Piezoelectric in Energy Harvesting Systems for Wireless Sensor Nodes

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Abstract—**The purpose of this study is to develop mechanical energy harvesting systems using piezoelectric materials for a wireless sensor node. This system is composed of piezoelectric material for mechanical energy harvesting, a power management circuit, an energy storage and a wireless sensor node. Testing shows that a sensor node can transmit a packet every 2.77 seconds or sleep 16.24 seconds interval with a piezoelectric plate attached with a 10-gram mass at the tip. Therefore, the piezoelectric plate is capable of providing the power for a sensor node**

Keywords— **Energy Harvesting Systems, Piezoelectric, Wireless Sensor Node**

I. Introduction

Wireless Sensor Networks involve a large number of sensor nodes in creating networks for measuring various interesting environmental parameters. The data then back up new bodies of knowledge through computational processes or automatically respond to particular environmental changes. For instance, sensor nodes can be installed in chemicals pipeline to detect leakage; sensors can be set to measure machine vibration in factories so that malfunctions are shown and hence appropriate maintenance performed prior to detrimental damages; establishment of sensors to measure livestock health and positions in case of animal loss, etc.

Sensor nodes must be installed on the item we want to measure some parameters. Usually, they are installed at a point where the node is not able to receive electrical power [1], which may be due to difficulty, cost of wiring, or installation on moving items. Thus, sensor nodes require power from batteries. Studies have been conducted on power for wireless sensor networks so that sensor nodes can be used for the longest time possible without having to be removed for recharge. Protocols must also be improved to decrease power in transmitting-receiving data, together with improvement of sensor nodes to rely on less energy and utilization of external energy in battery charging[2].

Usable energy that can be harvested and converted into electrical energy is available in many forms, such as solar power [2], thermal energy [3], or mechanical energy [4], etc. Harvesting solar energy by installing with the nodes involves a number of difficult-to-manage problems, both the day and night time, and the weather. Thermal energy at present still cannot be tapped at a large amount. As for biomechanical energy in moving or vibrating things such as animals, automobiles, or factory machines can be a good alternative for recharging batteries of wireless sensor nodes [5].

Converting mechanical energy from animals to electrical energy is viable from the Piezoelectric Effect, which is a phenomenon a crystal of certain mineral generates electricity when a force is exerted on the crystal [6]. We can use animals' movement or shaking as an exertion of force on the crystal for electrical generation [5].

From above, this research emphasizes how to harvest mechanical energy from animal movement and convert it to electrical energy. The prototype was developed from piezoelectric plates and tested with vibration simulating device evaluating energy obtained. This experiment will test with 1 to 4 piezoelectric plates which are series and parallel connected. The piezoelectric plate also includes 1 to 10 grams mass to compare harvested energy. After that, the result aim to charge the sensor node battery where this research will refer to CC2530 ZNP Mini Target Board energy consumption.

The rest of this paper is organized as follow: Section II present related work. In Section III, the experiment used in our research including testing prototype is provided. Results of our experiment are in Section IV. Finally, the conclusion of our work provides in Section V.

II. Theory and Literature Review

A. *Energy harvesting*

Harvesting of external energy involves operation of the following different parts together [7]:

- Energy Harvester – external energy harvesting part which converts it into electrical energy. This can be energy from light, heat, or movement, etc.

- Power Management – the part managing energy, from conversion of the harvested energy into electrical energy for charging battery, or for system

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supply and even management of battery energy to prevent damage.

- Energy Storage – or battery, which stores or accumulates power for use.

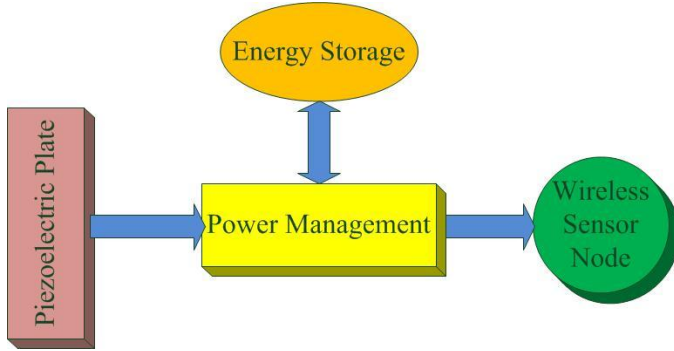A diagram of piezoelectric energy harvesting system for wireless sensor node is shown as Figure 1.

