A Test-bed based Guideline for Multi-Source Energy Harvesting

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Abstract

New battery recharging techniques should be developed for the continuous operation for the wireless devices and networks. This study investigates the setup of multi-source energy harvesting system and determines an efficient operating point to capture energy from various energy sources. With our multi-source energy harvesting system, we aim to operate system in different environmental conditions. The continuity of recharging the batteries all the time is a critical aspect of this approach. With this objective, we use multiple energy sources. We design our test set-up and perform measurements. Specifically, we use radio frequency, thermal, and solar energy harvesting sources in the same circuit structure. As expected, our results demonstrate that the continuity of charging is obtainable in the presence of multiple energy sources, which provides a robust energy harvesting system.

1. Introduction

Currently, energy requirement for communication networks is of great importance with the ever-growing communication networks. In practice, energy requirements of wireless and mobile communication devices are provided via disposable or rechargeable (by cable) batteries. Both of solutions, i.e. disposable and rechargeable batteries, cause some important problems. In case of using a disposable battery, the lifetime of devices (especially wireless devices) is limited by the capacity of disposable battery. If it is not changed when the battery runs out. The replacement of disposable batteries may not be feasible due to some challenges such as high operational costs, rough physical conditions, and large number of devices. Thus, wireless communication devices equipped with limited capacity disposable batteries also limit the lifetime of wireless communication network. On the other hand, in case of using a rechargeable battery, the discharge of battery requires recharging process. Wireless devices equipped with rechargeable batteries need an appropriate recharging device and an appropriate recharging environment. Otherwise, if the battery can not be recharged, the performance of wireless device and communication network deteriorates proportional to the time with insufficient energy.

In order to overcome these problems, energy harvesting has been proposed as a solution, and frequently studied in the recent years [1]. The fundamental aim of energy harvesting is to ensure self-sufficient devices and networks in terms of energy. Wireless communication devices equipped with energy harvesting circuits provide their own energies from the energy sources in the ambient. Possible energy sources in the ambient for energy harvesting can be classified as radiative energy sources (sunlight, radio frequency (RF) waves) [2, 3], thermal energy sources (air heat, body heat) [4], and mechanical energy sources (air flow, body move, vibration) [5]. All these sources have advantages and disadvantages based on the environmental conditions and the target application. For instance, although sunlight is the most available source of energy, it shows important change according to the various times of day and different weather conditions.

Generally, the research studies have been carried out based on a single energy source. However, the amount of energy may not be sufficient in case of using single energy source. More than one energy sources among various types of energy in the ambient can be jointly used in an energy harvesting system. Many benefits, which increase system performance, can be obtained simultaneously with the use of multi-source in the energy harvesting systems. Using multiple energy sources provides energy diversity gain to the energy harvesting system. This approach alleviates the energy outage problem. It makes possible to power wireless devices equipped with energy harvesting circuits without batteries or with low capacity rechargeable batteries. We can possibly obtain all-time active wireless devices with no need to recharge the battery from the end user perspective.

In this paper, we investigate the use of two or more energy sources in the energy harvesting systems, which not only increases of amount of harvested energy but also makes it possible to harvest required energy on time. We investigate the setup of multi-source energy harvesting. We highlight the different usage areas by comparing the properties of parallel and serial connection architectures. We design and implement multi-source energy harvesting system by combining RF energy, thermal energy, and solar energy in our test system. We compare single-source and multi-source system performances in terms of the

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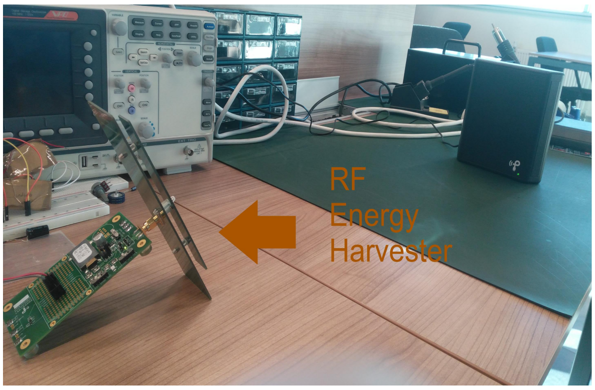

Figure 1: Test setup of RF energy harvesting system.

