Development of RF Energy Harvesting Technique for Li-Fi Application

By

Abdelrahman Ali

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A final year project dissertation submitted to the
Electrical and Electronics Engineering Department
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL AND ELECTRONICS ENGINEERING)
SEPTEMBER 2015

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CERTIFICATION OF APPROVAL

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Approved by,

____

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein have not been undertaken or done by unspecified sources or person.

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Abdelrahman Ali

Acknowledgment

I would like to express my deepest gratitude and appreciation to the individuals who have offered their continuous help, guidance, advice and time during the course of this project. The work presented hereby is a result of long working hours and a lot of dedication. However, this dissertation would not have been made possible without them.

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Abstract

Internet has become one of the basic needs for almost everyone in the recent era. It is known that you can connect to the internet via many different ways, such as Local Area Connection (LAN), Wireless Fidelity (Wi-Fi), or using mobile networks (GSM/2G/3G/4G). By the year 2010, scientists have started to develop a new way of broadcasting internet. This way basically depends on emitting data through LEDs. They named it the Light Fidelity (Li-Fi). As a client, you have to connect this light source to your router via LAN or Wi-Fi, and carry it everywhere inside your property. You shall have both light and internet at the same time.

While the world is at edge with power consumption, many critics see that Li-Fi is an unnecessary addition to the power consumption, as the device would need to be powered in order to be able to send and receive data.

To solve such a problem, as shown in this project, other ambient and renewable energy sources are proposed to be used. Radio Frequency is being harvested and converted into Energy through a small PCB board. Afterwards, the output energy is being used to charge a battery and/or power the LEDs. This will be of great help to reduce the need of the normal electrical system.

The above mentioned small PCB has been purchased from powercastco.com which is a manufacturer of **Powercast,** the great series of renewable power solution applications. This board is used to receive an input of 902-928 MHz and give an output of around 2-5V and 50 mA. The output of this board shall be introduced to another circuitry. This second circuit shall include a battery, switches, and the main LEDs for the Li-Fi application.

One other purpose of the project is to improve the efficiency of the RF energy harvesting techniques by studying the new products of Powercast and comparing its results with the previous results of the normal RF harvesting techniques.

By the end of this project, we shall cross the line into more flexible and convenient energy harvesting techniques to help humanity reach their needs easily and efficiently.

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Chapter 1
Introduction

1.1 Background Study

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. To mention 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. 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 project focuses on Electromagnetic (EM) energy as one of the energy harvesting techniques, especially Radio Frequency (RF). Nowadays, RF Energy Harvesting holds a promising future for generating electrical power in a small amount in order to drive partial circuits in wireless communication electronic devices. Research is still continuous about the RF energy harvesting. RF waves' energy used by devices can be harvested and used to operate in more efficient and effective way [2].

This project aims to provide a solution to Li-Fi problem mentioned in the abstract by using the technique of Radio Frequency (RF) Energy Harvesting and improving it.

1.2 Problem Statement

Basically, as mentioned earlier in the abstract, the Li-Fi source needs to be connected to the power grid in order to be able to transfer data and work efficiently. Critics against this are claiming that the world already has a power problem. Thus, there is no need to add extra loads to the grids. 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].

1.3 Objectives

1. To select the best option from Powercast to be purchased.

2. To select the load power rating of the Li-Fi device and the storage device.

3. To test the Powercast P2110-EVB Power harvesting evaluation board and troubleshoot it.

4. To fabricate, compile and demonstrate the final prototype that includes the testing and analyzing.

1.4 Scope of Study

1. Studying and researching about the RF Energy Harvesting.
2. Studying and analyzing the types and characteristics of power harvesters.
3. Doing a research on batteries and power storage devices.
4. Conducting the lab experiment to test the final prototype.

Chapter 2
Literature Review

It has become very important 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. Also, to be able 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. As well, in order 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 **Figure 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 **Figure 2** [5].

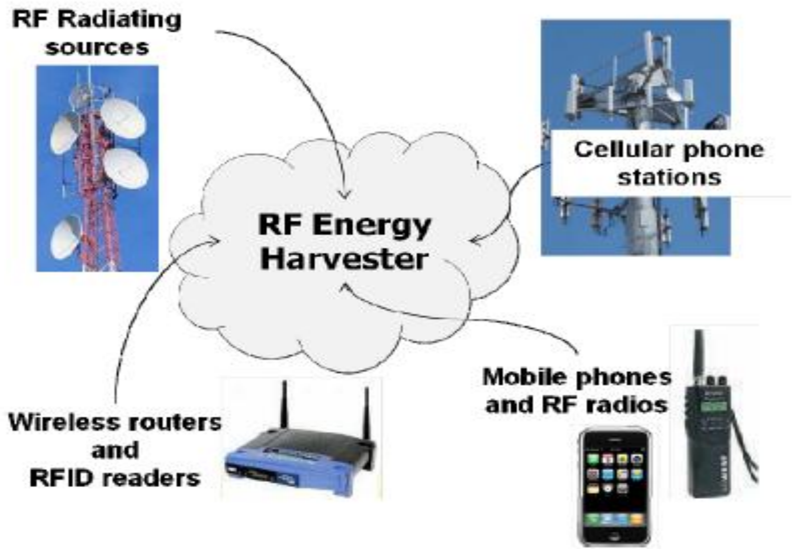


Figure 1: RF Energy Sources [5]

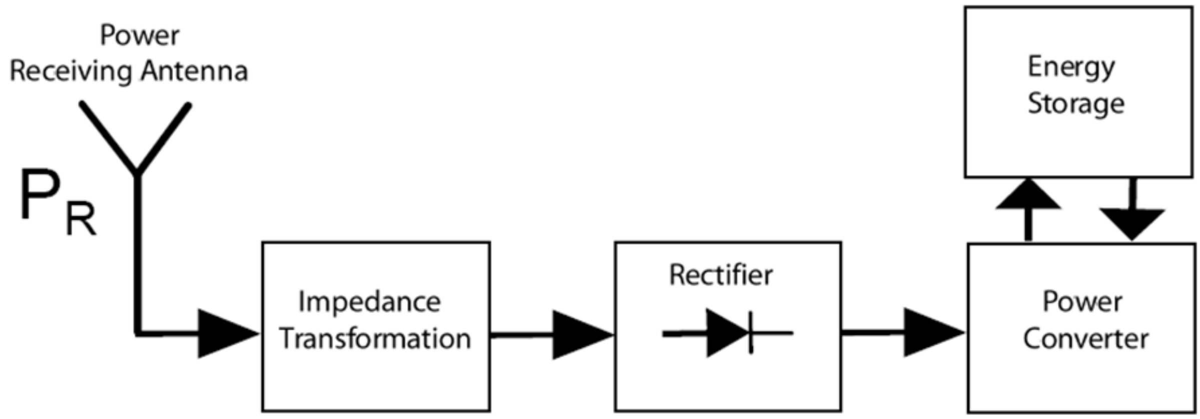


Figure 2: RF Energy Harvesting System [5]

Figure 2 shows the main concept of energy harvesting systems that collects Radio Frequency 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 being introduced to the system if necessary 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.

