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Applying Sensor Node with Zero Standby Power to Door Monitor

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***Abstract*—For the wireless sensor network (WSN), one of the most significant problems is the battery exchange for many sensor nodes. To make the battery changing rarely happen, we have proposed the sensor node architecture with zero standby power. We performed the preliminary experiments for the proposed node. However, we have never shown an application realized by it. In this paper, we demonstrate an application using our sensor node as the door monitor. The result of the case study have shown that our proposed sensor node can implement a door monitoring system in the WSN and significantly reduced the power consumption during the standby compared with the conventional one.**

***Index Terms*—wireless sensor network, sensor node, standby power, sleep-wakeup scheduling protocol, door monitor**

I. Introduction

FOR the wireless sensor network (WSN), one of the most significant problems is the battery exchange for many sensor nodes. It leads to the high maintenance cost. In the worst case, the WSN will never be used.

The intuitive approaches to tackle this problem are using an energy harvester for the power supply of the sensor node to eliminate the battery [1]. The most familiar energy harvester is the photovoltaic [2]. However, the photovoltaic cannot generate enough power at night and the dark places as the tunnel, the under-bridge and the inside of the room. Other harvesters generating the intermittent power such as the vibration, heat and pressure cannot make the WSN stable [1]. Instead of the energy harvesting, Naveen et al. has attempted to make the battery life longer by using an efficient cyclic sleep/wake-up scheduling protocol [3]. However, some standby power is always consumed by the sensor node during standby mode in order to detect an event, e.g. timer alarm and external trigger, for waking-up even if any efficient scheduling protocol is used.

Thus, we have proposed a sensor node architecture with zero standby power which wakes up adaptively at event occuring [4]. Since this node in standby mode cuts the ground line by a transistor, the standby power consumption becomes zero. An energy harvester, e.g. piezo-electric device, photodiode, and peltier element, is attached to the sensor node and generates some electromotive force when an event occurs. Instead of using this electromotive force as main power supply, it is only used to turn on the transistor cutting the ground line. As a result, the sensor node starts running adaptively at event occurring and continues to run by turning on the transistor instead of the energy harvester used. The proposed sensor node is the stable node correctly handling the WSN by using the battery without the wasted sampling, while any power is never consumed during the standby mode. Thus, the WSN stability improvement and the battery life extension can be accomplished by our proposal.

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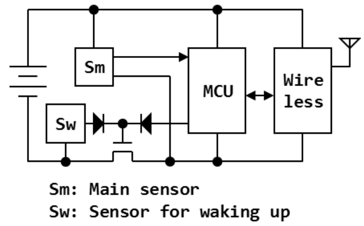

Fig. 1. Sensor Node Architecture.

Previously, we have shown the concept of our sensor architecture and performed some preliminary experiments to confirm the realization of our proposal [4]. However, we have never demonstrated an application using our sensor node and never evaluated the power consumption in detail. In this paper, we demonstrate a case study applying our sensor node to the door monitor. The result of the case study shows that our proposed sensor node can implement a door monitoring system in the WSN and significantly reduce the power consumption during the standby compared with the conventional one.

The rest of the paper is organized as follows. Section 2 describes the architecture of the proposed sensor node and the overview of the WSN using it. Section 3 demonstrates how to realize the door monitoring system with the proposed sensor node. Section 4 confirms the realization of the door monitoring system and evaluates the standby power consumption compared with the conventional sensor node. Finally, Section 5 concludes this paper.

II. Wireless Sensor Network using sensor node with zero standby power

A. Sensor Node with Zero Standby Power

Fig. 1 shows the architecture of the proposed sensor node. The sensor node basically consists of a sensor to measure the targeted environment or event (S_m), a micro-controller (MCU), a wireless module, and a battery. Instead of the conventional sensor node, a power transistor bridging the ground line exists. In addition, a sensor (S_w) to wake up the sensor node is included. The S_w is an energy harvester which turns on the power transistor to provide the battery power for the sensor node.