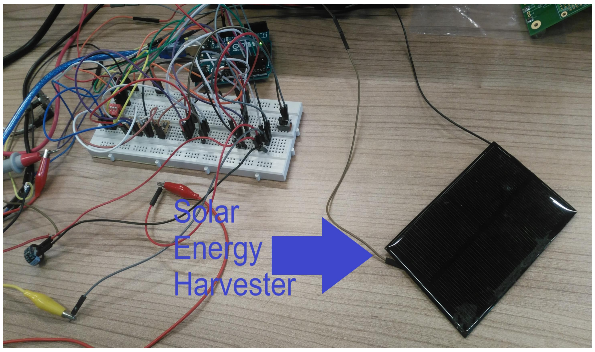

Figure 2: Test setup of solar energy harvesting system.

time required to recharge the capacitor.

This paper is organized as follows. In Section 2, we provide an overview of the energy harvester types based on energy sources. In Section 3, we investigate parallel connection and serial connection options for multi-source energy harvesting, and then investigate their practical implications. In Section 4, we detail the test system for the multi-source energy harvesting circuit and provide measurement results. Finally the paper is concluded in Section 5.

2. Energy Harvester Types

2.1. RF Energy Harvester

Generally, RF signals with low carrier frequencies are preferred as a target RF source due to its lower path-loss. Although RF signals at various frequency flow through air, their signal power may be weak with respect to the required minimum RF input power of harvester systems. Even the most efficient RF energy harvesters may not be able to harvest RF signals with an energy below -20 dBm. Therefore, transmitters dedicated specifically for RF energy transmission are essential within short distance. Fort these reasons, 915 MHz, which is allowed to use for industrial purposes, is chosen as RF harvester target frequency. Powercast P2110, which operates down to -11.5 dBm input power, is used as a RF to direct current (DC) converter, as detailed in Section 4. Evaluation board of Powercast P2110 is shown in Fig. 1. It provides 3.3 V output voltage.

2.2. Solar Energy Harvester

Sun is one of the most preferred energy harvesting sources. Unlike RF sources, the intensity of sunlight is high enough for energy harvesting in the daytime. Main disadvantages of solar energy harvesting over RF energy harvesting is the fact that the availability of solar energy highly depends on weather conditions. In solar harvester circuits, a solar panel is employed to absorb the sunlight at the first stage. The output voltage of the solar panel varies from 0 to 5 V according to intensity of the light. Thus, a 78l03 regulator is used to obtain 3.3 V constant output voltage. Test setup of solar energy harvesting system is shown in Fig. 2.

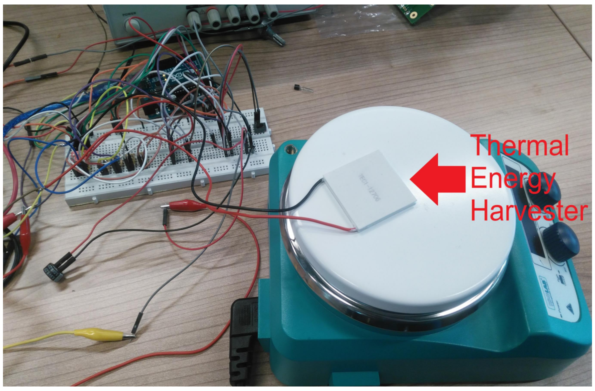

Figure 3: Test setup of thermal energy harvesting system.

2.3. Thermal Energy Harvester

The thermal energy harvesters utilize a thermoelectric generator to convert thermal energy to electrical energy. Thermoelectric generators are robust devices due to their long life operation and extremely reliable features. Thermoelectric generators have p-type and n-type semiconductor materials between hot and cold junction. They generate electricity by dissipating the heat between its hot and cold side. Therefore, temperature difference between two side of the thermoelectric generator is required. On the contrary of solar panels, thermoelectric devices generate a low DC output voltage. Thus, DC-DC converter, LTC3108 is used to obtain 3.3 V constant output voltage. Test setup of thermal energy harvesting system is shown in Fig. 3.