Yet, in our case, the first stages of receiving the Radio Frequency, impedance matching and rectifying circuitry are being done by the Powercast P2110-EVB Power harvesting evaluation board. The following steps are done by research, simulating, implementing and testing of the circuits in the labs and in real life application.

Anyways, I am going to give a summarized explanation on how the above mentioned steps are being done and operated, then I shall be briefly explaining on how the real project of mine works.

2.1 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. To know how radiation can be emitted from an antenna, how radiation occurs should be known first. 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. **Figure 3** shows how the antenna can radiate. A connected voltage source to a two conductor transmission line is shown. An electric field is created -which is sinusoidal in nature- when a sinusoidal voltage is applied across the line. Thus, electric lines of force -which are tangential to the electric field- are created. The bunching of the electric lines of force indicate the magnitude of the field. The electric lines of force are forcibly displacing the free electrons on the conductors. The current flow is caused by these charges movement, then it creates a magnetic field. Electromagnetic waves then are created and they travel between conductors because of the time varying electric and magnetic fields. Connecting the open ends of the electric lines would form free space waves after the waves approach open space. EM waves are continuously created as the source is continuously creating an electric disturbance due to its sinusoidal nature. These EM waves travel through the antenna across the transmission line and then they would be radiated in the free space. Inside the transmission line and the antenna, the EM waves are sustained due to charges, but as soon as they enter the free space, they form closed loops and are radiated [6].

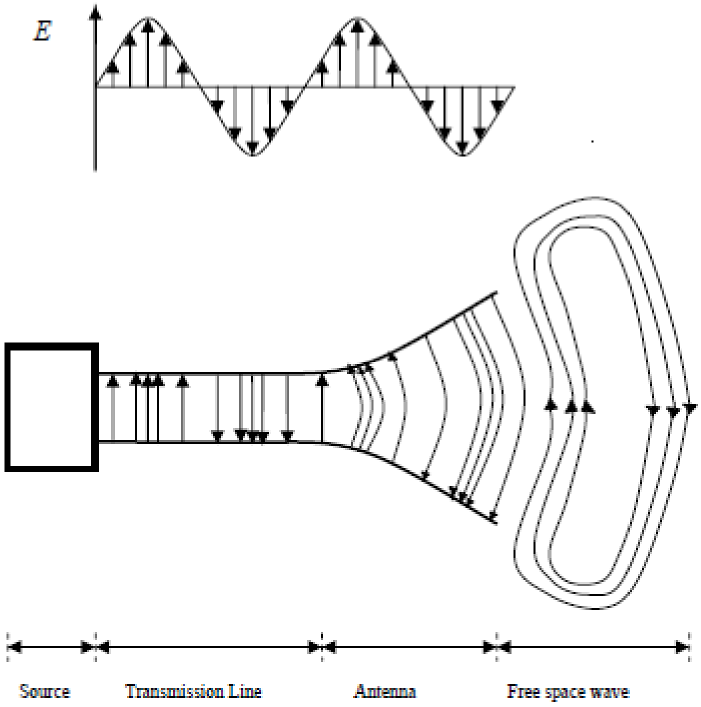


Figure 3: Radiation from an Antenna [6]

2.2 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].

2.3 Rectifier

Rectification means the conversion of AC voltages and currents to DC voltages and currents. It 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].

Full-wave rectifier and half-wave rectifier circuits are shown in **Figure 4** and **Figure 5** respectively.

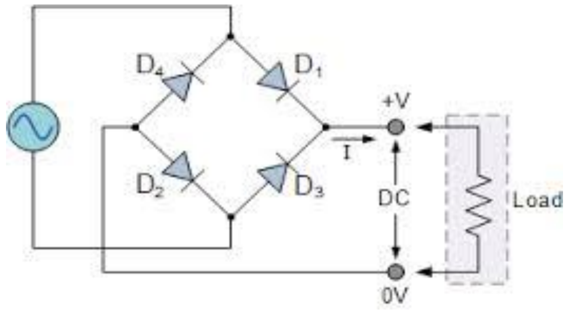


Figure 4: Full-Wave Rectifier **[8]**

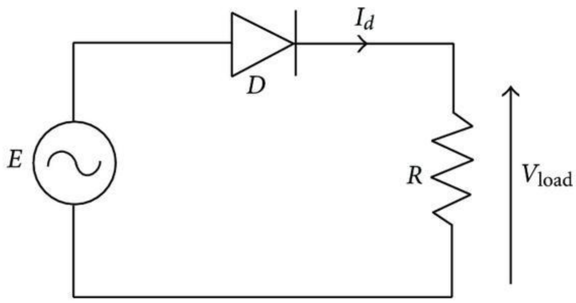


Figure 5: Half-Wave Rectifier **[8]**

2.4 Powercast P2110-EVB Power harvester [9]

The Powercast **P2110-EVB** Power harvesting evaluation board is a board that contains a microchip (**P2110**) that is used to convert Radio Frequency to DC power. It also contains the proper connections and components for testing and measurement purposes and for 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 that is being converted from RF energy. After achieving the charge threshold on the capacitor, the P2110 Power harvester enables the output voltage and sets it by boosting the voltage. It is suitable for charging **coin cell batteries** and **thin-film cells batteries** as well. The absolute maximum parameters of the P2110 Power harvester are shown in **Table I**.

