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Experimental Investigation of Remote Vibration Sensing with Locally-Powered Devices

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Abstract

Self-power sensors at multiple places in a network will be required for advanced wireless communication infrastructure, which comprises remote sensing technologies, networks, and data management. It is still difficult to power these sensors and their related transmitters or receivers. Local energy harvesting presents a chance to mitigate or eliminate the impact of this problem as an enabling technology. We create a self-powered real-time point-to-point wireless communication system, also known as transmission power self-optimization, that adapts the transmission power of a specific node in a wireless sensor network to the requirements. The transmitter module co-located with a vibrating object harvests and stores energy from vibration through piezoelectric components. Even when the vibrating source has very little energy, the collected energy allows for reliable wireless communication. The proposed system is discussed in detail, and data on voltage sensing, harvested power storage, and current are examined.

Keywords: *Smart sensors; Energy harvesting; Internet of Things; Vibration sensing; Wireless transmission*

1. Introduction

In the context of the Internet of Things and intelligent systems, effective sensing relies on the wireless connectivity of spatially distributed autonomous sensors and devices that acquire and transmit data to a primary location. To date, the majority of sensing and wireless transmission devices rely on wired connections or batteries that require frequent replacement, which may not be practical depending on the needs and applications. Although the lifespan of batteries can be extended in some applications by setting the sensor in the sleep mode and waking it up only when data is needed, fitting and replacing batteries may not always be possible, especially in remote and inaccessible locations. In contrast, advances made towards the development of low-power microcontrollers and sensing devices and ultra-low-power wireless technologies open the opportunity for substituting depletable batteries with low levels of locally-harvested energy to power sensing and communication devices.

The predominant approach to exploit locally harvested energy is to use an auxiliary harvester, such as a solar, thermoelectric, or mechanical energy harvester, to operate vibration/flow sensing and transmission devices [1]. However, there exist some challenges. Simjee and Chou [2] noted that, in low-power applications, the interaction between the harvesting circuit of small-scale solar harvester systems and the powered device affects the feasibility of designing a solar harvester independently from the embedded systems. Similar issues must be addressed when using low-current piezoelectric transducers or low-voltage thermoelectric generators. Al Nuaimi et al. [3] proposed a phenomenological model for energy harvesting from galloping oscillations using piezoelectric.

Given that a monitored quantity, such as vibrations, temperature, or flow speed, can also be considered as an energy source, it would be advantageous in many applications to use the monitored system as the energy source. There is better matching between the required power and sensing needs with this capability. Furthermore, the size of the sensing and communication elements is reduced because there is no need to attach an auxiliary energy harvester. More importantly, using the monitored system as the energy source allows for implementing sensing and communication in challenging environments and applications. For instance, it is impossible to add an auxiliary device to power a fish tag that monitors the

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migration behavior and survival of fish species. In that respect, using a depletable battery is not an option. One approach would be a piezoelectric energy harvester from fish motion to power a piezoelectric-based acoustic transmitter such as the one developed by Deng et al. [4].

Different approaches have been considered to use the monitored system as the energy source. Liu et al. [5] proposed a self-sustained flow-sensing microsystem consisting of a PZT micro-cantilever beam powered by an array of similar micro-cantilevers that harvest energy from wind-driven vibrations without consideration of wireless transmission. Li et al. [6] implemented a battery-free acoustic transmitter powered by a flexible piezoelectric beam which harvests energy from fish swimming. Tan et al. [7] used a wind turbine to generate power for a wireless sensing node that measures the wind speed for predicting wildfire spreading. Alrowaijeh et al. [8] presented autonomous airspeed sensing without a need for wired connections to an external power source or batteries.

Recognizing the challenges in supporting self-powered wireless vibration measurement systems using power harvested from piezoelectric beams, in this work we performed experiments that identify these challenges and approaches to overcome them. Particularly, we established a self-powered real-time point-to-point wireless communication system between a vibration sensor and transmission and receiving modules. The sensing device and transmission module are powered by the vibrating object using a piezoelectric energy harvester. The communication is established by using two XBee modules. A schematic of the proposed system is presented in Figure 1. The interest is in remote sensing of the vibrations of a beam attached to the vibration source. Towards that objective, an energy harvesting module is also connected to the vibrating source to harvest energy that would power the sensing circuit and transmission module. The energy harvesting module includes a piezoelectric beam, a circuit, and a capacitor for energy storage. This capacitor powers the sensing circuit and the transmitting XBee module. The transmitted signal is then received wirelessly by another XBee controlled by an Arduino and a computer.