In the standby mode, the power transistor is turned off; the ground line is disconnected. Since the consumption current never appears and the standby power becomes zero, the battery is not used in the standby mode. When an event

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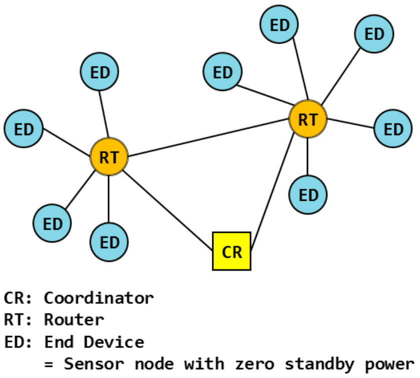

Fig. 2. Wireless Sensor Network with Proposed Node Based on Zigbee

occurs on the S_w, S_w generates some electromotive force. This force drives the power transistor and the ground line is connected. The woken-up MCU starts to drive the power transistor instead of the S_w, and acquires the sensing data from S_m. Then, the MCU sends the sensed data to the wireless sensor network from the wireless module. Finally, the MCU stops driving the power transistor and the sensor node goes to the standby mode with zero power consumption again.

This is very simple mechanism but it is the powerful feature which can greatly reduce the standby power.

B. Wireless Sensor Network

The wireless sensor network (WSN) is the attractive research and development domain. To diffuse the WSN widely, some standards are proposed. The most famous one is ZigBee [5]. Fig. 2 shows the overview of a Zigbee organization including the proposed sensor nodes.

The Zigbee WSN consists of the coordinator, the routers and the end devices. The coordinator is the master node of the personal area network (PAN). One coordinator must exist in the PAN. The router plays a network router over PAN. The coordinator and the router are equipped to the places which has the already installed power rail such as the commercial power supply. This is because they have to always consume some power to manage the network traffic on the WSN. On the other hand, the end device is a leaf node of the WSN and runs by using the battery power. Using the battery, they measure the environment or event targeted and send the sensed data to the WSN stably. The end device has the sleep mode to make the battery life longer. However, the conventional sensor node has to consume some power to accept the timer alarm or the external event to exit the standby mode.

The proposed sensor node can be applied to the end device in Zigbee WSN. By using the proposed node, the end device can reduce the standby power to zero in the sleep mode. As a result, the maintenance cost of changing the battery of the end devices and the total power consumption of the WSN can be significantly reduced.

III. Door Monitor

In this paper, we demonstrate an application example of the proposed sensor node. The example supposes a door monitoring system for the security of home, office and factory. Fig. 3 shows the overview of the door monitoring system using the WSN with the proposed sensor nodes.

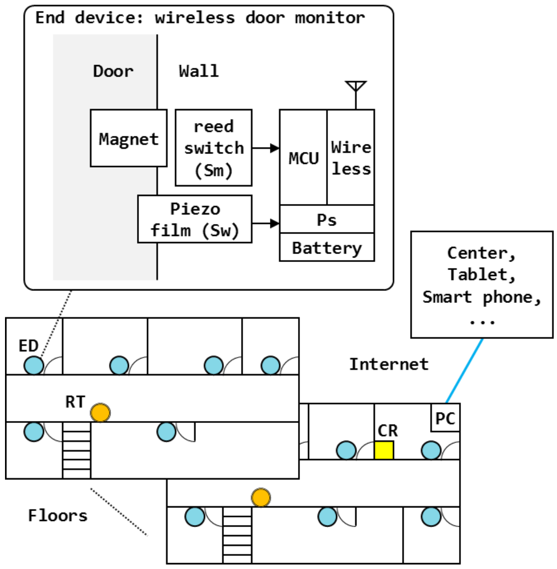

Fig. 3. Door Monitoring System.

In each room, the end device is attached to the wall near the door. Conventionally, the most door sensor uses the magnet and the reed switch [6]. The magnet is attached to the door and the sensor node with the reed switch is equipped to the wall. When the door is closed, the magnet exists close to the reed switch. As a result, the reed switch is turned on. When the door is opened, the reed switch is turned off because the magnet is far away from the reed switch. By reading the status of the reed switch, the sensor node can recognize whether the door is opened or closed.

In addition to this conventional organization, a piezo film as the harvester to wake up is attached to the sensor node. The edge of the piezo film is set so as to overlap the door. When the door is opened or closed, the door flicks the piezo film and some electromotive force is generated from it. This force drives the power transistor disconnecting the ground line, and the sensor node awakes. The woken-up sensor node checks the status of the reed switch and identifies whether the door is opened or closed. The sensor node sends the sensed status of the door to the WSN. Finally, the sensor node goes to the standby mode by releasing the gate of the power transistor.