Table I: Absolute Maximum Parameters - P2110

Parameter	Value	Unit
RF Input Power	23	dBm
RF_{IN} to *GND*	0	V
D_{SET} to *GND*	6	V
RESET to *GND*	6	V
V_{CAP} to *GND*	2.3	V
V_{OUT} to *GND*	6	V
I_{OUT} to *GND*	100	mA
Storage Temperature Range	-40 to 140	°C
Operating Temperature Range	-40 to 85	°C

Yet, the normal operating parameters and specifications are somehow different from the maximum values of the parameters. The specifications of the Powercast P2110 are shown in **Table II**.

Table II: Specifications of P2110 Power Harvester

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
RF Characteristics						
Input Power	RF_{IN}		-10		10	dBm
Frequency			902		928	MHz
DC Characteristics						
Output Voltage	V_{OUT}		1.8	3.3	5.25	V
Output Current	I_{OUT}				50	mA
V_{CAP} Maximum	V_{MAX}			1.25		V
V_{CAP} Minimum	V_{MIN}			1.02		V
Signal Strength	D_{OUT}	RF_{IN} = 0dBm		275		mV
Boost Efficiency		I_{OUT} = 20mA		85		%
Maximum *INT* Current				0.1		mA
Digital Characteristics						
RESET Input High				1		V
D_{SET} Input High			1.8			V
INT Output High			V_{MIN}		V_{MAX}	V

Timing Characteristics						
D_{SET} Delay				50		µs
RESET Delay				6.6		µs
RESET Pulse Width			20			ns

The Powercast P2110 functional block diagram is shown in **Figure 6**.

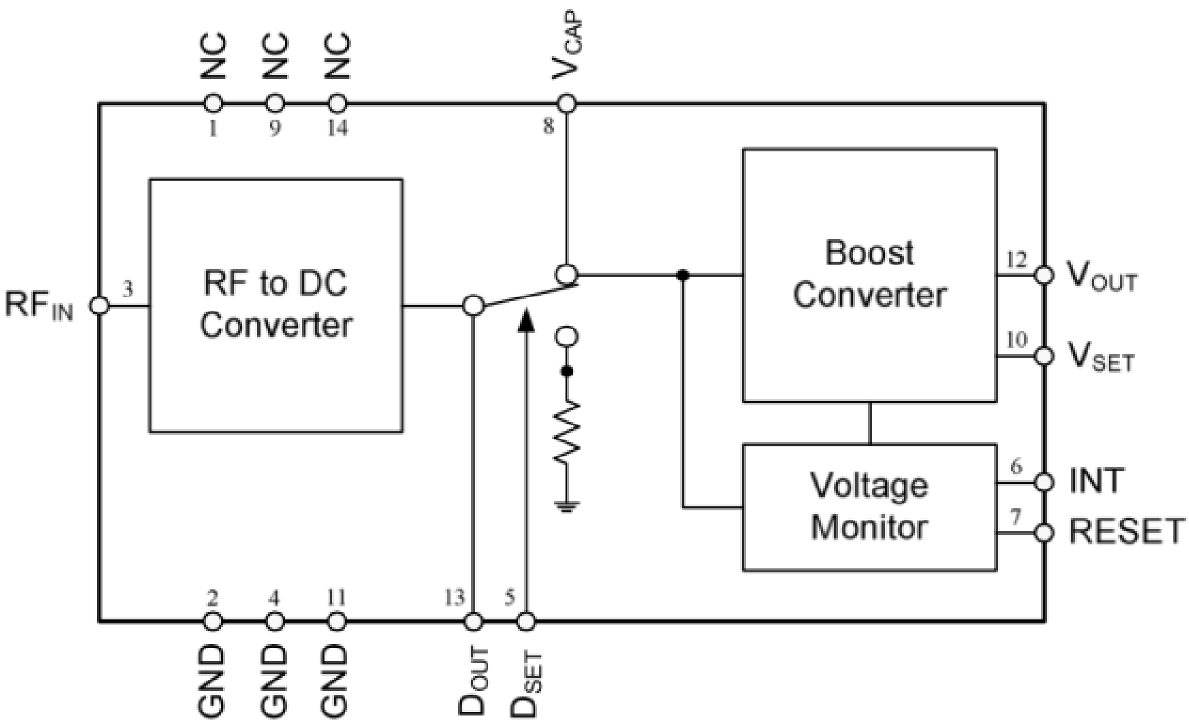


Figure 6: Functional Block Diagram of P2110 [9]

The RF input *RF_{IN}* is an unbalanced input from the antenna. A 50 Ω, 902-928 MHz antenna is to be used in order 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 1µA at 1.2V. The capacitor ESR should be 200m Ω 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 the equation shown below:

$$C = 15(V_{OUT})(I_{OUT})(T_{ON})$$

Equation 1: Capacitance Value at V_{CAP}

Where, V_{OUT}→Output Voltage, I_{OUT}→Output Current, and T_{ON}→On-time of the Vout.

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, this can be controlled 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 1.25V and 1.02 V during normal operation approximately. Protection of the low voltage supercapacitors will require the capacitor's voltage to be internally clamped in case of too large voltage from harvested energy. At approximately 1.8V, the clamping will begin and the voltage will be limited to less than 2.3V 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 50µs settling time approximately, 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. D_{SET} 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 above, with D_{SET} high, D_{OUT} 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 Powercast transmitter, the data can be read by the P2110. The voltage level will need 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. Do not connect the *RESET* if it is not going to be used, so it is internally pulled 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. Such as the *RESET* function, do not connect the *INT* functionality in case of not using it.

To set the DC output voltage, an external resistor is to be added to decrease or increase the output voltage using the following equations:

$$\boldsymbol{K = 10^3}$$

Equation 2: K Value

A resistor calculated by the following equation is to be used from V_{SET} to V_{OUT} to **decrease** the output voltage. A minimum of 1.8V can be achieved.

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

Equation 3: R to decrease V_{OUT}

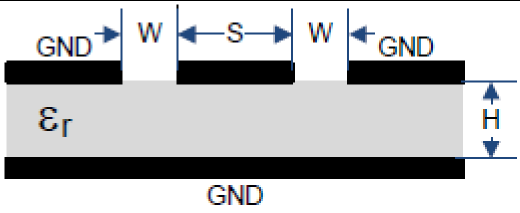
A resistor calculated by the following equation may be used from V_{SET} to *GND* to **increase** the output voltage. A maximum of 5.25V can be achieved.