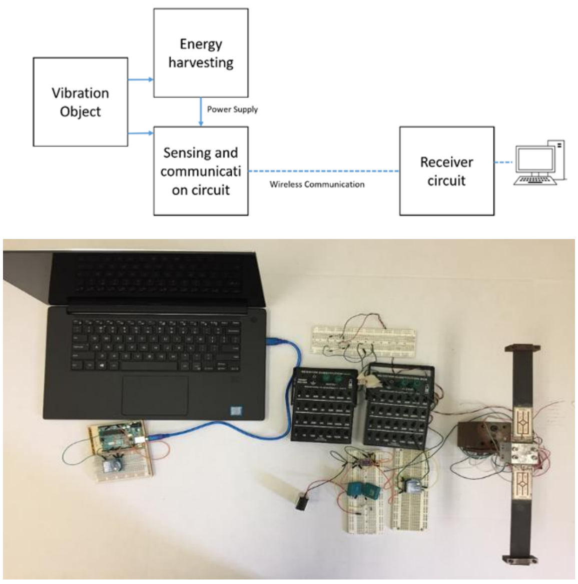

Fig. 1: Overall layout of the implementation scheme

2. Methodology

A 900-lb permanent-magnet shaker driven by an amplified signal from a function generator is used as the vibration source, as shown in the schematic presented in Figure 2. The harvester consists of a cantilever beam with a piezoelectric patch that is mounted on the shaker. The composite beams geometric, material, and of piezoelectric patch properties are presented in Table 1 and Table 2, respectively.

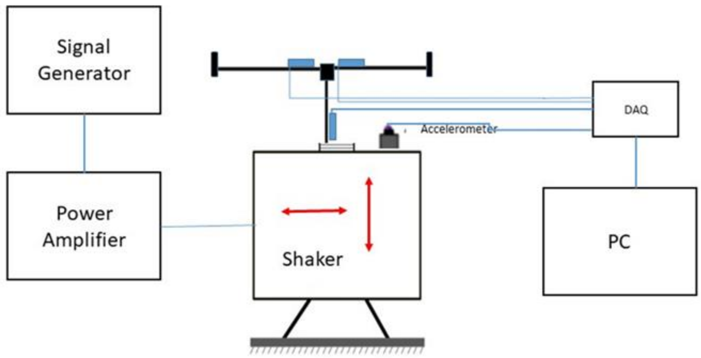

Fig. 2: Illustration of the vibration source

Table 1: Material and geometric parameters of the composite beam

Property	value
Mass density (ρ)	1409 Kg/m^3
Young's Modulus (E)	60 GPa
Length (l)	150 mm
Width (b)	25.4 mm
Thickness (t)	1 mm
Mass of the tip (m)	35.2 gm

Table 2: Piezoelectric patch PPA-1001 (MIDE engineering solutions) materials properties

Layer material	Thickness(mm)
Polyester	0.05
Copper	0.03
PZT 5H	0.15
Stainless Steel 304	0.15
Polyimide	0.03
Total	0.46

3. Results and Discussion

The power output of the piezoelectric device is intermittent, alternating, and noisy, depending upon the vibrating source. Therefore, a suitable interface is needed to store the available power from the piezoelectric device and provide a stable power supply. Moreover, a backup medium-term to a long-term storage device may be required to ensure uninterrupted communications during instances of low vibrational energy. Based on these considerations, a battery and super-capacitor-assisted energy harvester circuit is developed using the energy harvesting module LTC-3588. The overall scheme for the energy harvester circuit is shown in Figure 3. The voltage output of the LTC-3588 is set to 3.3V.

