Development of RF Energy Harvesting Technique for Li-Fi Application

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Abstract— **This work aims to improve the power generation by applying and experimenting a new technique of Radio Frequency (RF) energy harvesting using products of Powercast. This energy is used to activate a Light-Fidelity (Li-Fi) sample device and charge an energy storage system simultaneously. The final outcome of the system is now able to activate the Li-Fi sample device and charge a battery system at the same time. With the project being improved on a wider scale, many power problems can be solved in such a way that will help all humankind.**

Keywords — **RF Energy Harvesting, Powercast, Light Fidelity, Energy Storage System.**

I. INTRODUCTION

Researchers and companies are encouraged to think of new techniques and ideas for driving wireless mobile devices for an enhanced or infinite period of time because of the finite electrical life of batteries. Somehow, the answer lies in capturing the energy from external ambient sources for miniature and mobile electronic devices, this technology is widely known as Energy Harvesting. Fuel is being taken from ambient sources present around us and thereby free to all users by these Energy Harvesters. Some of the types of ambient sources available around us for the technique of energy harvesting are solar, wind, vibration, temperature gradient, electromagnetic, thermoelectric, push buttons, heel strike, and finally, Radio Frequency (RF). So far, known energy harvesting techniques generate small power depending on the used technique. It may be sufficient to drive small electrical devices or devices with low power consumption. But a promotable future is being presented by energy harvesting technology in low power consumption electronic devices and wireless sensor networks [1].

This work focuses on Electromagnetic (EM) energy as one of the energy harvesting techniques, especially RF where it holds a promising future for generating electrical power in a small amount in order to drive partial circuits in wireless communication electronic devices. RF waves' energy used by devices can be harvested and used to operate in more efficient and effective way [2]. Basically, the Li-Fi source needs to be connected to the power grid in order to be able to transfer data and work efficiently. Another problem appears that the Li-Fi device needs to be in a fixed place for the user to have a good connection, meaning that the device cannot be portal. Also, most of today's world technology gadgets are dependent on the battery power. This may create a problem of having the battery constantly charged, which is hard to maintain outdoors [3].

II. PROJECT OVERVIEW

It is essential to adopt green, inexpensive communication strategies because of the growth of popularity, applications of large-scale and sensor-based wireless networks. Deployment of a self-powered nodes network that can harvest energy from many types of sources, either natural or man-made sources, is one of the approaches to develop a sustained network operation. Associated cost of periodic batteries replacement can be significantly reduced by this method. On another hand, battery replacement may not be economically and practically feasible in some deployments according to the location of the sensor. It may even involve risks of high threats to human life. That is why wireless sensor networks (WSN) are now strongly motivated to be enabled to reduce part or all cost of operation by having the capability to harvest energy, thereby taking the first steps towards realizing the vision of perennially operating network [4].

Direct power to electrical battery-free systems, auxiliary power source for rechargeable batteries, battery activation, and remote power with or without battery backup are some of several benefits of implementing a wireless power source that depends on RF Energy Harvesting. Significant flexibility in designing power systems for wireless sensors and interactive devices that is communicating through low power wireless networks is provided by this implementation. High sensitivity of the harvester is needed to enable it to harvest from very low levels of RF energy in order to have the maximum performance, the best design and the flexibility of applications.

In order to ensure the most usable power of that harvested energy, high efficiency of the harvester is critically needed. To support a wide range of operating conditions such as input power, load resistance, and output voltage, the range of efficiency should be sufficiently broad. Additionally, to optimize and achieve system power management, smart power management capabilities should be acquired by the harvester.

In any surrounding area, many ambient RF power sources are available. Internal sources, anticipated ambient sources, and unknown ambient sources are the three general categories of RF power sources around us, as shown in Fig. 1. Typically, the main components of RF Energy Harvesting circuit are the Antenna with Impedance Matching Circuit, Rectifier, Power Conversion and Energy Storage part as shown in Fig. 2 [5].

