Wireless Temperature and Illuminance Sensor Nodes With Energy Harvesting from Insulating Cover of Power Cords for Building Energy Management System

Masanobu Honda, Takayasu Sakurai, and Makoto Takamiya
University of Tokyo
Tokyo, Japan

***Abstract*—A new energy harvesting with low installation cost is proposed to enable stable power supply to battery-less wireless sensor nodes for energy management systems. Two electrodes (copper tapes) are attached on the insulating cover of two-wire power cords and the leakage electric-field energy is harvested by the capacitive coupling between the electrodes and the core wires. The proposed energy harvesting does not require an additional ground connection and the current in the power cords. 3-4V, 1.4μW is harvested with 20-cm electrodes from 100-V AC power supply. Temperature and illuminance sensor nodes with the proposed energy harvesting and ZigBee modules for the building energy management system are demonstrated. Both the temperature and illuminance are measured and transmitted to a wireless receiver within a 100-m radius every 250s.**

***Index Terms*--Energy harvesting, energy management system, wireless sensor node, temperature, illuminance**

I. INTRODUCTION

In the building energy management system (BEMS), sensor nodes are required to monitor the indoor environment (e.g. temperature, humidity, and illuminance) and the measured data are used to control the air conditioning and the lighting of the building for reducing the energy consumption. The requirements of the sensor nodes for BEMS are: (1) low-cost installation, (2) low operational cost, and (3) stable and continuous monitoring. The conventional sensor nodes with wires for power supply and communication increase the installation cost. The conventional wireless sensor nodes with batteries require regular battery replacement, which increases the operational cost. The energy harvesting (e.g. solar cell, thermoelectric generator, and vibration energy harvester) is a promising approach to eliminate the need for battery replacement. The energy harvesting, however, does not guarantee the continuous monitoring, because the energy source is not always available. To solve the problems, this paper focuses on an energy harvesting from the insulating cover of power cords.

In the conventional energy harvesting from leakage magnetic-field energy from the insulating cover of power cords [1]-[4], the current in the power cords is required, which does not guarantee the continuous monitoring, because the magnetic-field is not available when the current is zero. In the conventional energy harvesting from leakage electric-field energy from the insulating cover of power cords [5], a dedicated ground connection (i.e. attaching a metal plate on a concrete wall with conductive adhesives after peeling off the paint on the wall) is required, which increases the installation cost. To solve the problems, a new energy harvesting from the insulating cover of power cords (EHICPC), which does not require the current in the power cords and the dedicated ground connection, is proposed in this paper. The proposed EHICPC enables the low-cost installation, the low-cost operation, and the stable and continuous monitoring.

In Section II, the operation principle and measured results of the proposed EHICPC are shown. In Section III, the demonstration of temperature and illuminance sensor nodes with EHICPC and ZigBee modules for BEMS is shown. In Section IV, EHICPC is compared with the previously published energy harvestings from the insulating cover of power cords. Section V draws the conclusions of this paper.

II. PROPOSED ENERGY HARVESTING FROM INSULATING COVER OF POWER CORDS (EHICPC)

A. Operation Principle

Fig. 1 shows an operation principle of the proposed EHICPC. Two electrodes (copper tapes) with the length of L are attached on the insulating covers of two-wire power cords, respectively. The electrodes are capacitively coupled to the core wires, and the leakage electric-field energy from the core wires is harvested. The two electrodes are connected to a full-wave rectifier and AC input is converted to DC output. Fig. 2 shows a photo of the two-wire power cords with the two electrodes for EHICPC.

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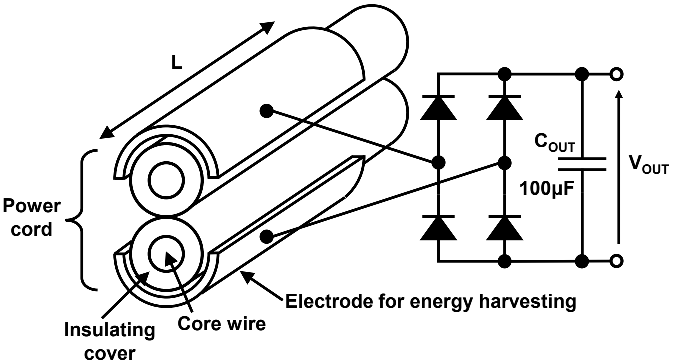


Fig. 1. Operation principle of proposed energy harvesting from the insulating

Fig. 2. Photo of the two-wire power cords with the two electrodes for EHICPC.

