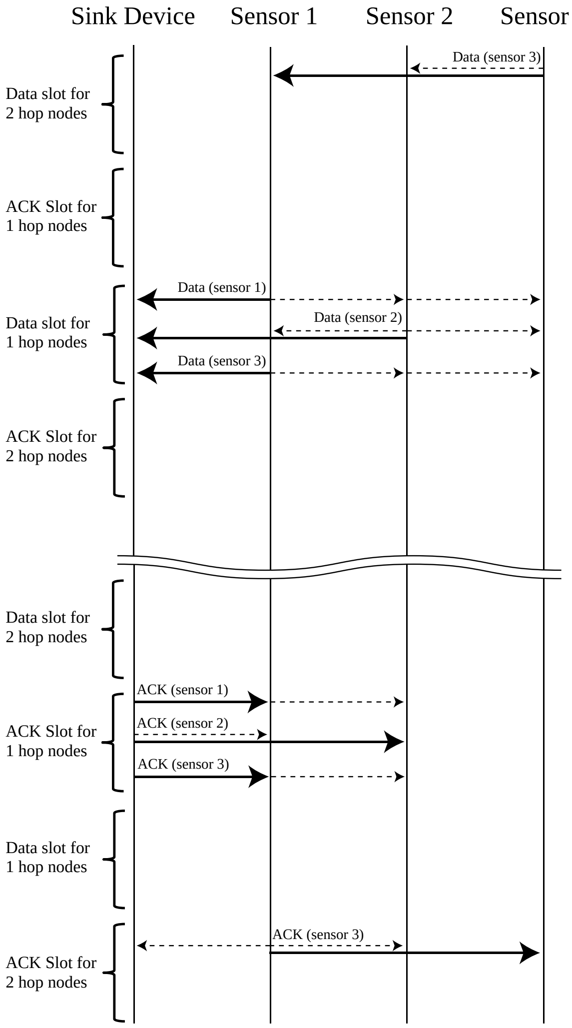

Figure 7: Data transmission process

Then, the first sensor device and the second sensor device transmit their data packets to the sink device. Additionally, the first sensor device transmits the received data packet from the third sensor device to the sink device.

In the proposed protocol, acknowledgement packets are replied from the sink device to confirm the successful data transmission from sensor devices. Then, the sink device transmits acknowledgement packets at next frame interval.

In the example, the sink device transmits three acknowledgement packets for all sensor devices at the acknowledgement sub-slot for one hop. The first sensor device recognizes that the acknowledgement packet for the third sensor device should be received by its own device. It saves the received acknowledgement packet into its own acknowledgement-packet buffer. Then, it transmits the acknowledgement packet for the third sensor device at the acknowledgement sub-slot for two hops.

6 Experimental results

In order to evaluate the performance of the implemented sensor devices, we performed an experimental measurement for one day. In the experimental measurement, each sensor device observes a temperature and an illuminance every five minutes interval. Then, it transmits a data packet to the sink device and retransmits again if an acknowledge packet is not received. Eleven sensor devices are installed in the laboratory like as Fig. 8. In this evaluation, we focus on network performance of the proposed mechanisms. Therefore, every sensor device is connected to commercial power supply. Table 1 shows the detail parameters.

Figure 9 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 results, sensor device one, two, and three retransmit some data packets even if they locate near the sink device. This is caused by some computers always operate in the room, and communication may be interfered by noise. Additionally, some IEEE 802.11 devices, which use the same frequency band of IEEE 802.15.4, also operate. Therefore, some data packets or some acknowledgement packets are lost frequently due to the interference. Moreover, some sensor devices, that locate far from the sink device, retransmit data packets more. In the proposed implementation, the acknowledgement transmission is performed between the sink device and the sensor device. However, acknowledgement transmission should be performed between each sensor device in high packet error rate environment.

Additionally, the sensor device retransmits the data packet again if it does not receive the acknowledgement packet from the sink device. The retransmission is performed until it receives the acknowledgement packet. Therefore, the data arrival ratio of the proposed implementation is 100 [%]. To achieve reliable data collection system is an important factor in the field sensor networks. Hence, our implementation is one of the candidate devices for field sensor networks.

Figure 10 shows the hop count value from the sink device. From results, we can find that the hop count value is more stable with decreasing distance between the sensor device and the sink device. The reason for this is that sensor devices will reconstruct a route if they receive Route-Request control packets from their upstream devices. Therefore, sensor devices prefer to reconstruct with increasing of distance between the sensor device and the sink device.

Figure 11 shows the number of route constructions per number of observations. From results, we can find that sensor devices with long distance from the sink device reconstruct

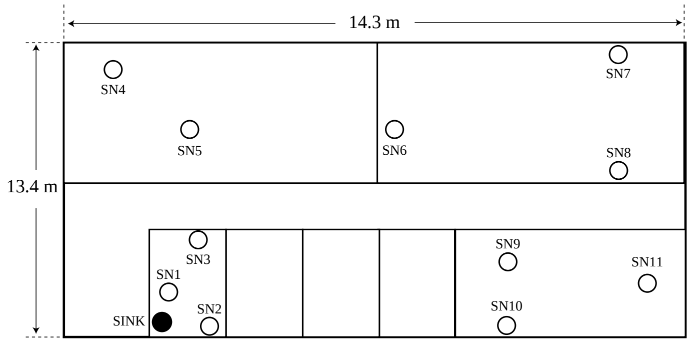

Figure 8: Location of sensor devices.