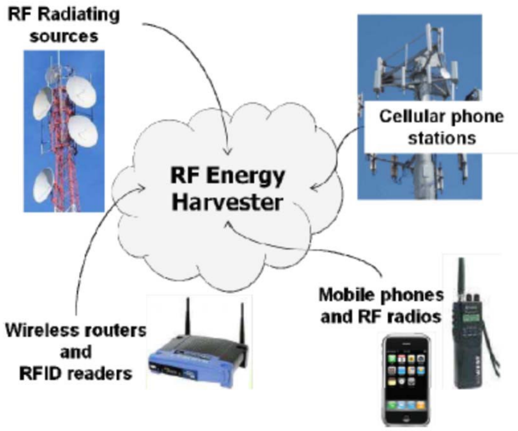

Fig. 1: RF Energy Sources [5]

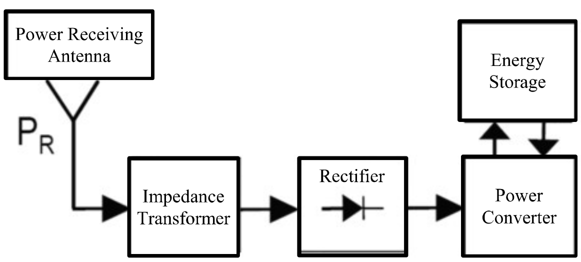

Fig. 2: RF Energy Harvesting System [5]

Fig. 2 shows the main concept of energy harvesting systems that collects RF energy through an antenna, converts it to electrical energy. This energy (voltage and current) has to pass by a very accurate impedance matching circuit in order to achieve the maximum efficiency of the collected energy. Afterwards, a rectification or a current boost circuits are introduced to the system in order to achieve the desired voltage or current output. By achieving the desired output of the system, it can be used in various applications especially in charging a small battery and turning on the required number of LEDs, as this represents the loading requirement of the Li-Fi device/module.

The first stages of receiving the Radio Frequency, impedance matching and rectifying circuitry are managed by the Powercast P2110-EVB Power harvesting evaluation board. Some of the details are indicated as follow.

A. Power Receiving Antenna

In order to radiate and receive electromagnetic (EM) energy, metallic structures known as Antennas are designed. They are used for the guiding device as a transmission line or a wave guide and the free space to be having a transitional structure between them. Time-variant current or acceleration of charge causes a conducting current to radiate. There would be no radiation in the wire with no charge motion in it, since no flow of current occurs [6].

B. Impedance Matching Circuit

In high-frequency circuit design, impedance matching is a critical problem. Its concern is to achieve the maximum power transfer between the two parts by matching one part of the circuit to another one. Impedance matching has many techniques to be done, such as the Q factor approach to matching, L matching circuit, and T matching circuit [7].

C. Rectifier

Rectification is used in order to charge batteries, supply DC motors and so on. There are two types of diode rectifiers: Half-wave and full-wave rectifier. Full-wave rectifier has better performance than half-wave rectifier, yet it needs more number of diodes than the half-wave rectifier [8].

D. Powercast P2110-EVB Power harvester

The Powercast P2110-EVB Power harvesting evaluation board contains a microchip (P2110) used to convert RF to DC power. It also contains proper connections and components for testing and producing the desired output power. It provides power management of RF energy harvesting for micro-power devices. It uses a capacitor as a storage of DC energy to convert from RF energy.

The RF input, RF_{IN} as shown in Fig. 3, is an unbalanced input from the antenna. A 50Ω, 902-928 MHz antenna is used to achieve the highest efficiency. It must be isolated from the ground. For the storage capacitor selection, V_{CAP}, an external capacitor needs to be added to the circuit. The value of that exact capacitor is most crucial in determining the amount of energy that can be achieved at the V_{OUT} pin. Leakage current of the capacitor has to be as small as possible, maybe less than 1µ A at 1.2 V. The capacitor ESR should be 200 mΩ or less. The smaller the capacitor, the faster the charging, but with shorter operation cycles. And vice versa, the larger the capacitor, the slower the charging, but with longer operation cycles. The minimum required capacitor value of the capacitor can be determined using Eq (1).