The sensed statuses of the door from the end devices are gathered to the cordinator through the routers. The status of the doors is sent to the security center, user's tablet and smart phones.

IV. Experiment and Discussion

A. Prototype of Sensor Node

To investigate the realization of the application exapmle as the door montoring system and evaluate the standby power consumption in detail, we have developed a prototype hardware system.

Fig. 4 shows the block diagrams of the proposed sensor node and the conventional one we have developed. For both nodes, the microcontroller is STMicroelectronics

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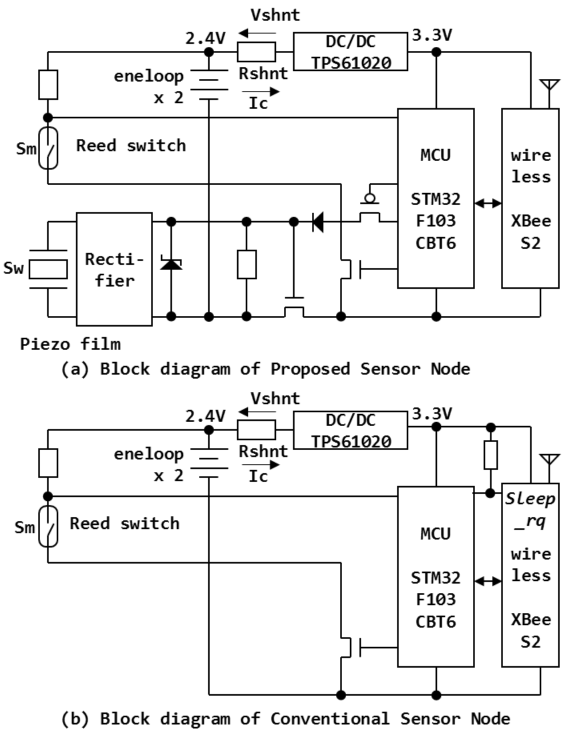

Fig. 4. Prototype Sensor Node for Experiment.

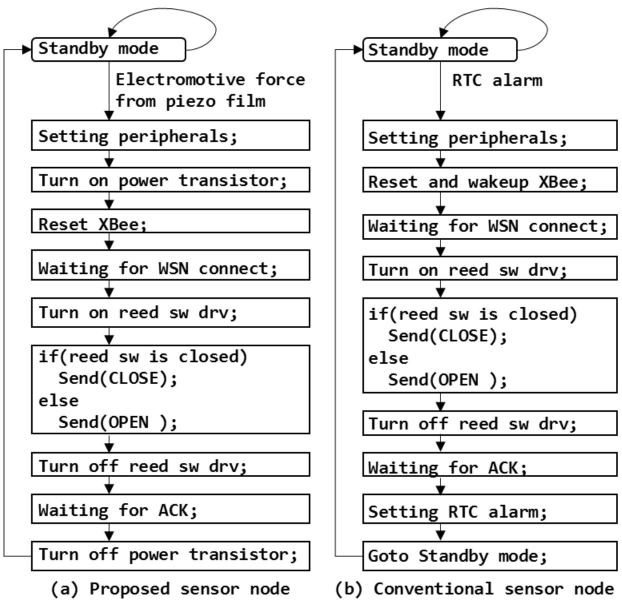

Fig. 5. Flow Chart of Sensor Node Exection.

STM32F103CBT6. The wireless module is Digi international XBee S2. The battery consists of two Panasonic eneloops whose nominal value of the output voltage is 2.4V. Since the microcontroller and the wireless module need 3.3V power supply, the DC-DC converter (Texas Instruments TPS61020) is used. To measure the consumption current by the whole sensor node, a shunt resistor ($\mathrm{R_{shnt}}$) can be inserted into the power line. For the reed switch, one terminal is pulled up and the other terminal is connected to the ground through the transistor. This transistor is used to eliminate the constant current flow through the closed reed switch.

As for the proposed sensor node shown in Fig. 4 (a), the piezo film and the power transistor bridging the ground line are attached. The output of the piezo film is converted to the DC wave by the rectifier. The level of the rectified wave is limited by the zener diode and reaches the gate of the power transistor. The gate of the power transistor is pulled down by the large resistor to absorb the electrical charge remaining the gate when the transistor is turned off. When the sensor node is the standby mode and the ground line is cut, all outputs of the microcontroller is pulled up by the battery. The p-type transistor is inserted into the output of the microcontroller driving the gate of the power transistor so that the output is electrically isolated by the p-type transistor in the standby mode.