Figure 1 A system which piezoelectric energy is harvested

B. *Piezoelectric Materials*

Piezoelectric is conversion of a material's mechanical force exerted on it into electricity, as shown in Figure 2(a). Such energy conversion is called direct effect. On the contrary, when the material receives electrical energy, it will deform mechanically, as shown in Figure 2(b), which is referred to as indirect effect [6].
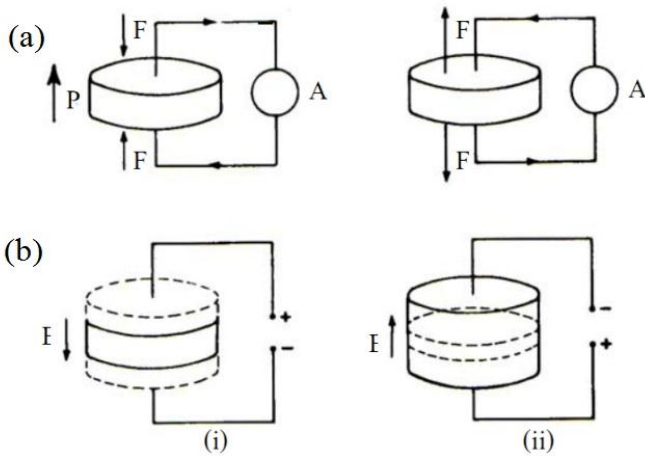

Figure 2 (a) direct effect, (b) indirect effect
(i) contracting material, (ii) expanding material [8]

C. *Energy Consumption of Wireless sensor nodes*

Appropriate design of energy harvesting system for wireless sensor nodes is based on how much energy the nodes consume in order for the system to harvest adequate energy for the wireless sensor nodes without having to unnecessarily enlarge the sensor size.

The research [9] tested energy consumption of CC2530ZNP principally using CC2530 ZNP Mini Kit (Figure. 3), which has the CC2530 ZNP Mini Target board as the wireless nodes.

Figure 3 ZNP Mini Kit [9] (a) ZNP Mini Kit Target board,
(b) eZ430 USB Stick with target board (c) ZNP Mini Kit Battery board

Energy consumption is measured from current flowing past and decreasing voltage on a constant resistant, as shown in Figure 4.
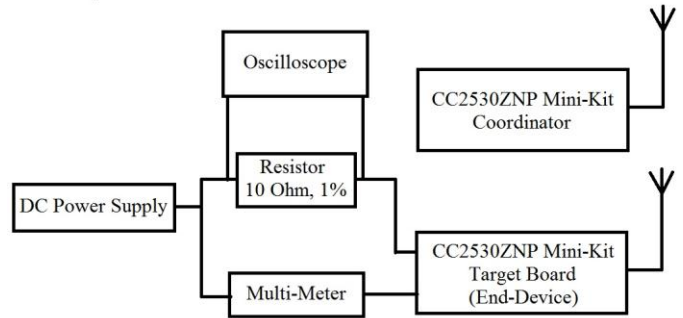

Figure 4 Energy Consumption Measurement pattern [9]

Calculation of energy consumption starts from basic relationship, i.e., $V = I * R$.

When V is the voltage, R is the resistance, and I is the current, measurement starts from the power supply. The voltage on the target board declines from resistance. Then

$$V_{Target\ Board} = V_{Power\ Supply} - (I * R)$$

As long as current remains in the range of some ten of mA, and resistance is relatively small, resistance has little impact on the decline of voltage. In general, this is usually not calculated. So,

$$V_{Target\ Board} = V_{Power\ Supply}$$

Only when $(I * R) << V_{Power\ Supply}$

$(I * R) << V_{Power\ Supply}$ where $V_{Power\ Supply} > 10 * (I * R)$

Given R = 10 Ohm, the condition is true as long as I < 30 mA. We know average I from any equation:

$$I_{avg} = \sum(T_i/P_i * I) + (1 - \sum (T_i/P_i)) * I_{Sleep}$$

When

T_i = the time the device consumes an average current Ii

P_i = the total time cycle for averaging measurement of energy consumption

I_{Sleep} = the current consumed during sleep mode

I_{avg} = Average consumption of electricity in cycle Pi

Electricity consumption is measured by wireless sensor nodes sending packets continuously every 10 minutes. Then an oscilloscope is used to measure voltage as in Figure 5.
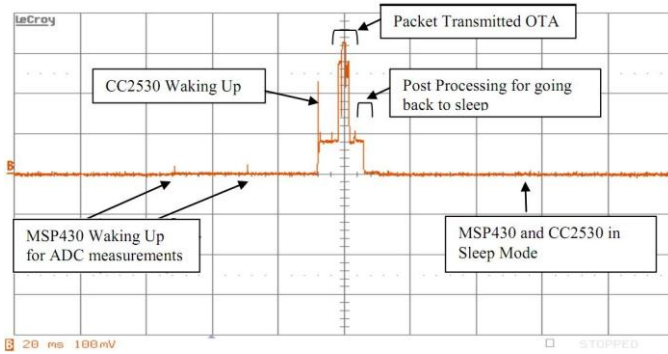

Figure 5 Current while sensor nodes transmit a packet [9]

The voltage measured in Figure 5 is calculated to obtain power consumption as shown in Table 1.

Table 1 Measured current consumption while a packet is transmitted

id	Description	Duration [ms]	Current [mA]	Power [ms*mA]
1	ADC Conversion	44	0.17	7.48
2	Synchronize and processing data	6	8.5	51
3	transmit packet and receive ACK	3.5	28.9	101.15
4	Post processing and deep sleep	5	8.5	42.5
	Sum	58.5		202.13
	Average		3.46	

The data obtained is calculated for average current while the data is sent. Current consumption of wireless sensor nodes during sleep mode is 4.8 uA, we get:

$((58.5)/10000*3.46) + (1-(58.5)/10000) * 0.0048$ mA $= 0.0249$ mA

thus, the average current consumption when data is sent is 0.0249 mA.

III. Experiment

We use piezoelectric plates V21BL from Mide Technology Corporation shown in Figure 6 and its dimension is shown in Figure 7.

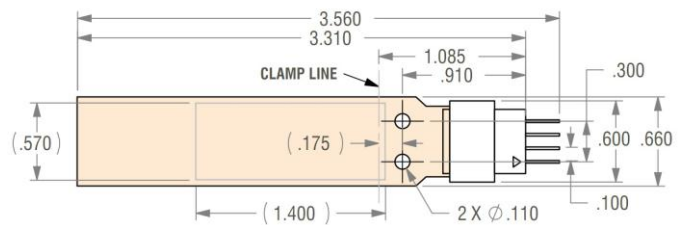Figure 6 Piezoelectric plate (V21BL)

Figure 7 Dimensin of V21BL piezoelectric plate

An energy harvesting circuit EH301 from Advanced Linear Devices, Inc is selected as in Figure 8. The circuit allows piezoelectric plates to charge the capacitor until 5.2 volts before it distributes the power to the loads (a battery, resistor or sensor node) until the voltage drop to 3.1 volts and then recharge again. Therefore, approximately 8.3 mJ is obtained from each cycle.

Figure 8 An energy harvesting circuit (EH301)

To emulate animal walking step, the vibration simulator was designed as shown in Figure 9. Figure 10 shows the complete prototype. Figure 11 illustrates the piezoelectric plates attached on a 2 Kg mass which is also mounted with 4-circle Floor Care pad 28 mm and thick 5 mm to reduce mass's impact. The mass is lifted 9 cm height. The other end of the prototype is fixed with a motor which rotates 50 rpm to lift and drop the mass. The piezoelectric plates are connected to EH301 as shown in Figure 12.
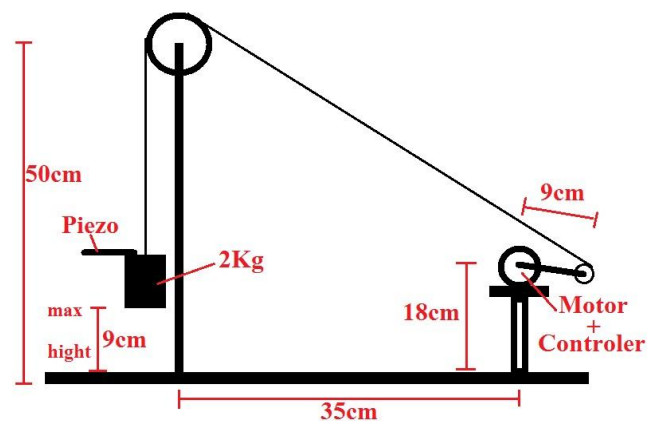