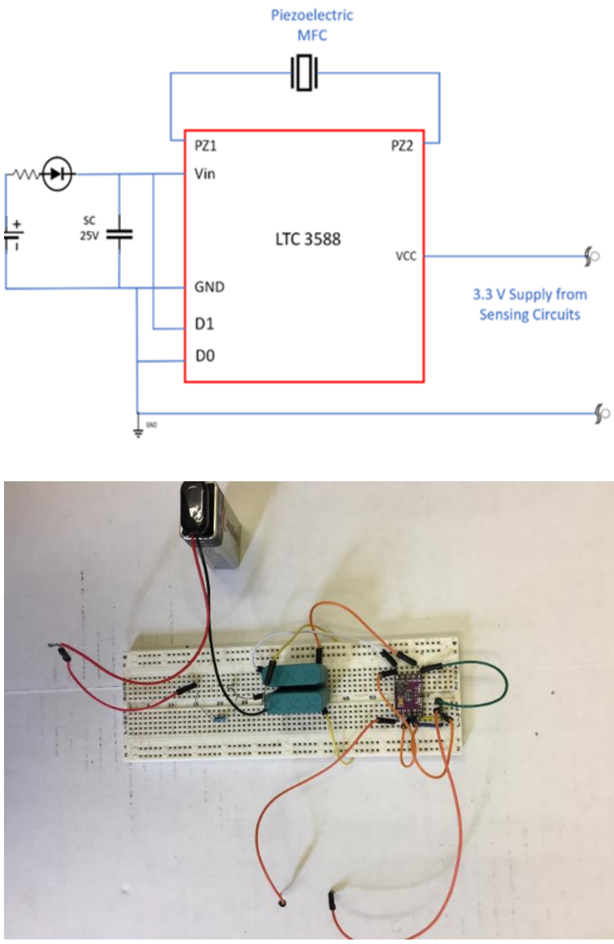

Fig. 3: Block diagram of the energy harvesting circuit and 3.3V supply to sensing circuit

The energy harvested from the piezoelectric device is stored in the super-capacitor. A backup 9-Volt battery is connected in parallel with the super-capacitor to ensure uninterrupted communications even if the piezoelectric device does not generate energy for a considerably long time. Note that a diode and a resistor are inserted between the battery and super-capacitor to limit the current and possible reverse power flow that could damage the battery. Finally, the 3.3V DC power output from the Vcc pin of LTC-3588 IC is sent out to the sensing circuit as required by the communication circuit

These requirements result in the sensing circuit diagram presented in Figure 4 attached to the transmitting module. The full-wave bridge rectifier shown in this figure is built using four diodes. For an input signal X(t), the output of the full-wave rectifier is the absolute value of |X(t)|. A resistance potential divider is used to step down the voltage in the range of the XBee. For the input signal |X(t)| to the potential divider, its output at the acquisition point is R2|X(t)|/(R1+R2). It should be noted that the voltage step-down factor depends only on the relative magnitudes of the resistance limbs R1 and R2 and not on individual values. However, large values for R1 and R2 help in keeping the power loss in the potential divider low. Hence, the values of the two resistances were chosen to be R1=1 MΩ, R2=100 kΩ. Thus, for an input voltage signal from piezoelectric between -35 V and +35 V, the final signal R2|X(t)|/(R1+R2) transmitted to the XBee module is limited to values between 0 and 3.3 Volts, which is within the desired limits. The output signal from the potential divider, conditioned for the ADC input of XBee, is then sent to the D0 pin of XBee1, which is configured as an ADC pin. The XBee1 serves as a router that sends the local measurements to the remote receiving unit XBee2. The transmission range for the XBee modules used in this setup is between 30m (indoor) and 50m (outdoor). Higher configuration devices may be used to extend the communication range, as needed. The ADC in XBee1 needs a reference voltage Vref to serve as the analog equivalent of the highest discrete value of 10^2. To attain the maximum resolution, the reference is chosen as Vref = 3.3V. Thus, the Vref pin on XBee1 is connected to the Vcc, the supply voltage pin.