Table I Parameters in EHICPC

		Thickness of cord	
		Thin	Thick
Length of electrodes (L)	10cm	○	
	20cm	○	○
	30cm	○	
	40cm	○	

B. Measured Results

To systematically quantify the harvested power, EHICPC with different L and two types of power cords are measured. Table I summarize the parameters in EHICPC. Fig. 3 shows a photo of the thin (VFF) and thick (VCTFK) power cords.

Fig. 4 shows a measured waveform of the output voltage (V_{OUT}) of thin power cord with L = 20cm. To understand the operation principle of EHICPC, an equivalent circuit of EHICPC is made and compared with the measured result. Fig. 5 shows the equivalent circuit of EHICPC of thin power cord with L = 20cm. C_1 is the capacitance between two wires. C_3 and C_4 are the capacitance between the electrode and the nearby wire. C_2 and C_5 are the capacitance between the electrode and the distant wire. Fig. 4 also shows a simulated

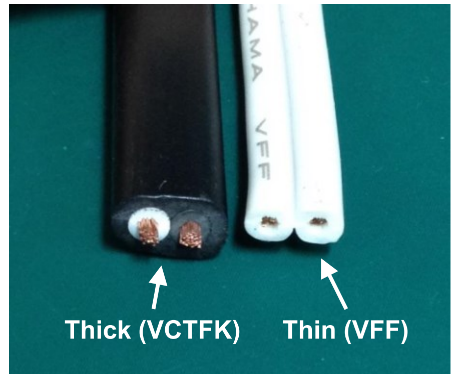


Fig. 3. Photo of thin (VFF) and thick (VCTFK) power cords.

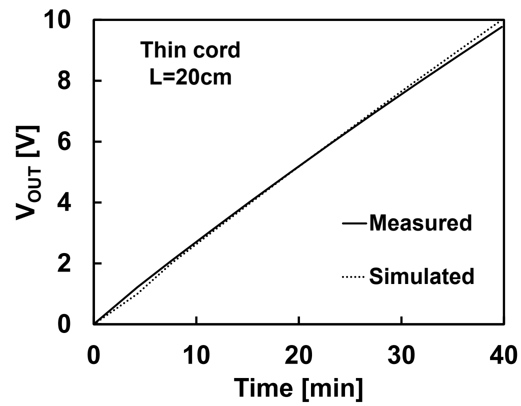


Fig. 4. Measured and simulated waveforms of V_{OUT} of thin power cord with L = 20cm.

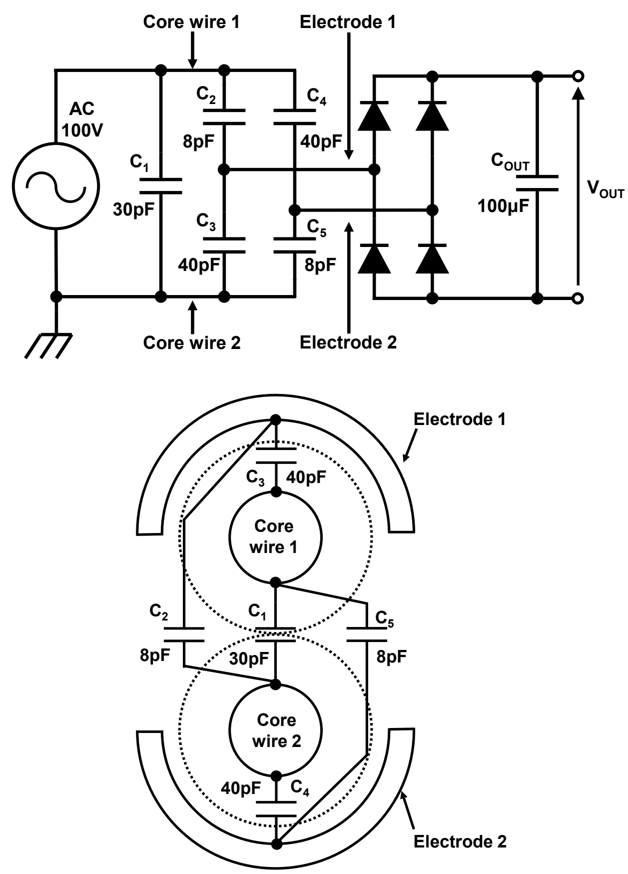


Fig. 5. Equivalent circuit of EHICPC of thin power cord with L = 20cm.

waveform of V_{OUT} with the equivalent circuit in Fig. 5. The simulated waveform shows very good match with the measured waveform, which shows the validity of the equivalent circuit in Fig. 5.