$$C = 15 \times V_{OUT} \times I_{OUT} \times T_{ON} \qquad (1)$$

Where, V_{OUT} is output voltage, I_{OUT} is output current, and T_{ON} is on-time of the V_{OUT}. The importance of the capacitor size decreases while using the *RESET* function. Since more energy is required, intermittent functions can be facilitated by using a larger capacitor. In order to minimize the required recharge time, some amount of energy need to be removed during the operation from the capacitor by the *RESET* function. While using *RESET*, charge time will not be affected by using a larger capacitor during operation. But to charge from a totally discharge state, more time will be required. V_{CAP} will vary between 1.25 V and 1.02 V during normal operation approximately.

Protection of the low voltage super capacitors will require the capacitor's voltage to be internally clamped in case of too large voltage from harvested energy. At approximately 1.8 V, the clamping will begin and the voltage will be limited to less than 2.3 V at the maximum rated input power. As for the D_{OUT} and D_{SET}, the amount of harvested energy is provided by sampling the received signal, which is allowed by the function of the ***RSSI*.** Setting the D_{SET} high will direct the harvested DC power to an internal sense resistor, and the D_{OUT} pin will be provided with the corresponding voltage. After a 50 µs settling time, the D_{OUT} pin output voltage can be read. Storage of the DC harvested power is not an option during the usage of the *RSSI* functionality. If the *RSSI* functionality is not used, D_{OUT} and D_{SET} should be left unconnected. *DSET* is internally pulled down. Also, Using D_{OUT} and D_{SET} it is possible to collect data from the RF transmitter that is supplying power to the P2110.

As discussed, with *DSET* high, *DOUT* will provide a voltage across R3 that can be read by an ADC. However, the voltage on D_{OUT} will also follow the power level of the RF field as the power level changes. If the RF field is being provided by a transmitter that is also communicating by modulating its amplitude, such as the Powercast TX91501-3W-ID transmitter, the data can be read by the P2110. The voltage level is gained up using operation amplifiers and supplied to a device that can read the data pattern supplied by the transmitter. Recharge time back to the activation threshold, V_{MAX}, can be improved by turning off the voltage from V_{OUT} before reaching the lower threshold, V_{MIN}, of the storage capacitor. This can help save energy as well. A microcontroller can be used in order to implement the *RESET* function. Output voltage, V_{OUT} can be disabled by setting the *RESET* high after completing the function of the microcontroller.

Care should be taken to make sure that the *RESET* is not inadvertently driven high by the microcontroller during power-on especially. The output voltage will be immediately shut down. Presence of voltage or current at the V_{OUT} pin is digitally indicated by the interrupt function. To bring a microcontroller from a deep sleep mode, an external interrupt can be used. Also, *INT* can be used in systems with other storage elements. *INT* pin's digital high level will be between V_{MIN} and V_{MAX}. A maximum current of 0.1 mA can be provided by the *INT* pin. In order to set the DC output voltage, an external resistor is to be added to decrease or increase the output voltage using Eq. (2).

$$K = 10^3 \tag{2}$$

A resistor calculated by Eq. (3) is used from V_{SET} to V_{OUT} to decrease the output voltage. A minimum of 1.8 V can be achieved.

$$R = \frac{249K(Vout-1.195)}{(3.32-Vout)} \tag{3}$$

A resistor calculated using Eq. (4) may be used from V_{SET} to *GND* to increase the output voltage. A maximum of 5.25 V can be achieved.

$$R = \frac{297.47\ K}{(Vout-3.32)} \tag{4}$$

In minimizing the feed losses, the *RF* feed line is designed as a 50 Ω trace and should be as short as possible. A via located next to the pads under the receiver is used to connect the *GND* pins on each side of the RF_{IN} pin to the PCB ground plane. The resistor connected to the V_{SET} pin should be as close as possible to it while setting the output voltage. This pin does not require any addition of any external capacitance. Lo-level analogue voltage signal can be contained by the D_{OUT} pin. An additional filtering capacitance next to the A/D converter may be required in case of connecting a long trace to this pin. The D_{SET} delay time will be increased by introducing an additional capacitance on this pin. To minimize the series resistance of the trace, the trace from V_{CAP} to the storage capacitor should be as short as possible and have a width of greater than 20 mils [9]. The Powercast P2110 functional block diagram is shown in Fig. 3.