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

Equation 4: R to increase V_{OUT}

To minimize the feed losses, the RF_{IN} feed line should be designed as a 50Ω trace and should be as short as possible. The following table provides recommended dimensions for 50Ω feed lines (CPWG) for different circuit board configurations. The dimensions considerations are provided in the following table, **Table III**.

Table III: Layout Considerations

<table>
<tr><td colspan="4">PCB Side View</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td>Material</td><td>Thickness
(H)</td><td>Trace Width
(S)</td><td>Spacing
(W)</td></tr>
<tr><td>FR4
(ε_r = 4.2)</td><td>62</td><td>50</td><td>9</td></tr>
<tr><td>FR4
(ε_r = 4.2)</td><td>31</td><td>50</td><td>20</td></tr>
</table>

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 analog 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 20mils.

2.5 Powercast TX91501-915 MHz Transmitter [9]

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 5V DC. It also has an indicator LED to provide feedback of the connection status as shown in **Table IV**.

Table IV: Powercast TX91501 LED Indication

LED	Status	Description
Off	Off	5VDC is not applied
Green	Active	Normal Transmission
Red	Fault	Transmission stopped

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.

2.6 SZJ 80H2A Ni-MH BUTTON CELL

The **SZJ 80H2A Ni-MH button cell** 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]

Figure 7: SZJ 80H2A Ni-MH button cell [10]

Battery specifications are as shown in **Table V**.

Table V: SZJ 80H2A Ni-MH Battery specifications

Model	Voltage	Capacity	Recommended Trickle Charge Current	Nominal Charge Current	Normal Charging Time	Nominal Discharge Current	Weight
80H2A	3.6V	80mAh	2.4~4mA	8mA	14~16h	16mA	10.2g

2.7 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.

Chapter 3
Methodology

3.1 Project Methodology

1. In this project, a research and study has to be conducted for the RF Energy Harvesting technique and its components that include: Powercast P2110-EVB Power harvesting evaluation board, battery sizing, and LEDs.

2. After that, the project shall be divided into four main phases. The first of them would involve the selection phase of the best type of Powercast harvesters. Second phase would contain the design of the Li-Fi circuitry as a load. Third phase is going to be finalizing the battery sizing for the energy storage. At last, the fourth and final phase will be the compiling of the input and the output. Then checking the values and calculations in the design in order to do any needed modifications and improvements.

3. The testing stages of the prototype should be running separately from each other, so that we can ensure that each section is functioning properly. Then the whole system is to be installed and tested.

4. Afterwards, the results have to be analyzed to ensure that the required voltage and current are achieved.

3.2 Design Approach

3.2.1 Powercast P2110B RF Energy Harvester

1. At the initial stage of the project, the suitable RF energy harvester was to be chosen from Powercast in order to achieve the best power output.

2. Based on the datasheet of P2110B power harvester, the resulting output should be 375mW, with voltage varying between 2V to 5.5 V, and an average current output of 50 mA.

3. The P2110B had to be mounted to a PCB with specific parameters as shown in **Table III**. In order to achieve that, the work has been done in the PCB fabrication laboratory in Universiti Teknologi PETRONAS with the help of the technicians to provide with the best quality PCB.

4. Afterwards, a proper selection of the resistance R and the capacitor C was needed in order to achieve the exact desired power output. The equations used in the selection of both parameters are Equations 2, 3&4 and Equation 1 consequently.

5. The antenna is to be connected to the RF_{IN} in the microchip P2110B. Proper selection of the antenna is required, as its frequency should be in the range of 902-928 MHz, so a 915 MHz antenna has been chosen. Also, the gain of the antenna must not be less than -10dBm and not higher than 10 dBm.

6. Testing and troubleshooting the prototype is to take place in order to verify the resulting power, improve it and make any required modifications.

After troubleshooting, due to undesired and unclear circumstances, P2110B failed to produce the desired output power. Based on that, the second stage of design had to take place immediately.

3.2.2 Powercast P2110-EVB RF Energy Harvesting Development Board

1. As one of the best options, the P2110-EVB has been chosen to be used in this project.

2. The evaluation board of P2110-EVB has all the required connections amongst it, so no need to do any mounting or welding to any component, which may have been the reason why P2110B did not work in the first place.