Figure 9 Dimension of vibration simulator
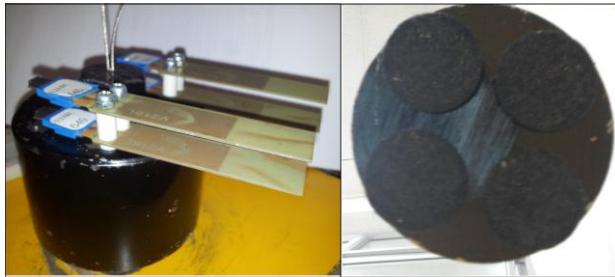
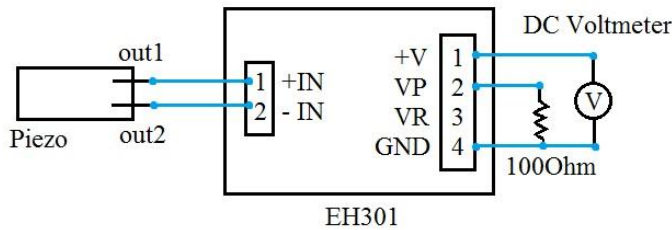Figure 10 Vibration simulator

Figure 11 Piezoelectric and 2Kg mass

Figure 12 Connecting of prototype for tesing

First, we study the average cycle time of the EH301circuit by serial and parallel piezoelectric plates. Table 2 shows the average time for the different number of plates installed. Note that because of series and parallel connection required a bridge as shown in Figure 13, the complete cycle time is higher in case of single piezoelectric plate. However, when we increase the number of piezoelectric plates, the cycle time is lower as expected. Moreover, testing shows that the serial connection is faster the cycle time than the parallel connection.

Table 2 Average time for harvesting a cycle of energy

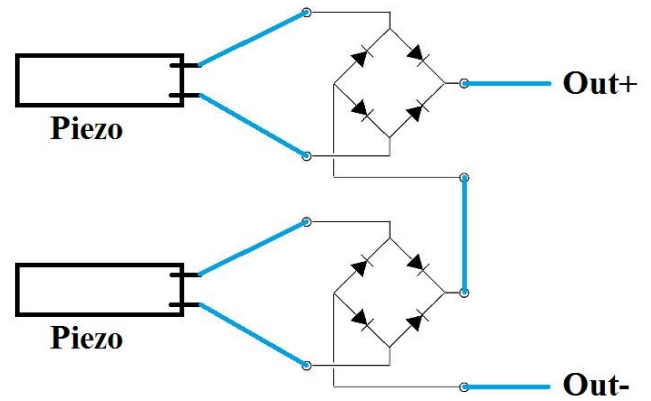| Quantity Connecting	1	2	4
Direct connect	621.7 s		
Series-Bridge	782.8 s	485.2 s	298.6 s
Parallel-Bridge	782.8 s	504.6 s	328.8 s

Figure 13 Piezoelectric with bridge rectifier which are connected in series

Figure 14 compares the harvested energy per second. This confirms that the serial plates give a better energy than that of parallel plates.
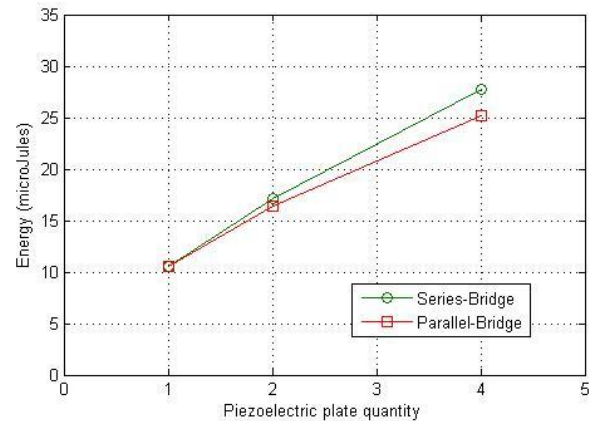