As for the conventional sensor node shown in Fig. 4 (b), the microcontoller becomes the standby mode nominally with less power and the wireless module stays the sleep mode by asserting the *sleep_rq* pin. The microcontroller in the standby mode cannot drive almost pins; they become floating. Since the *sleep_rq* pin is pulled up, the wireless module becomes the sleep mode naturally when the microcontroller becomes the standby mode.

B. Process Flow of Sensor Node

Fig. 5 shows the flow charts of the sensor node execution. The proposed sensor node is woken up by the electromotive force when the door flicks the piezo film. The conventional sensor node performs the cyclic sleeping by using the real time clock (RTC). Thus, the sensor node is woken up by the alarm from the RTC.

In the proposed node, the MCU sets the peripherals and turns on the power transistor to execute following processes. The MCU resets the wireless module, XBee and waits for the WSN connection from the coordinator. Once the WSN connection is established, the MCU tries to confirm the door status by reading the output of the reed switch. The reed switch driver is turned on only when checking the status of the reed switch. This fact indicates that the constant power consumption through the reed switch never occurs even if the reed switch is closed when the door is closed. The MCU sends the door status to the coordinator and turns off the reed switch driver. Then, the MCU waits for the WSN acknowledgement for the transmission mentioned above from the coordinator. After that, the MCU turns off the power transistor and goes to the standby mode with zero power consumption.

The conventional node performs similar processes mentioned above. After waking up, the MCU negates the *sleep_rq* pin to wake up the wireless module. In addition, before going to the standby mode, the MCU resets the RTC alarm and goes to the standby mode by the maker-specified procedure.

C. Current Sensor

The consumption current in the standby mode may be weak such as μA or nA order. Thus, we have to use the measuring mechanism with high precision that can obtain such weak current. Unfortunately, we cannot introduce the comercial measuring instrument due to the cost. To resolve this problem, we have developed a current sensor shown in Fig. 6.

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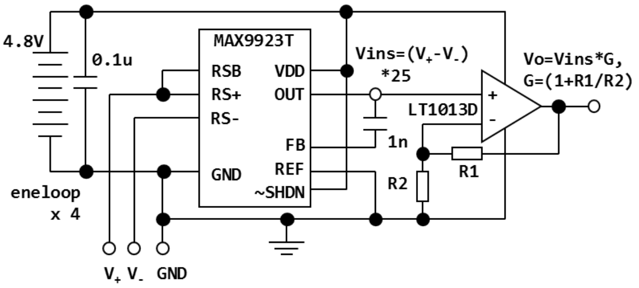

Fig. 6. High Side Current Monitor.

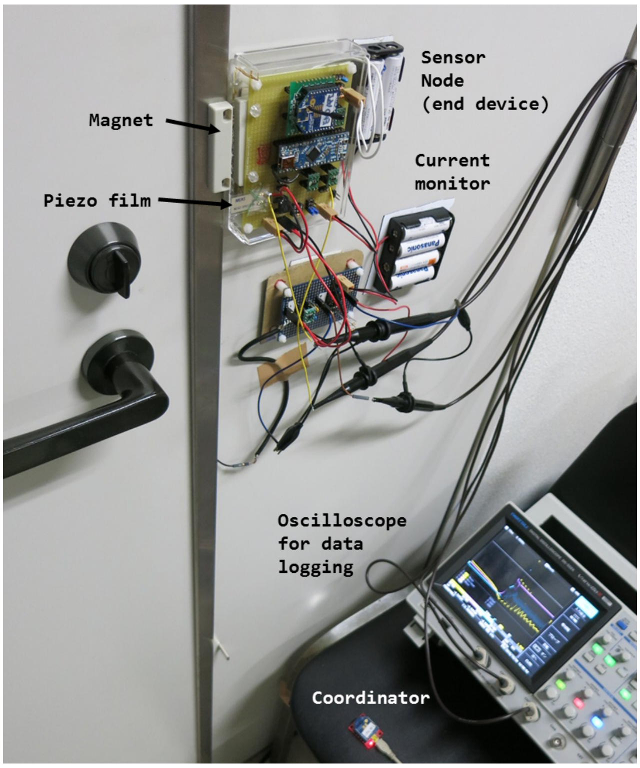

Fig. 7. Picture of Experimental Setup.