3. The main internal components in the board are shown in **Figure 8** and **Table VI**.

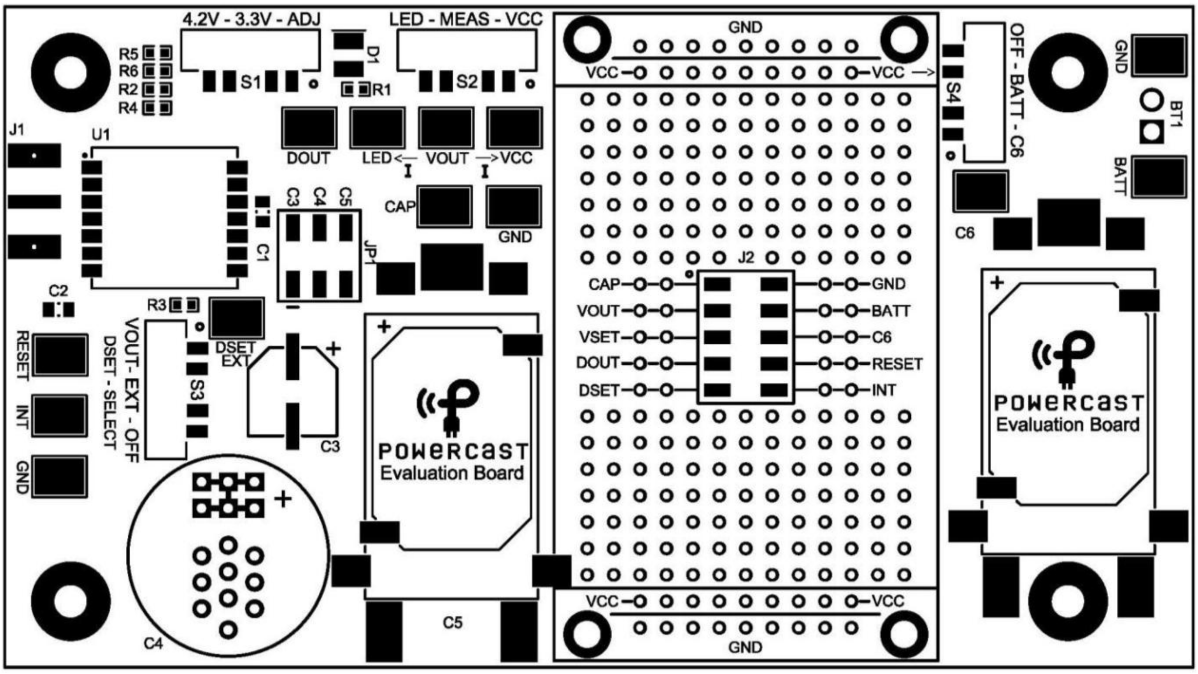


Figure 8: P2110-EVB Design

4. The P2110-EVB consists of two main parts: the P2110 Powerharvester Receiver, and the 915MHz Patch Antenna.

5. The P2110 RF energy harvester basically as mentioned before 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.

Table VI: P2110-EVB Design

Component	Description
S1	Not used
S2	Output Power Switch: LED: Send power to turn on LED D1 MEAS: Use with test points VOUT to LED or VOUT to STORE VCC: Send power to test area and S4
S3	DSET selection switch: (If used, RSSI is available at DOUT) VOUT: Not used EXT: Enabled by external source through DSET EXT test point OFF: Normal charging operation
S4	Powering external circuit through BT1(BAT) switch
JP1	Capacitors C3, C4 and C5 selection
D1	LED for visual indication of power output
R1	LED (D1) resistor
R2	VSET to GND connection to increase output voltage above 3.3V
R4	VSET to VOUT connection to decrease output voltage below 3.3V
R5, R6	Not used
C1	10 µF, output filtering for VOUT (Optional)
C2	0.1 µF, output filtering for RESET (Optional)
C3	1000 µF capacitor
C4	User selectable capacitor
C5	50 µF capacitor
C6	Not Used
BT1	External circuit connection
J1	Female SMA Connector for RF input (Antenna)
U1	P2110 RF energy harvester

6. Connection of the patch antenna is the next step, in order 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.

7. Adjustments of switches S2, S3 and S4 are to be made as mentioned in **Table VI** to achieve the desired settings. For our case, S2 is to be set to VCC, S3 to OFF and S4 is to be set to BATT.

8. The TX91501-915 MHz transmitter is to be switched on, the distance between the transmitter and the receiver has to be less than one (1) meter in order for the them to be able to connect to each other.

3.2.3 Li-Fi Load Requirement

1. The design approach for the Li-Fi application would require tens of LEDs, less or more depending on the desired speed of transmission and the availability of the power supply. Yet in this project in order to do the experimentation on the RF energy harvesting technique, only seven (7) red LEDs are chosen to represent the Li-Fi application.

2. 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.

3. For the red LEDs, they need a voltage of 1.67 V to be turned on. Meaning that they would require a resistance to be connected in series with the combination of them in order to decrease the input voltage that is applied to them either from the P2110-EVB (3.3 V and above) or from the battery system that is going to be explained in the next section (3.6V). The value of this resistance can be calculated through Ohm's law:

$$\boldsymbol{V = IR}$$

Equation 5: Ohm's Law

In this project, only a sample for Li-Fi device is used. For further stages, a bigger scale device can be designed with the same specifications. That can be shown in results and conclusion.

3.2.4 Energy Storage

1. In order to make the Li-Fi application portal, 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.
2. Both batteries are to be connected in parallel in order to have a final battery system with 3.6V and 160 mAh, which is suitable to activate the Li-Fi application effectively and efficiently. This time is being measured through E**quation 6**.

$$Td = \frac{Battery\ Capacity}{Id}$$

Equation 6: Discharge Time

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

3.3 Project Activities

The project flow and activities are illustrated in **Figure 9**. The project started with the research and the literature review to acquire the required knowledge to perform the project. Then, the design and the calculations of the system have been conducted based on the design approach. Subsequently, the implementation of the RF energy harvesting system and the Energy Storage system has been performed to validate the results that have been obtained. Eventually, the system is installed and tested on the prototype.

The key milestone for FYP 1 and FYP 2 are shown in **Tables VII** and **VIII**. While the Gantt chart for FYP 1 and FYP 2 are illustrated in **Tables IX** and **X**. The tables show the work and the activities performed during the 28 weeks. In addition, it demonstrates the required time to complete each phase of the project.