Fig. 6 shows measured waveforms of V_{OUT} of thin and thick power cord with L = 20cm. V_{OUT} of the thick power cord is lower than that of the thin power cord, because C_3 and C_4 of the thick power cord are smaller than those of the thin power cord. Fig. 7 shows measured waveforms of V_{OUT} of thin power cord with L = 10cm, 20cm, 30cm, and 40cm. V_{OUT} increases with increasing L. The harvested current ($I_{HARVEST}$) is calculated by

$$I_{HARVEST} = \frac{C_{OUT} V_{OUT}}{t} \qquad (1)$$

where C_{OUT} is the output capacitance in Fig. 1 and t is the time. Fig. 8 shows measured L dependence of $I_{HARVEST}$ in the thin power cord. $I_{HARVEST}$ is proportional to L. For example, $I_{HARVEST}$ is 400nA at L = 20cm, and $I_{HARVEST}$ / L is 20nA/cm.

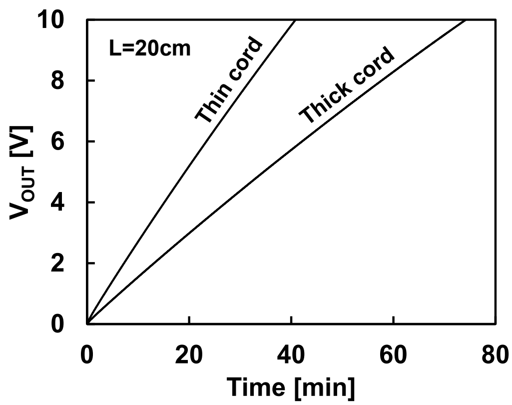


Fig. 6. Measured waveforms of V_{OUT} of thin and thick power cord with L = 20cm.

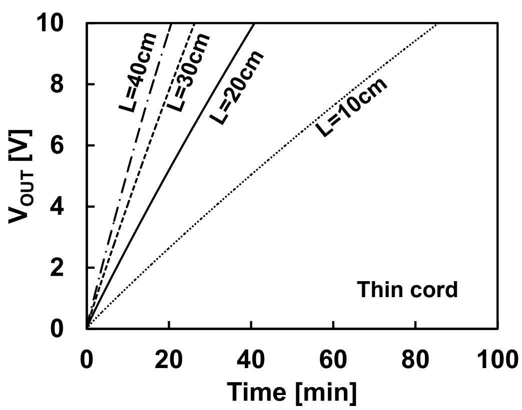


Fig. 7. Measured waveforms of V_{OUT} of thin power cord with L = 10cm, 20cm, 30cm, and 40cm.

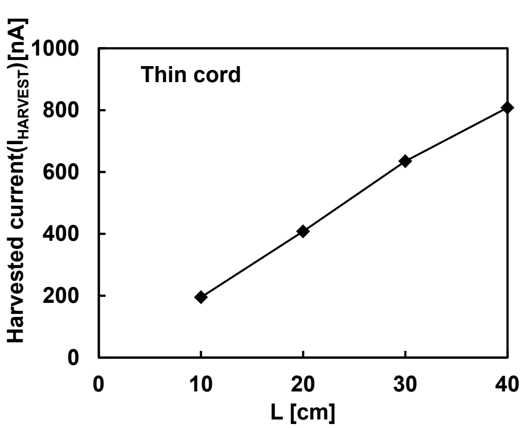
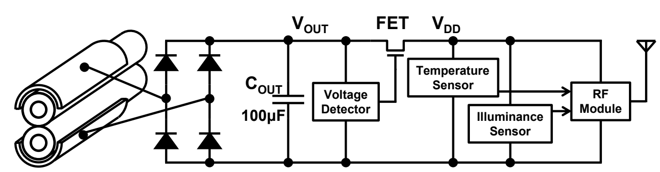


Fig. 8. Measured L dependence of $I_{HARVEST}$ in thin power cord.

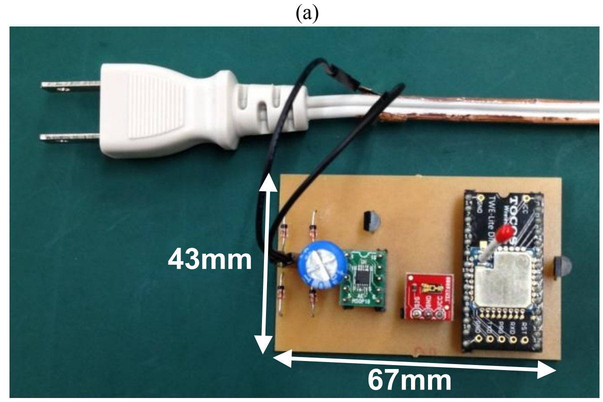
III. WIRELESS TEMPERATURE AND ILLUMINANCE SENSOR NODES WITH EHICPC

In this section, battery-less temperature and illuminance sensor nodes with the proposed EHICPC and ZigBee module for BEMS is demonstrated.