This is the trivial current sensor using the instrumentation amplifier. The used instrumentation amplifier is MAXIM MAX9923T. The terminals of V_+ and V_- are connected to both side of the shunt resistor, R_{shnt}, shown in Fig. 4. The offset voltage of MAX9923T is 25μV and its input bias current is 1 pA. The gain is fixed by 25. This gain is relatively small. So, the following amplifier, Texas Instruments LT1013D, is attached to gain the output voltage so that the oscilloscope we have can obtain. The consumption current, I_c shown in Fig. 4, can be calculated by the following equation.

$$I_c = V_o/G/25/R_{shnt} = V_o/(1 + R1/R2)/25/R_{shnt} \text{ [A]}$$

We have prepared the dedicated battery for the current sensor. This battery has higher output voltage than the battery of the sensor node. This is because we attempt to improve the precision by make the measuring range large.

Fig. 7 shows the picture of the experimental setup. We have attached the sensor node to the wall near the door in my lab room. The coordinator is connected to the host PC via the USB cable. The host PC displays the status of the door sent by the sensor node. The oscilloscope used is IWATSU DS-5524 for data logging.

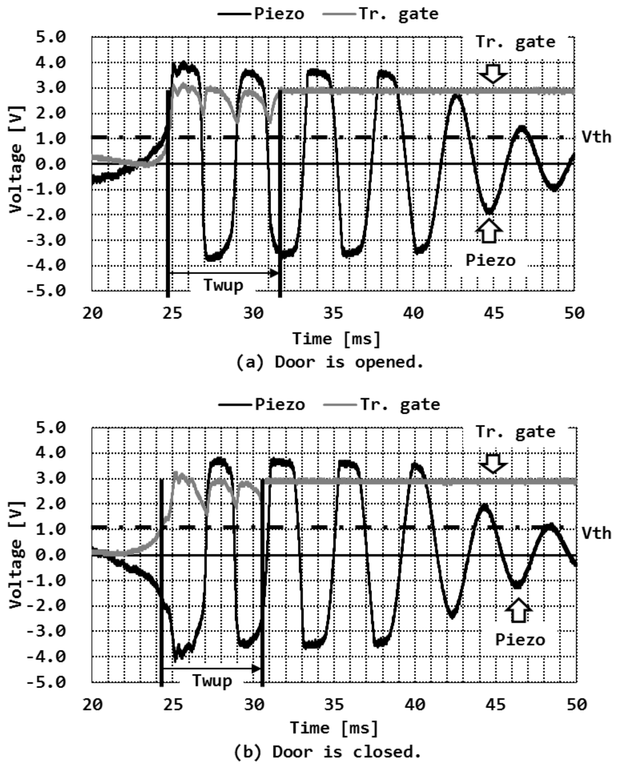

Fig. 8. Wakeup Time.

D. Wake-up and Network Transmit Time

To confirm the realization of the door monitor by using the proposed sensor node, we measured the wakeup time by the osciloscope and confirmed the display of the host PC.

Fig. 8 shows the waveform indicating the wakeup time. The output of the piezo film is generated when the piezo film is flicked by the closed and opened door. The output of the piezo is rectified to the DC wave and reaches the gate of the power transistor. When the rectified wave exceeds the threshold voltage (V_{th}) of the power transistor, the microcontroller wakes up and drives the gate of the power transistor instead of the piezo film. This time duration is shown as T_{wkup} in Fig. 8. As shown in Fig. 8, once the MCU drives the power transistor, the waveform of the gate becomes stable unlike the bounding waveform from the piezo film. In this experiment, T_{wkup} is about 6ms to 7ms.

After the MCU wakes up, the host PC correctly displays the status of the door. This duration is about 350ms. In the case of the door monitoring, we think that this duration is acceptable.

E. Power Consumption

To briefly measure the power consumption during the standby mode and the execution mode, we obtain the consumption current by setting the R_{shnt} shown in Fig. 4 to 0.1Ω and setting the G shown in Fig. 6 to 1.0. Fig. 9 shows this result. After the sensor node wakes up at 0.05s, some consumption current is measured during about 0.35s while the sensor node is running.