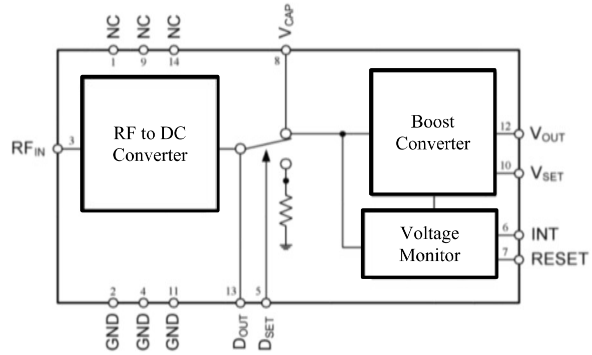

Fig. 3: Functional Block Diagram of P2110 [9]

E. Powercast TX91501-915 MHz Transmitter

The TX91501 Powercast transmitter is designed to provide data and power to RF receivers that contain one of the Powercast harvesters: P2110 or P2110B. It works at 5 V DC. It also has an indicator LED to provide feedback of the connection status. Transmission would stop if there is any obstruction in close proximity. The obstruction has to be removed in order for the transmission to take place again. The output RF power from the TX91501 transmitter is 915 MHz [9].

F. 60H3A3H Ni-MH BUTTON CELL

It is a typical rechargeable nickel–metal hydride (Ni-MH) battery. With a flexible cylindrical shape, it offers 80 mAh capacity with a voltage of 3.7 V. It is a very low cost solution for a project such as this with LEDs usage that does not require high discharge current. Within the battery lies an integrated protection PCB as a protection system to prevent from the over-charge/over-discharge effects [10].

G. Li-Fi as Loading Requirement

Li-Fi basically consists of Light Emitting Diodes (LEDs). A single p-n semiconductor junction forms the very basic structure of an LED. The p-type and the n-type materials are being charged positively and negatively respectively though a process called Doping. In the n-type material, atoms have extra electrons, while at the p-type material, atoms have empty electron holes. By applying current to this diode, the extra electrons at the n-type material will rush in the direction of the electron holes in the p-type material allowing current to flow though the diode [11]. For the loading requirement of the Li-Fi circuitry, a proposed design of 7 LEDs are to be used. The required voltage would be 1.67 V, and the required current is to be 8 mA.

III. Methodology

A. Setting up Powercast P2110-EVB RF

As one of the best options, the P2110-EVB is chosen in this work. The board has all the required connections, so there is no need to do any mounting or welding to any component. The main internal components in the board are shown in Fig. 4.

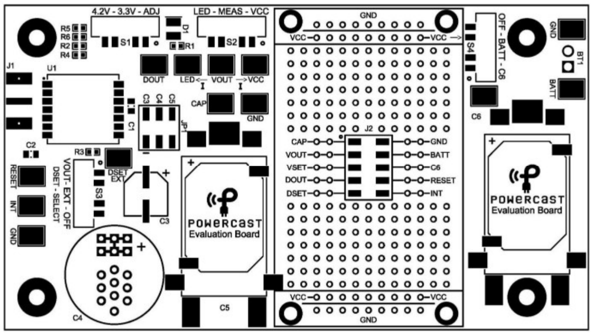

Fig. 4: P2110-EVB Design [9]

The P2110-EVB consists of two main parts: the P2110 Powerharvester Receiver, and the 915 MHz Patch Antenna. The P2110 RF energy harvester collects RF energy and converts it into DC power. The microchip stores this DC power in a capacitor to provide an intermittent, regulated voltage output. Connection of the patch antenna is to allow RF input into the P2110 energy harvester receiver. The 915 MHz PCB Patch antenna used with the evaluation board has two layers, with the RF connector located in the middle of the back side of the antenna. The front side should be pointed towards the transmitter with the same polarization. Antenna gain is 6.1 dBi.