Table 1: Experimental parameters.

Sensor device	Sun SPOT
Number of devices	11
Monitor interval	5 [minute]
Monitor period	24 [hour]
T_{Frame}	1 [minute]
T_{Req}	1 [second]
T_{Rep}	3. 5 [second]
T_{Route}	5. 5 [second]
$T_{Data(n)}$	2. 5[second]
$T_{Ack(n)}$	2. 5[second]
Maximum hops N	10 [hop]
Transmission power	-9 [dB]
Size of data packet	134 [Byte]
Size of ACK packet	119 [Byte]

routes frequently. In the implementation, the sensor devices perform the data packet retransmissions for three times. If the sensor devices fail to receive acknowledgement packets, they start to reconstruct routes. Additionally, the sensor devices also reconstruct routes if they receive route request control packets from their upstream sensor device. This is because the route is not available when the upstream sensor device transmits the route request control packets.

Figure 12 shows the delay performance. The delay is defined as the period between the observation time and the arrival time at the sink device. In the proposed implementation, the observed data is transmitted at next data slot. Then, the sink device replies acknowledgement packets after the next data slot if it receives the data packets. From results, delay performance of some sensor devices with long distance from the sink device is large.

7 Conclusions

In this paper, we have implemented field sensor network devices based on Sun SPOT, which is a small sensor device produced by Sun Microsystems. Our protocol employs especially simple mechanisms. Therefore, it is easy for small sensor devices to implement the proposed protocol. In order to connect some general sensors, we produced special sensor interface boards connecting to the interface of Sun SPOT. Additionally, Sun SPOT devices can control power of whole sensor interface circuits and some parts of sensors by using the produced interface boards. From the experimental trial, we could find that our implementation can construct the reliable field sensor networks for periodical environmental measurement.

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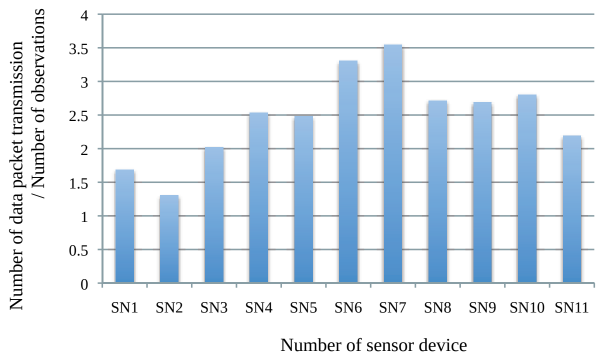

Figure 9: Number of data packet transmission per number of observations.

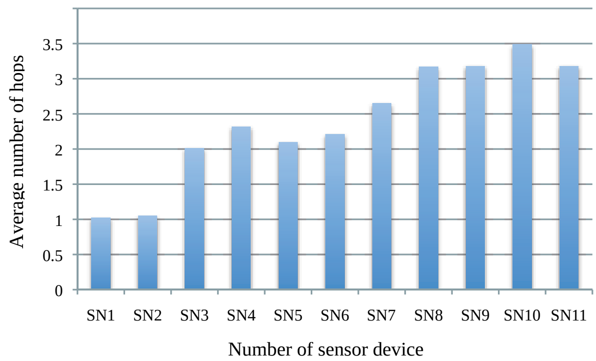

Figure 10: Number of hop counts.

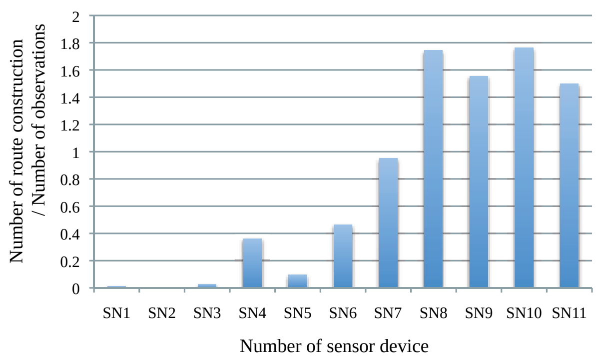

Figure 11: Number of route constructions.

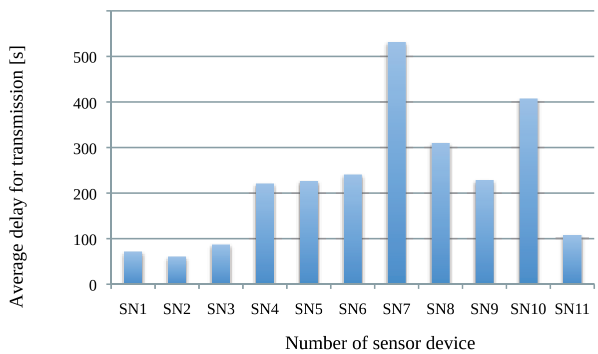

Figure 12: Delay performance.