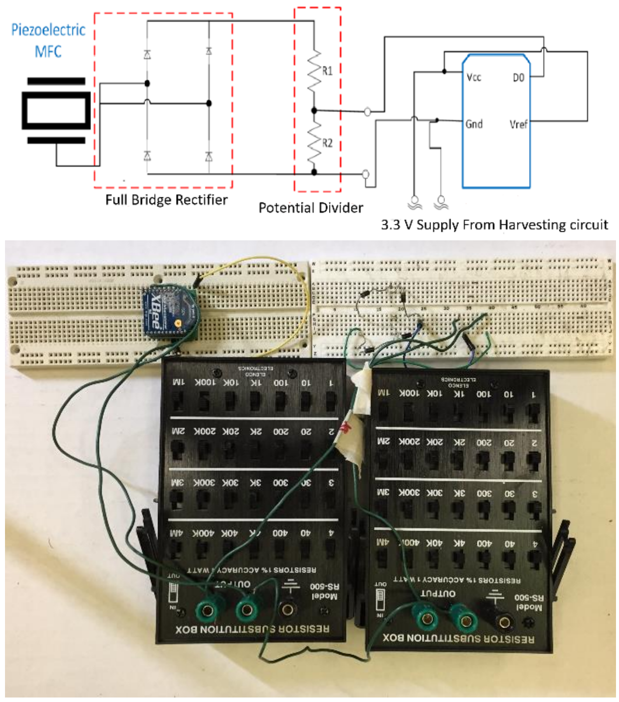

Fig. 4: Block diagram of the sensing circuit along with the actual setup

The receiver XBee-2 receives the data transmitted by XBee-1 shown in Figure 5. XBee-2 passes on the data received from XBee-1 to an Arduino circuit through the Tx-Rx pins. The onboard 3.3V DC power supply from the Arduino board is used to power XBee-2. The Arduino board can conveniently communicate with a PC using a USB connection. However, the data received by XBee-2 is in a specific XBee protocol, which needs to be externally decoded in the Arduino web editor software. A detailed list of components used in building the energy harvesting, sensing, and receiver circuits is provided in Table 3. They need to be configured suitably to establish successful communication between the two XBees. To do so, the open-source configuration software X-CTU 6.3 was used. For each node, we used X-CTU software provided by Digi International. This software enables the user to update the parameters and efficiently perform communication testing. The router radio is also loaded with AT Firmware, and the Coordinator's Source Address (Serial Number SH, SL) is presented as the Destination address DH, DL.The PAN ID and Baud Rate should be the same for both router and coordinate. The pin 20 (Digital Input/Output) DIO 0 of Router to be connected to the pin is declared as DIGITAL INPUT. Also, the IR sampling rate is set as hex value 1388, which equals 5000 in decimal, i.e., a digital sample is sent every 5000 ms or 5 seconds in the router node.

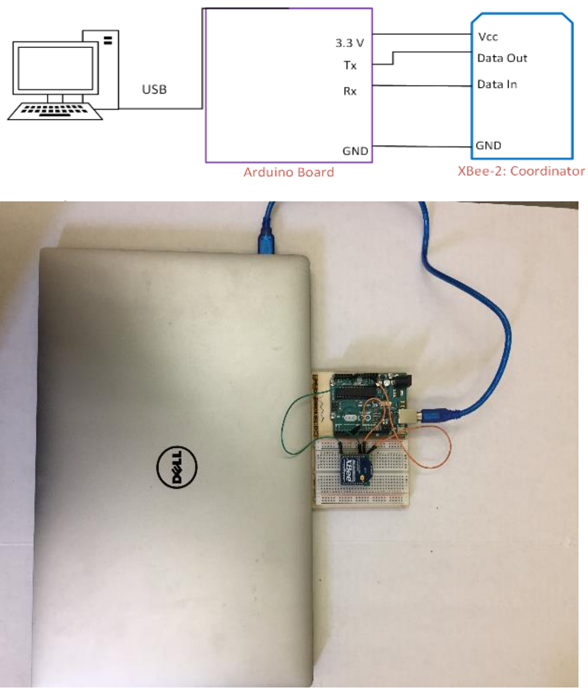

Fig. 5: Block diagram of the communication circuit

Table 3: Component description for the circuits

Sr No.	Component name	Circuit	Description
1	XBee-1 & XBee-2	Communication	Series 1, 1mW modules from Digi International
2	Diodes	Sensing	1N4007 Rectifier Diode 1a 1000v
3	Resistances	Sensing	R1 = 1 MΩ, R2 = 100kΩ
4	Piezoelectric Patch	Sensing	PPA-1001
5	Supercapacitor	Harvesting	9V1F ESR, 350 mΩ 8x22 mm Radial Lds
6	LTC-3588	Harvesting	Energy Harvest Collector
7	ARDUINO UNO	Receiver	ATMEGA328, ARDUINO UNO R3 SMD ED