Referring to Fig. 5, adjustments of switches S2, S3 and S4 are to be made to achieve the desired settings. Here, S2 is set to VCC, S3 to OFF and S4 connects to BATT. Using TX91501-915 MHz transmitter, the distance between the transmitter and receiver has to be less than one (1) meter in order for them to communicate to each other.

B. Configuring Li-Fi Loading

The design approach for the Li-Fi application would require tens of LEDs, yet in this work, only seven (7) red LEDs are used to represent the Li-Fi application. The red LEDs are connected in parallel, so that they can draw the same voltage, and also they can draw the same current each as no other component is connected in parallel with them. For the red LEDs, they need a voltage of 1.67 V to turn on. Meaning that they would require a resistance to be connected in series with the combination of them to decrease the input voltage applied to them either from the P2110-EVB (3.3 V and above) or from the battery system. The value of this resistance can be calculated through Ohm's law as in in Eq. (5):

$$V = IR \qquad (5)$$

C. Setting up Energy Storage

In order to make the Li-Fi application portable, a battery (energy storage) system has to be added. This system would consist of two SZJ 80H2A Ni-MH button cell batteries, each of them is 3.6 V/80mAh. Both batteries are connected in parallel in order to have a final battery level with 3.6 V/160 mAh, which is suitable to activate the Li-Fi application effectively and efficiently. This duration is calculated using Eq. (6).

$$Td = \frac{Battery\ Capacity}{Id} \qquad (6)$$

where T_d is the discharge time (Hours), Battery capacity is in (mAh), and I_d is the discharge current (mA).

IV. Results and Discussion

A. Overview of the System

The RF Energy Harvesting module for Li-Fi application is divided into three main parts: P2110-EVB power harvesting evaluation board, energy storage system, and Li-Fi load. The main design of the system is shown in Fig. 5.

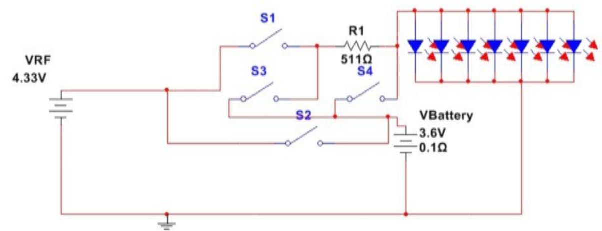

Fig. 5: System Overview

The system receives 915 MHz of RF energy via the patch antenna, then it converts to DC power. The resulting voltage shall be introduced to two main switches, S1 and S2. S1 is to connect the Li-Fi application directly to the P2110-EVB output voltage, while S2 is used to connect the P2110-EVB output to the energy storage system. There are six (6) modes of operation for the system which shall be discussed in the following section. The normal output voltage of the system is 3.3 V from the BATT pin. In order to increase that voltage, Eq. (4) is used. The calculated resistance value is R2 = 250 kΩ.

B. Modes of Connection

Mode I: No Connection

In this mode, the switches S1 and S2 are open, meaning that there will be no connection between the P2110-EVB and the Li-Fi application nor the battery (energy storage) system. In that case, using a resistor R2 = 250 kΩ, the resulting output voltage at BATT pin is $V_{RF} = 4.33$ V.

Mode II: Battery Charging Only (S2 Closed)

During this mode, only switch S2 is closed, allowing the battery system to be recharged using the output power from the RF energy harvester P2110. An illustration of this mode is available in Fig. 6, and the measurements of the system are available in Table I.