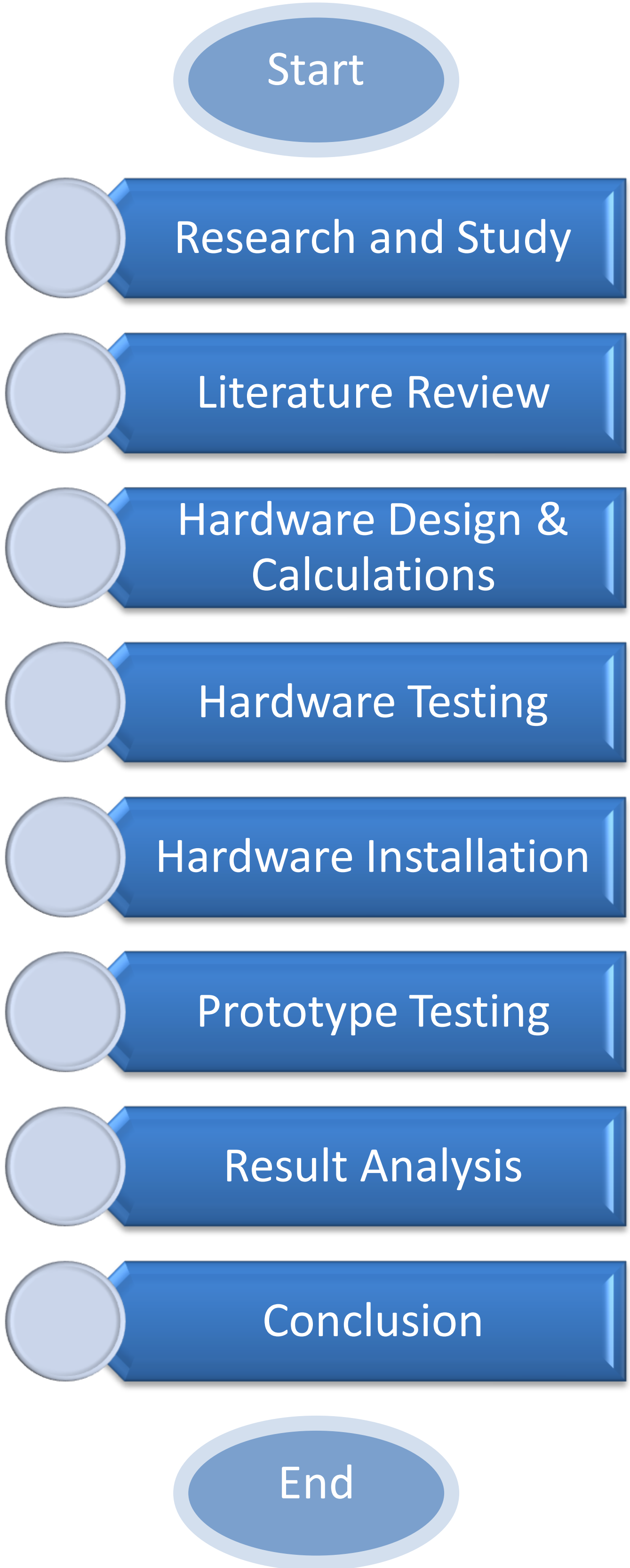


Figure 9: Project Activities

3.4 Key Milestone

Table VII: FYP I Key Milestone

No.	Week/Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection and Confirmation of Project Title														
2	Research, Study and Preparation for the Extended Proposal														
3	Proposal Defence Preparations														
4	Proposal Defence														
5	Preparing for Interim Report														
6	Interim Draft Report Submission														
7	Interim Report Submission														

Table VIII: FYP II Key Milestone

No.	Week/Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Work Continues														
2	Pre-SEDEX Preparation														
3	Preparation for Draft Final Report														
4	Preparation for Dissertation (Soft Bound)														
5	Preparing for Technical Paper														
6	Preparation for Viva														
7	Preparation for Dissertation (Hard Bound)														

3.5 Gantt Chart

Table IX: FYP I Gantt Chart

No.	Week/Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Title														
2	Extended Proposal Submission														
3	Proposal Defence														
4	Interim Draft Report Submission														
5	Interim Report Submission														

Table X: FYP II Gantt Chart

No.	Week/Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Progress Report															
2	Pre-SEDEX															
3	Draft Final Report															
4	Dissertation (Soft Copy)															
5	Technical Paper															
6	Viva															
7	Dissertation (Hard Bound)															

3.6 Tools

Table XI: Tools used in the project

Hardware Tools	➢ Powercast P2110-EVB Power Harvesting Evaluation Board ➢ 915 MHz Patch Antenna ➢ TX91501-915MHz Transmitter ➢ Two SZJ 80H2A Ni-MH button cell Batteries ➢ Resistors ➢ Red LEDs ➢ Electrical wires ➢ Digital Multi-meter DMM
Software Tools	➢ Multisim Software ➢ Eagle Software

Chapter 4
Results and Discussion

4.1 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 **Figures 10** and **11**.

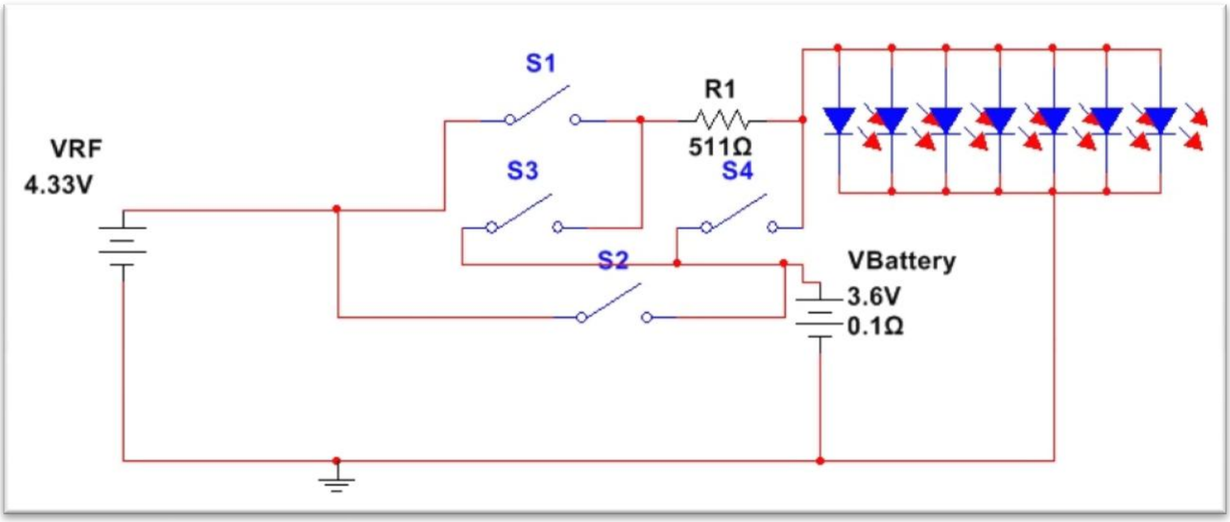


Figure 10: System Overview

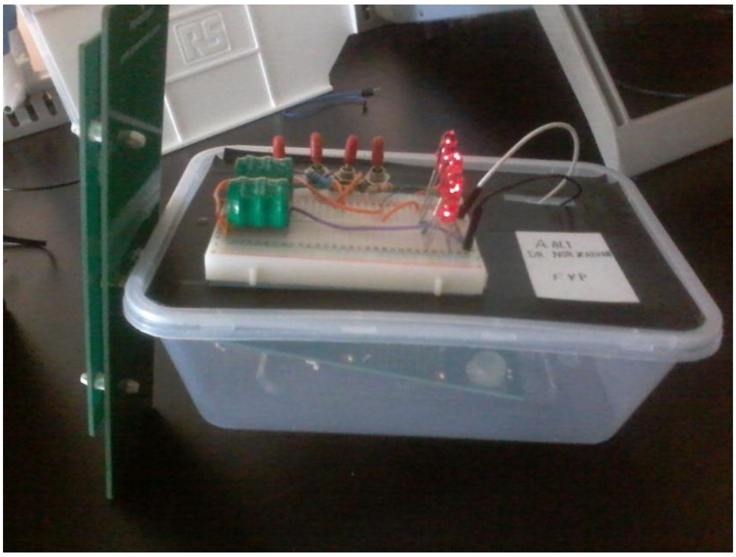


Figure 11: Prototype Overview

The system is to receive 915MHz of RF energy via the patch antenna, then it will be converted inside the P2110 Powerharvester receiver into 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 3.3V from the BATT pin. In order to increase that voltage, **Equation 3** is being used. The calculated resistance value is: **R2** = 250 KΩ.