2.4. Hybrid Energy Harvester

Hybrid energy harvesters utilize different energy sources like solar, RF and thermal energy to improve the performance of energy harvesting systems. Fig. 4 shows the investigated multi-source energy harvesting system. Each source is connected in parallel. The harvested signals from RF source is alternative current (AC) signal. It is converted to DC signal by AC-DC converter. Energy harvested from solar and thermal energy sources are obtained in DC form. Since zener diodes have a lower reverse leakage current compared to Schottky diode, each parallel branch is connected with a zener diode to avoid reverse current flow from storage capacitor. To avoid reverse current flow up to

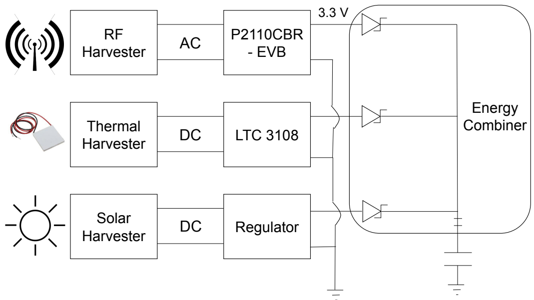

Figure 4: A block diagram of hybrid energy harvesting system.

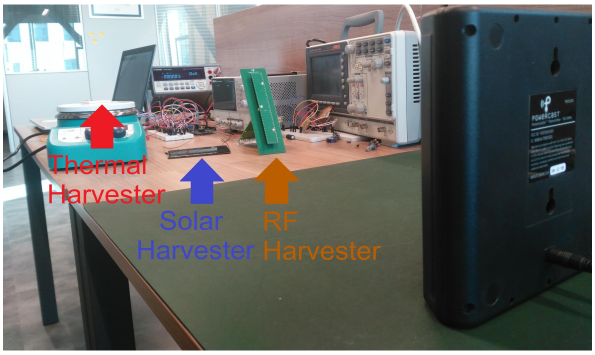

Figure 5: Test setup of multi-source energy harvesting system.

3.3 V voltage difference between capacitor and harvester circuit outputs, zener diode with 3.3 V breakdown voltage is used.

3. Connection Architectures for Multi-Source Energy Harvesting

In multi-source energy harvesting systems, it is critical to properly combine the used energy sources. In general, low-power electrical devices such as wireless sensor nodes need DC signal. Therefore, even if the transducer of an energy harvester for a particular energy source generates AC signal, it should be converted to DC by the use of a rectification circuit. In this case, DC signals need to be properly combined in the multi-source energy harvesting systems. Researchers have been studying this problem [6, 7, 8, 9]. In [6], different connection types of solar cells, including serial, parallel and hybrid serial-parallel connections, are examined to obtain the maximum output power. In [7], the rectified signals obtained from the different RF bands are combined in serial (summation of voltages) and parallel (summation of currents) forms. In [8], it is shown that different energy sources can be connected with three different ways in serial by changing the used power control approaches. In [9], DC signals are connected in serial, parallel, and cascaded forms. Their performances are analyzed in terms of conversion efficiency, output DC voltage, and output DC current. Both serial and parallel connection methods have some advantages and disadvantages.

Serial connections provide a higher voltage level by summing the voltage of each energy source, which reduces the likelihood of the need for a voltage booster. Serial connections also make it easier to reach the voltage sensitivity level of energy harvester. On the other hand, in serial connection, all energy sources share the same current, which may cause each energy source to fail to deliver the maximum power. An energy harvesting system with serial connection is designed according to the total voltage level of energy sources. In that case, the outage of an energy source may lead to the outage of the energy harvesting system, which reduces the robustness of the energy harvesting system.