Figure 14 Energy which is harvested in a second

The second experiment was done by attaching 1-10 gram mass to the tip of piezoelectric plate. Figure 15 and Figure 16 show results of this experiment. The mass has a significant effect to the average cycle time because it increase bending distance of the piezoelectric plate.
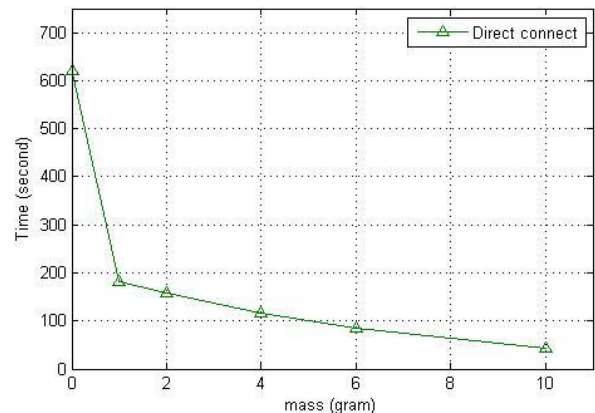

Figure 15 Time to harvesting a cycle when mass is add

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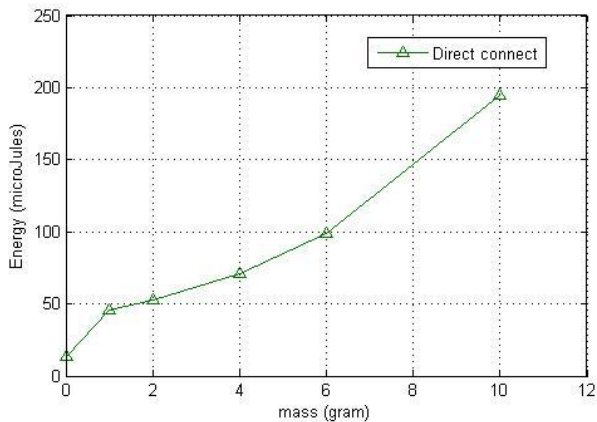
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Figure 16 Energy which obtain in a second when mass is added

For above result, we refer to CC2530 ZNP Mini Target board which consumes 4.8 uA in sleep mode [9]. For a packet transmission, the board consumes 3.46 mA in 58.5 ms [9]. To analyze the harvested energy, we consider Figure 16 when the a 10-gram mass is used and CC2530 ZNP Mini Target board supplies by 3 volts battery. Therefore,

The sleep mode requires

$$4.8 \text{ uA} * 3 \text{ V} = 14.4 \text{ uJ/s}$$

A packet transmission requires

$$3.46 \text{ mA} * 58.5 \text{ ms} * 3\text{V} = 607 \text{ uJ/packet}$$

A walking step gives

$$194.84 * 60 / 50 = 233.81 \text{ uJ/step}$$

Thus, each step can supply the sensor node in the sleep mode

$$233.81/14.4 = 16.24 \text{ seconds}$$

The number of steps required to transmit a packet is

$$607 / 233.81 = 2.6 \text{ step}$$

Assumed that a step per second, thus a sensor node can transmits a packet at every

$$607 / (233.81 - 14.4) = 2.77 \text{ seconds}$$

IV. Conclusion

This research reveals that the energy obtained is adequate for application with wireless sensor nodes. The attached mass at the tip of piezoelectric plate can increase the harvested energy and reduce the complete cycle time of the harvesting circuit. For instance, if a piezoelectric plate added with 10 gram is forced as simulator with 1 hertz, the sensor node is able to transmit a packet every 2.77 seconds. Also, the addition of piezoelectric plate can reduce the average cycle time by half. Therefore, the use of piezoelectric plate can applied to the sensor node.

Acknowledgment (Heading 5)

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