4.2 Connection Modes of the System

4.2.1 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 $\mathbf{V_{RF}}$ = 4.33 V. This mode can be shown in **Figure 10**.

4.2.2 Mode II: Battery Charging Only (S2 Closed)

During this mode, only the 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 **Figures 12** and **13**, and the measurements of the system are available in **Table XII**.

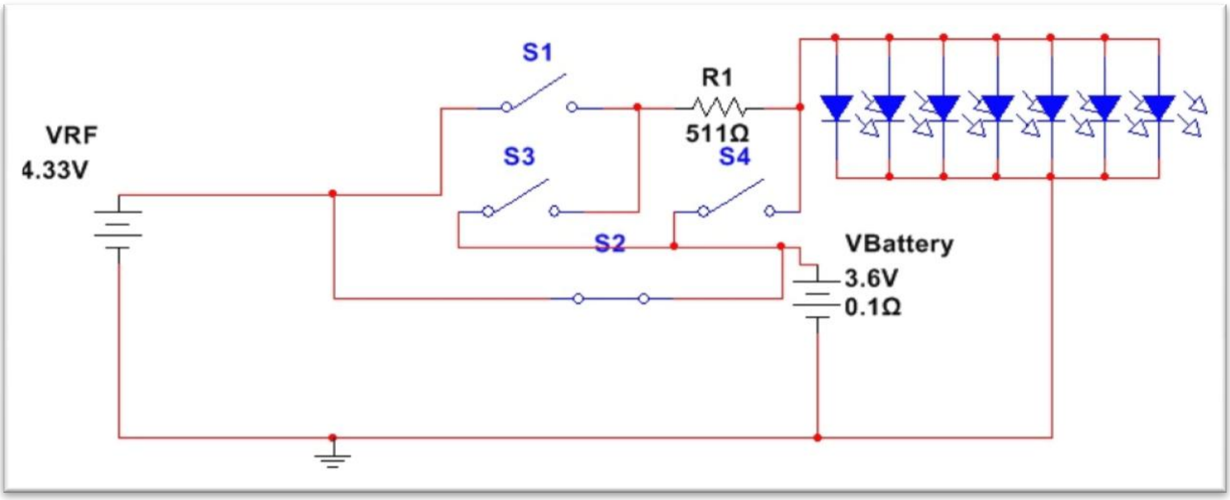


Figure 12: Mode II

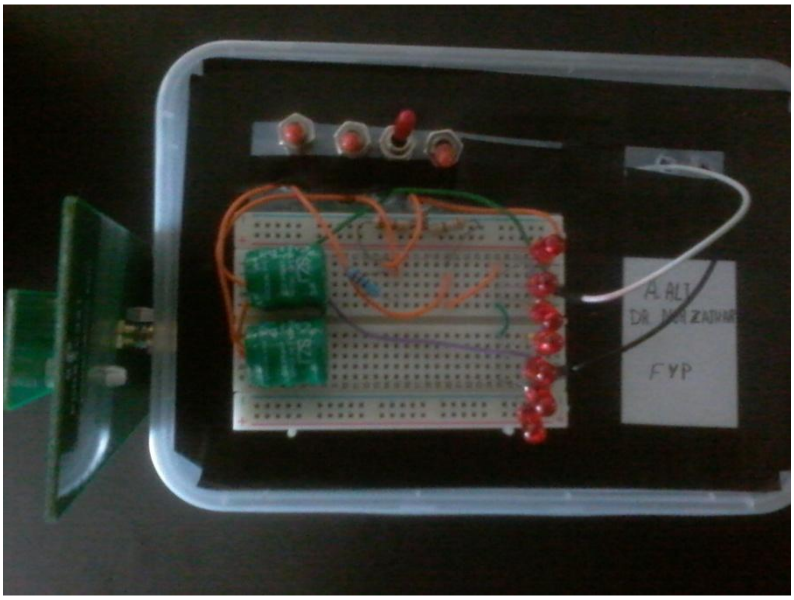


Figure 13: Mode II

Table XII: Mode II

Parameter	Value	Remarks
VRF (V)	4.33	
VBATTERY (V)	X	X is increasing, starting from battery's voltage level till 4.33 V
IBATTERY (mA)	16.77	Decreasing
TCHARGE (hours)	10	With Losses

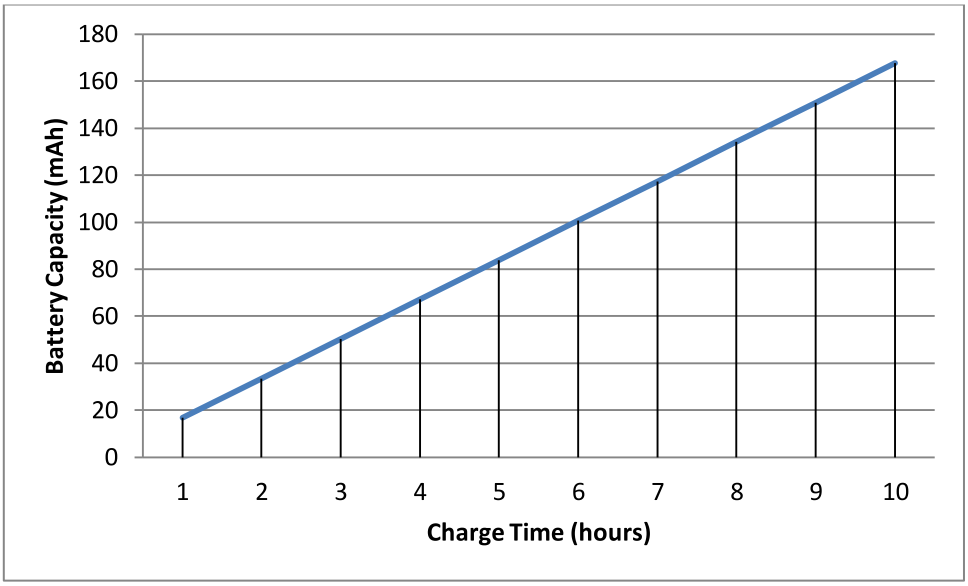


Figure 14: Charging Time

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

In this mode, only the 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 **Equation 5**. An illustration of this mode is available in **Figures 15** and **16**, and the measurements of the system are available in **Table XIII**.