On the other hand, parallel connections provide parallel combination of energy sources, which allows to run each DC power supply at its maximum power point. In addition, each source can individually feed the energy harvesting system, hence possibly preventing the outage of the energy harvesting system. Parallel source connections improve the robustness of the energy harvesting systems. On the other hand, in parallel connection, the output voltage level of each source should be close to each other. Otherwise, only an energy source with higher voltage level becomes more dominant. In this paper, we preferred to use the parallel connection method to ensure the robustness of the energy harvesting system, as detailed in the following section.

4. Test System Design and Measurement Results

4.1. Test System

The proposed energy harvester system consists of RF, thermal, and solar energy harvesting circuits. Test setup of multi-source energy harvesting system is shown in Fig. 5. All harvester circuits generate 3.3 V output voltage. The harvested energy is stored at 0.22 F super-capacitor. To monitor the output voltage values of each harvester circuit, output nodes of harvester circuits are connected to an Arduino development board. Also, a multimeter is connected to the hybrid structure output to measure the voltage of the capacitor and to monitor its changes with respect to time. All energy harvester circuits are connected to the storage capacitor by a zener diode to ensure one way current flow thereby avoiding discharge of the capacitor. Voltage drop on these diodes is approximately 0.9 V. Therefore, diodes will provide less current when capacitor voltage exceeds 2.4 V voltage level.

In the RF energy harvesting part, our antenna captures the radio waves in the air, then these radio waves are fed to the energy harvesting kit. This kit has different kinds of power, amplifier, and regulator circuits. Consequently, we can obtain stable 3.3V voltage that is required for our study. Powercast P2110CBR-EVB model is used as the RF energy harvesting kit. This energy harvester's interval of output voltage is 1.8 V to 5.2V. We use 3.3 V status during the tests. This kit seizes RF signals in AC form. Then it transforms the AC signal into DC signal.

In the thermal energy harvesting part, we use TEC1-12706 thermoelectric cooler. After the thermoelectric cooler, we use a regulator which is Linear Technology Ultralow Voltage Step-Up Converter and Power Manager LTC3108. This regulator's selectable output voltages are 2.35 V, 3.3 V, 4.1 V, and 5 V. We use it to keep the voltage stable at 3.3 V. Firstly, we heat the thermoelectric cooler with the purpose to create a temperature difference between thermoelectric cooler's top and bottom. Thus, we can harvest energy for the system. The voltage keeps stable again due to the presence of the regulator circuit.

A similar process is valid for sunlight for the solar energy

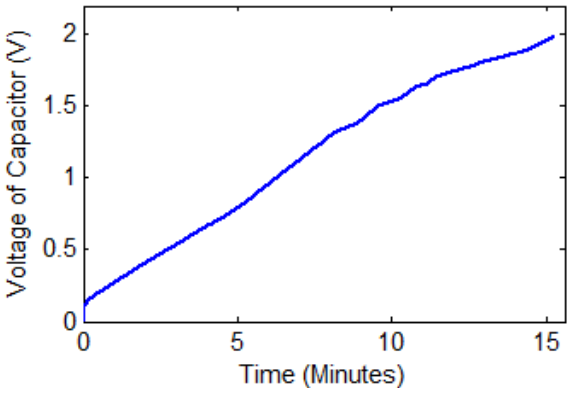

Figure 6: Measurement results of capacitor voltage during solar energy harvesting.

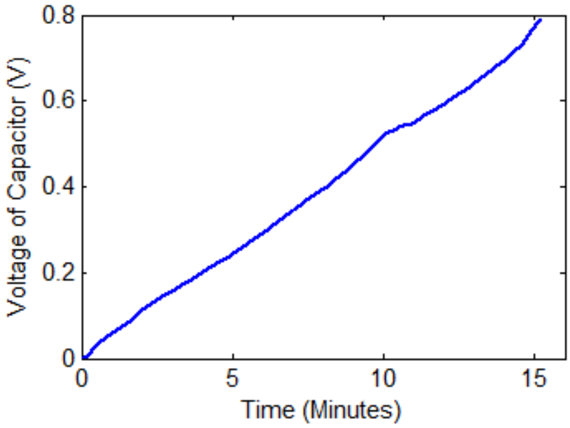

Figure 7: Measurement results of capacitor voltage during RF energy harvesting.