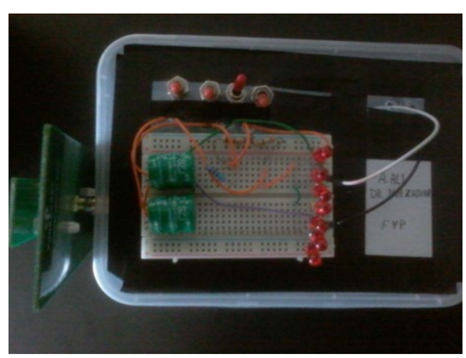

Fig. 6: Mode II

Table I. Mode II

Parameter	Value	Remarks
V_{RF} (V)	4.33	-
$V_{BATTERY}$ (V)	X	X is increasing, starting from battery's voltage level till 4.33 V
$I_{BATTERY}$ (mA)	16.77	Decreasing
T_{CHARGE} (hours)	10	With Losses

Mode III: Li-Fi Application Only (S1 Closed)

In this mode, only switch S1 is closed, while all others are open. The V_{RF} is connected directly to the Li-Fi application circuitry which consists of LEDs and a resistance in order to provide the LEDs with the exact needed voltage for them to illuminate without being damaged by high voltage or current. The R1 value is calculated using Eq. (5). An illustration of this mode is available in Fig. **7**, and the measurements of the system are available in Table II.

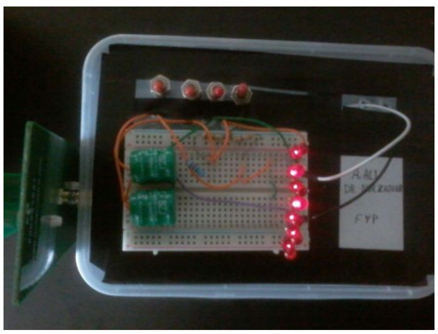

Fig. 7: Mode III

Table II. Mode III

Parameter	Value	Remarks
V_{RF} (V)	4.33	-
$V_{BATTERY}$ (V)	3.6	Considered as fully charged
$V_{Li\text{-}Fi}$(V)	4.33	-
R1 (Ω)	511	-
V_{R1}(V)	2.69	-
V_{LED}(V)	1.63	Enough voltage to illuminate
$I_{Li\text{-}Fi}$ (mA)	3.7	-

Mode IV: Battery Charging and Li-Fi Application (S2 & S1/S3 Closed)

In this mode, switch S2 and either switches S1 or S3 or both are closed, while switch S4 is open. The V_{RF} is connected to the battery system via switch S2 and also to the Li-Fi application circuitry via both switches S1 and/or S3. In this mode, the battery is charged and at the same time the Li-Fi application is activated. Yet, the battery may take longer time to charge as the withdrawn current is divided between both the battery and the Li-Fi application. An illustration of this mode is available in Fig. 8, and the measurements of the system are available in Table III.

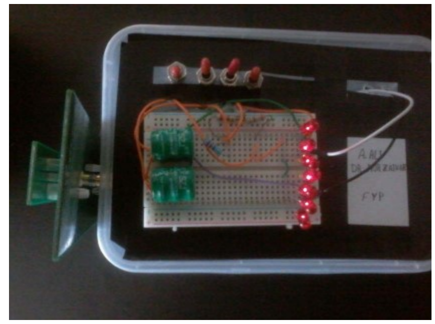

Fig. 8: Mode IV

Table III. Mode IV

Parameter	Value	Remarks
V_{RF} (V)	3.24	-
$V_{BATTERY}$ (V)	3.24	Considered as fully charged
$V_{Li\text{-}Fi}$(V)	3.24	-
R1 (Ω)	511	-
V_{R1}(V)	1.62	-
V_{LED}(V)	1.62	Enough voltage to illuminate
$I_{Li\text{-}Fi}$ (mA)	2.73	-
$I_{BATTERY}$ (mA)	11.94	Decreasing
T_{CHARGE} (hours)	13.4	-

Mode V: Activating Li-Fi Application using Battery System Only (S3)

In this mode, only the switch S3 is closed, while all other switches are open. The Li-Fi application circuitry is connected directly to the battery system via switch S3. In this mode, the Li-Fi application is using the storage of the battery (160 mAh) to be active. This mode can be used in case there is not enough RF power to power up the Li-Fi application alone. An illustration of this mode is available in Fig. 9, and the measurements of the system are available in Table IV.