The following figures present the results to demonstrate the process of recovering the signal from a vibrating object from the actual signal received by the receiver circuit of Figure 5. The rectified and scaled-down time-series signal from a vibrating object is shown in Figure 6. Considering that the original signal is alternating, the recovered shape of the original signal can be obtained by flipping the alternate half-cycles of the rectified signal received. The transformed signal is shown in Figure 7. From the resistance values of the potential divider used in the sensing circuit, it is known that the original signal was scaled down by a ratio of 11:1. Finally, the initially transmitted signal was retrieved by scaling up by the same factor, as shown in Figure 8.

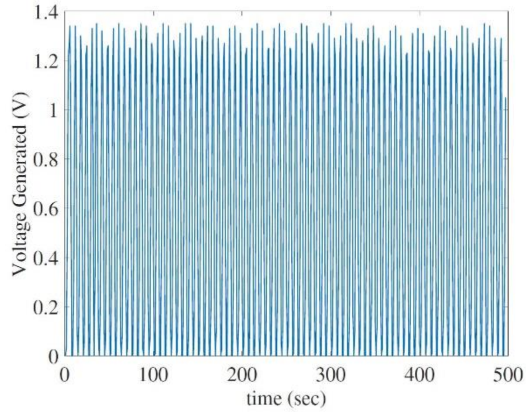

Fig. 6: Time series of the communicated signal

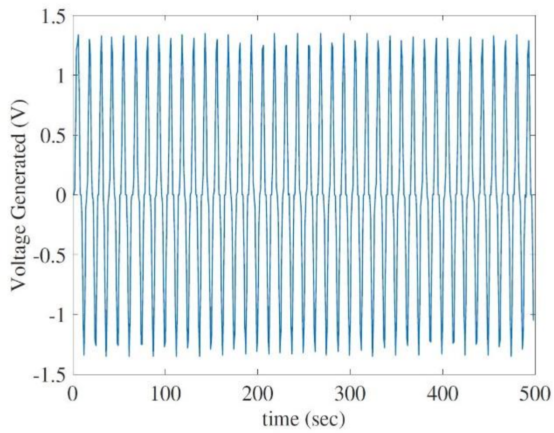

Fig. 7: Time series of the full wave rectifier original signal multiplied by a factor of -1

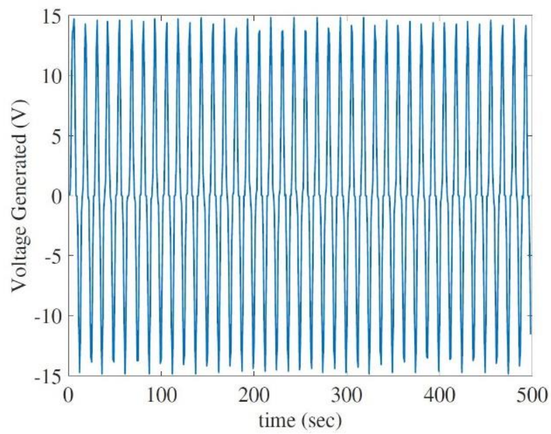

Fig. 8: Time series of measured signal multiplied by a factor of 11

4. Conclusion

Vibration-based energy harvesting technologies in support of powering sensing and communication devices. We presented a configuration that uses energy harvested from a vibration source to power communication modules of sensed vibrations of the source itself. The sensing device and transmission module are powered by the vibrating object using a piezoelectric energy harvester. The communication is established by using two XBee modules. The results demonstrated recovering the signal from a vibrating object from the actual signal received by the receiver circuit. The assessed the accuracy of the system by comparing the sensing voltage of the system.

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