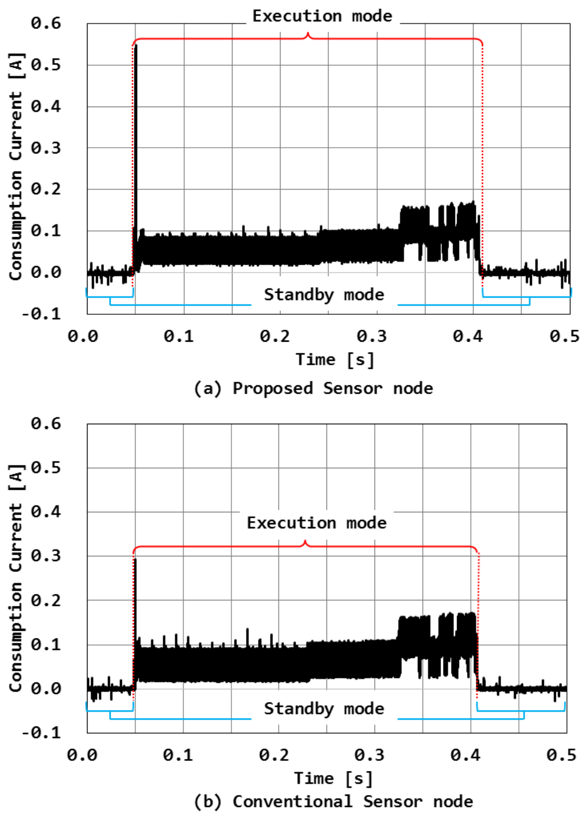

Fig. 9. All Consumption Current.

TABLE I
AVERAGE STANDBY CONSUMPTION CURRENT ($I_c = V_o/G/25/R_{shnt}$).

Node type	R_{shnt} [Ω]	G	V_o	I_c
Proposal	2.005M	3.217	0.109 [V]	0.676 [nA]
	0.996M	10.88	0.187 [V]	0.690 [nA]
	511.0K	101.5	0.916 [V]	0.701 [nA]
Conventional	1.000	1.000	12.88 [mV]	0.515 [mA]

In the execution mode, the average cunsumption current of the proposed sensor node is 63.64mA while that of the convetional one is 63.06mA. The proposed node increases the consumption current of 0.9% compared with the conventional one. At first in the execution mode, the waveform like spike can be seen at 0.05s. This is because the short-circuit current to charge several capacitors appears when waking up. The proposed sensor node expresses larger spike than the conventional one. In the standby mode, the proposed sensor node completely cuts the power while the conventional one keeps it connect. That is, the conventional node keeps the charge level of the capacitor during the standby mode. Thus, the proposed node in waking up shows the larger spike of 0.9% to charge more capacitors than the conventional one.

In the standby mode, the voltage between the shunt resistor is small. Thus, we have to gain the large voltage by the shunt resistor, the instrumentation amp, and its following amp. The results measured varying the some parameters are shown in Tab.I. For the proposed node, we chose these parameters so that the measurment can be performed correctly as follows.

(1) The offset voltage of the used instrumentation amp (25μA) does not affect the result.
(2) The following amp can correctly handle the input voltage range.
(3) The oscilloscope can obtain the voltage correctly.

As shown in Tab. I, the proposed sensor node can greatly reduce the standby power consumption compared with the conventional one. The standby consumption current of the proposed node may be a leakage current of used electronic devices because this is less than 1 nA. On the other hand, the conventional one shows relative large standby consumption current. As the nominal value, the used microcontroller can reduce the standby current to 3.4uA. However, the sensor node consists of several components in addition to the microcontroller. In this case, the other components are the dc-dc converter and the wireless module. They increased the standby consumption current totally.

We think the standby power reduction of the proposed sensor node can enough compensate the increased operational power of 0.9% compared with the conventional node.

V. CONCLUSION

For the wireless sensor network (WSN), one of the most significant problems is the battery exchange for many sensor nodes. To make the battery exchange rarely happen, we have proposed the sensor node architecture with zero standby power. We however just performed the preliminary experiments for the proposed node and have never demonstrated any its application. In this paper, we demonstrate an application using our sensor node as the door monitor. The result of the case study have shown that our proposed sensor node can implement a door monitoring system in the WSN and significantly reduced the power consumption during the standby compared with the conventional one.

As future work, we will apply the proposed sensor node to more applications and eveluate the performance of them. In addition, we will investigate the standby power in more detail on many kinds of sensor node organizations.

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