Figs. 9 (a) and (b) show a block diagram and a photo of the wireless and battery-less temperature and illuminance sensor nodes with the proposed EHICPC, respectively. AC input voltage is rectified to DC output voltage (V_{OUT}) using four diodes (1N914) and a 100-μF electrolytic capacitor. An FET (2SK4150) to isolate V_{OUT} and the power supply voltage (V_{DD}) is very important in the energy harvesting. Without the FET, C_{OUT} is not charged, because $I_{HARVEST}$ (400nA) is much smaller than the peak supply current of RF module (17mA). A voltage detector (AP4400A) is a key component to control the FET. Fig. 10 shows a measured waveform of V_{OUT} of the sensor nodes with the proposed EHICPC of a thin power cord with L = 20cm. The voltage detector has hysteresis between 3V and 4V. At start-up, when V_{OUT} is increased from 0V to 4V, the voltage detector turns off the FET to isolate V_{OUT} from V_{DD}. When V_{OUT} is 4V, the voltage detector turns on the FET, V_{OUT} is connected to V_{DD}, and C_{OUT} charges V_{DD}. Then, the temperature sensor (MCP9700) and the illuminance sensor (TEMT6000) start the sensing operation, and the 2.4GHz



(a)



(b)

Fig. 9. (a) block diagram and (b) photo of wireless and battery-less temperature and illuminance sensor node with proposed EHICPC.

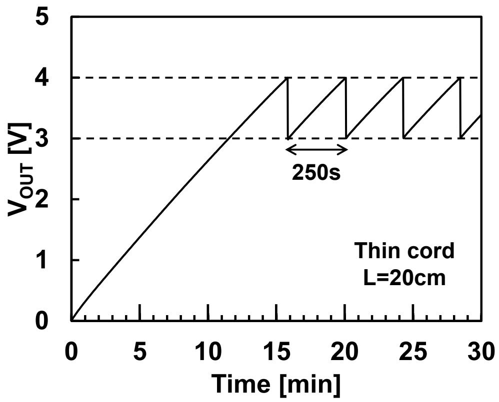


Fig. 10. Measured waveform of V_{OUT} of sensor nodes with EHICPC of thin power cord with L = 20cm.

ZigBee module (TWE-001L-DPC-WA) transmits the measured data. During the wireless transmission, V_{DD} rapidly decreases, because $I_{HARVEST}$ (400nA) is much smaller than the peak supply current of RF module (17mA). When V_{OUT} is reduced to 3V, the voltage detector turns off the FET. Then, V_{OUT} is charged to 4V again. Therefore, the sensing operation and the wireless transmission are done every 250s. The harvested energy per operation ($E_{HARVEST}$) and the harvested power ($P_{HARVEST}$) are calculated by

$$E_{HARVEST} = \frac{C_{OUT}}{2}\left(V_{OUT(final)}{}^2 - V_{OUT(initial)}{}^2\right) \quad (2)$$

$$P_{HARVEST} = \frac{E_{HARVEST}}{T} \quad (3)$$

where $V_{OUT(final)}$ (= 4V) and $V_{OUT(initial)}$ (= 3V) are final and initial V_{OUT} per charging, respectively. T (= 250s) is the charging period. In Fig. 10, $E_{HARVEST}$ is 350μJ and $P_{HARVEST}$ is 1.4μW.

Fig. 11 shows a measured power supply current of ZigBee module at V_{DD} = 3.3V. The first peak shows the activation of the module and the second peak shows the wireless transmission. Fig. 12 shows a measured breakdown of energy in the wireless sensor node. The total energy per operation is 268μJ, which is less than $E_{HARVEST}$ of 350μJ. The RF module and FET consume 76% and 23% of total energy.

Figs. 13 (a) and (b) show measured time dependence of temperature and illuminance in a meeting room for 24 hours, respectively. By using the developed battery-less wireless sensor node, both the temperature and the illuminance are simultaneously measured every 250s.