harvesting part. Nonetheless, solar energy voltage changes due to the sunlight captured by the solar panel. We use Star Solar CNC110X69-5 as the solar panel. Its maximum voltage 5V. In sunny days, they reach 5V easily so, we have to use a voltage regulator to keep the voltage level stable at 3.3 V. The used 78L03 regulator is a DC to DC regulator. After that, harvested energy reaches to the diode in every branch. Then, they are combined, and the hybrid energy harvesting system and charges the super-capacitor.

4.2. Measurement Results

During each measurement, artificial light for solar energy harvesting was used to adjust same light intensity for each test. Also, transmitter power of RF source and distance between RF source and antenna of RF energy harvester were same at every test. Moreover, heater was adjusted to same temperature for tests of thermal energy harvester circuit and hybrid structure. Measurement results of solar, RF, and thermal energy harvester circuits are given in Fig 6, 7, and 8, respectively. At each test, 0.22 F capacitor was employed. When hybrid energy harvester performance is compared with single source energy harvesters, 5th minute at which the capacitor linearly charges at each test was chosen. According to measurement results, storage capacitor voltage of thermal, solar, and RF energy harvester is 0.7 V, 0.95 V, and 0.24 V at 5th minute, respectively. At the same time interval, storage capacitor of the hybrid structure filled up to 2 V as shown in Fig. 9. It is obvious that hybrid structure harvest more energy thanks to usage of multiple energy source.

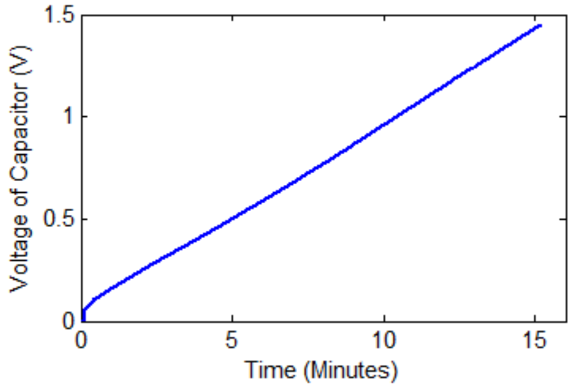

Figure 8: Measurement results of the capacitor voltage during thermal energy harvesting.

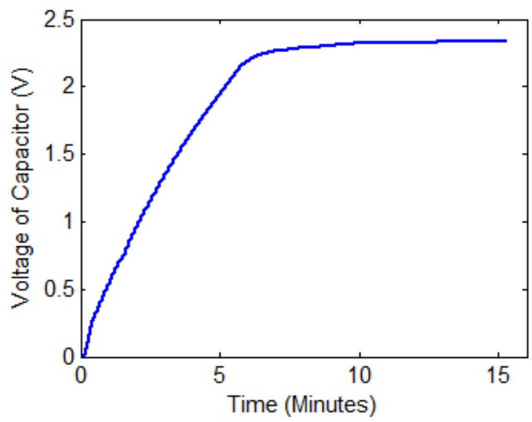

Figure 9: Measurement results of capacitor voltage when RF, thermal, and solar energy harvester systems jointly function.

5. Conclusions

In conclusion, an energy harvesting system with multiple source is designed to achieve a robust energy harvester. To obtain a constant voltage at the output, energy harvester circuits powered by various sources are connected to each other in parallel thereby supplying the storage capacitor simultaneously. Each energy harvester circuit were individually tested, and effectiveness of hybrid structure was examined by comparing measurement results of hybrid structure and single-source energy harvesters. As a result, it is observed that the hybrid structure outperforms single-source energy harvesters when same environmental conditions are satisfied for each energy source at each experiment.

6. References

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