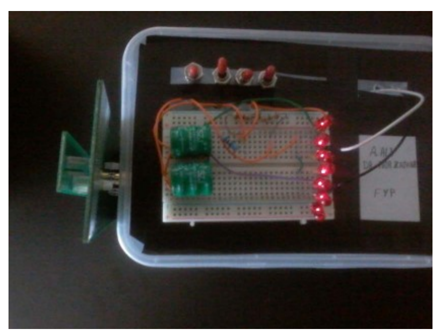

Fig. 9: Mode V

Table IV. Mode V

Parameter	Value	Remarks
$V_{BATTERY}$ (V)	3.24	Decreasing Voltage (Discharging)
$V_{Li\text{-}Fi}$(V)	3.24	Same as Battery, Decreasing
R1 (Ω)	511	-
V_{R1}(V)	1.62	Decreasing
V_{LED}(V)	1.62	Enough voltage to illuminate (Last to decrease)
$I_{Li\text{-}Fi}$ (mA)	3.7	Decreasing
$T_{DISCHARGE}$ (hours)	43	-

Mode VI: Activating Li-Fi Application using Battery System Only (S4 - High Power)

In this mode, only the switch S4 is closed, while all other switches are open. The Li-Fi application circuitry is connected directly to the battery system via switch S4. In this mode, the Li-Fi application is using the storage of the battery (160 mAh) to be active. Using this mode will cause the battery to activate the Li-Fi application directly without passing by the resistance R1. This will cause the LEDs to have higher illumination but at the same time will negatively affect the battery by decreasing the life-time or increasing the discharge rate. Important: Please note that while switch S4 is closed, switch S2 or the combination of switches S1 and S3 must never be closed. An illustration of this mode is available in Fig. 10, and the measurements of the system are available in Table V.

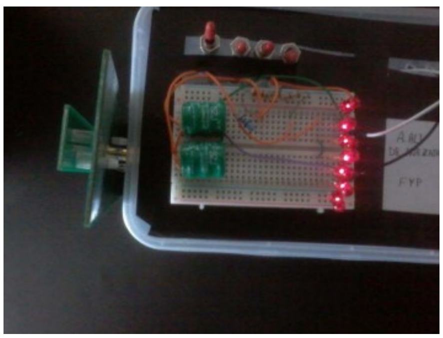

Fig. 10: Mode VI

Table V. Mode VI

Parameter	Value	Remarks
$V_{BATTERY}$ (V)	1.67	Decreasing Voltage (Discharging)
$V_{Li\text{-}Fi}$(V)	1.67	Same as Battery, Decreasing
V_{LED}(V)	1.67	Enough voltage to illuminate
$I_{Li\text{-}Fi}$ (mA)	5	Decreasing
$T_{DISCHARGE}$ (hours)	32	-

V. Conclusion

The Design and the calculations of the Li-Fi application circuitry and the battery (Energy storage) system have been performed accurately. Subsequently, the P2110-EVB has been studied and experimentations have been done on it. Secondly, the Li-Fi application circuitry has been designed and modified as a load requirement. Then the battery system has been sized, implemented with the load and tested. Finally, the whole system was integrated together to construct the complete RF energy harvesting system for the Li-Fi application. The system is installed on a prototype made from plastic to make the outer shape for it. Furthermore, the system has achieved the desired output voltage and current that enables it to charge the battery system and/or activate the Li-Fi application. Eventually, the designing, manufacturing and testing the RF energy harvesting system for the Li-Fi application has been accomplished successfully.

VI. Acknowledgment

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