IV. Comparison with Previous Works

The proposed EHICPC is compared with the previously published energy harvestings from the insulating cover of power cords. Table II shows a comparison of the energy harvestings from the insulating cover of power cord. Unlike the conventional energy harvesting from the insulating cover of power cords, EHICPC does not require the current in the power cords and the dedicated ground connection, which enables the low-cost installation and the stable monitoring.

V. Conclusions

EHICPC with low installation cost is proposed to enable stable power supply to battery-less wireless temperature and illuminance sensor nodes for BEMS. $I_{HARVEST}$ is 400nA and $P_{HARVEST}$ is 1.4μW at L = 20cm, which enables the wireless sensor node operation every 250s and the range of radio communication is within 100m. Not just BEMS, EHICPC could be applied to wide range of applications where the power codes are available (e.g. structural health monitoring and traffic management).

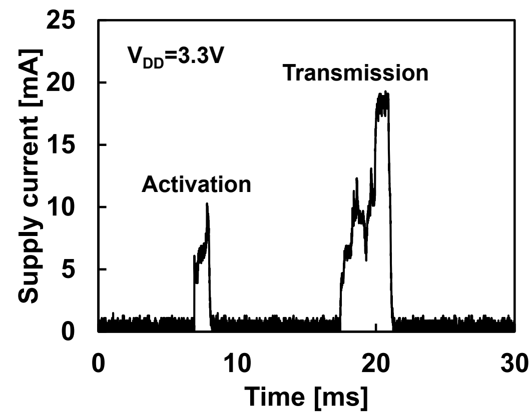


Fig. 11. Measured power supply current of ZigBee module at V_{DD} = 3.3V.

Component	Energy/Operation [μJ]
RF module	204
FET	62
Illuminance sensor	2
Temperature sensor	0.32
Voltage detector	0.004
Leakage of capacitor	0.002
Total	268

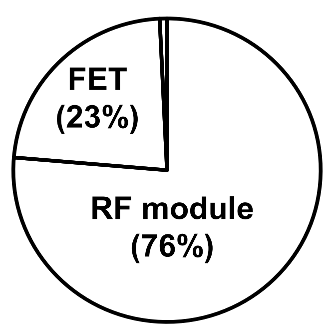
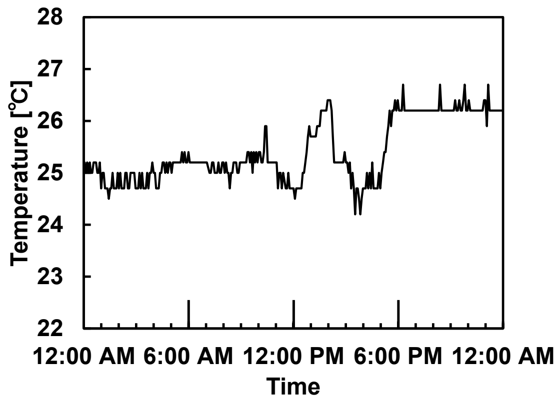
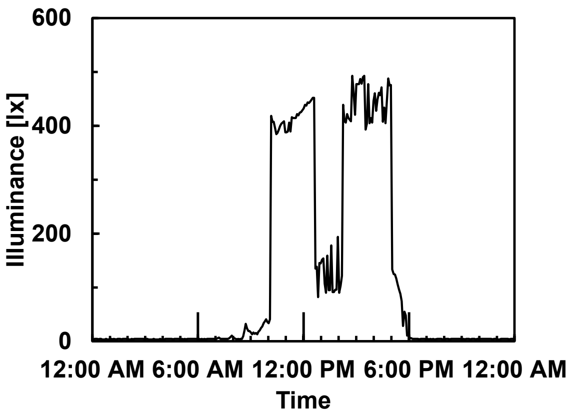


Fig. 12. Measured breakdown of energy in wireless sensor node.



(a)



(b)

Fig. 13. Measured time dependence of (a) temperature and (b) illuminance in meeting room for 24 hours.

Table II Comparison of energy harvestings from insulating cover of power cords

		[1]	[2]	[3]	[5]	This work
Power Source		Magnetic field			Electric field	
Component for energy harvesting		Current Transformer		Piezoelectric bimorph and permanent magnet	20-cm electrodes	
Operation w/o current in power cord		No	No	No	Yes ✓	Yes ✓
Dedicated ground		No ✓	No ✓	No ✓	Yes	No ✓
Harvested	Voltage	1.1-1.3V	2.2-4.7V	NA	19.8-21V	3-4V
	Current	NA	NA	NA	NA	400nA
	Power	940μW	1890μW @4A AC	1120μW @10A AC	8μW	1.4μW

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