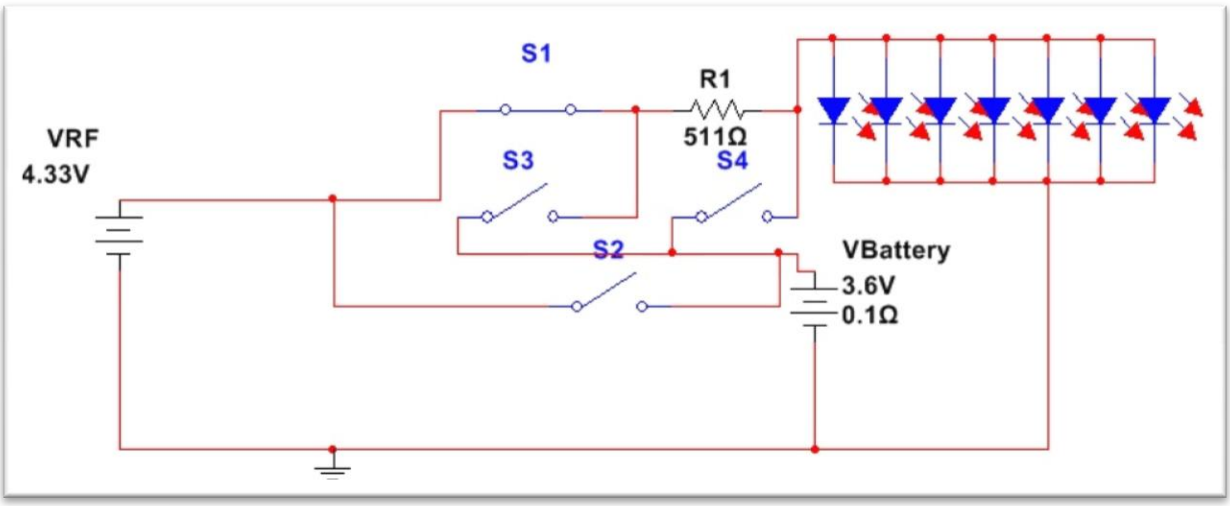


Figure 15: Mode III

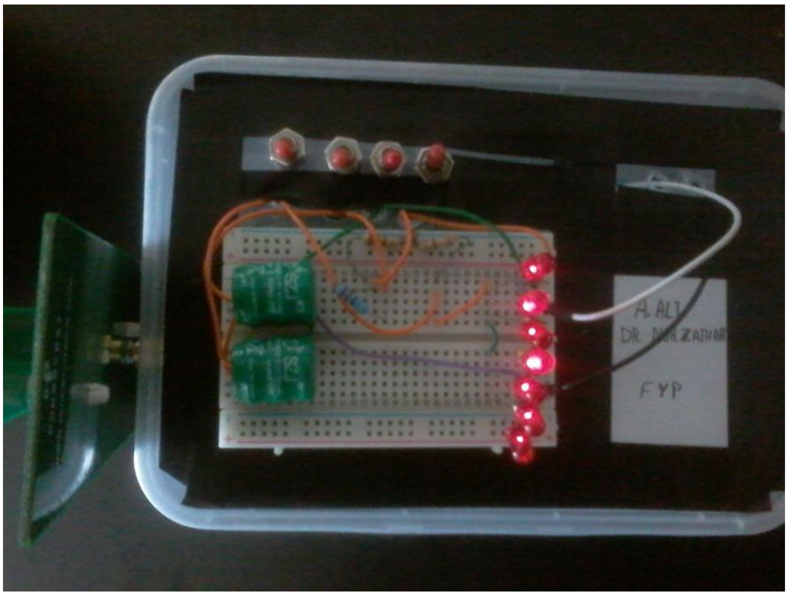


Figure 16: Mode III

Table XIII: 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)	761	
V_{R1}(V)	2.69	
V_{LED}(V)	1.63	Enough voltage to illuminate
$I_{Li\text{-}Fi}$ (mA)	3.7	

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

In this mode, the 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 being 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 **Figure 17** and **18**, and the measurements of the system are available in **Table XIV**.

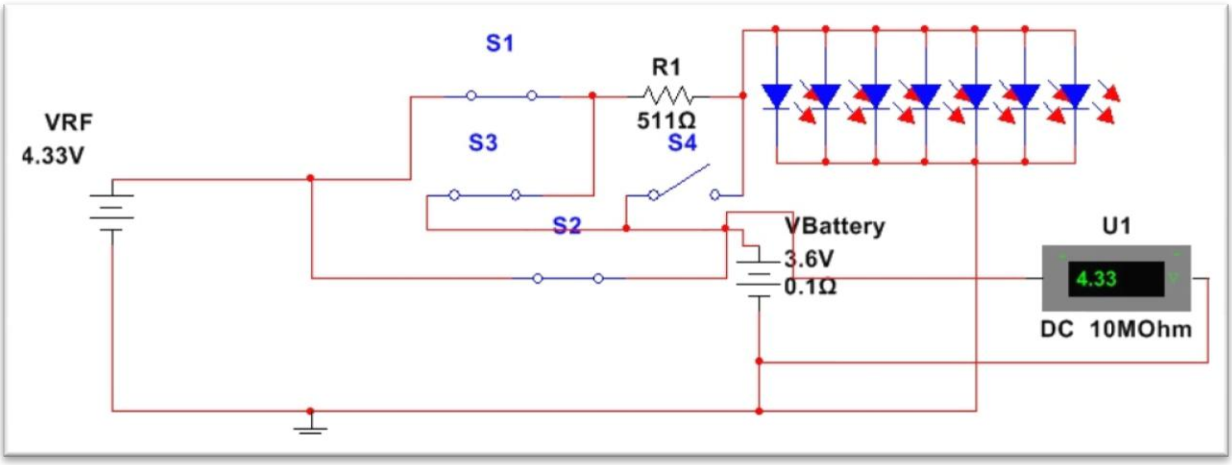


Figure 17: Mode IV

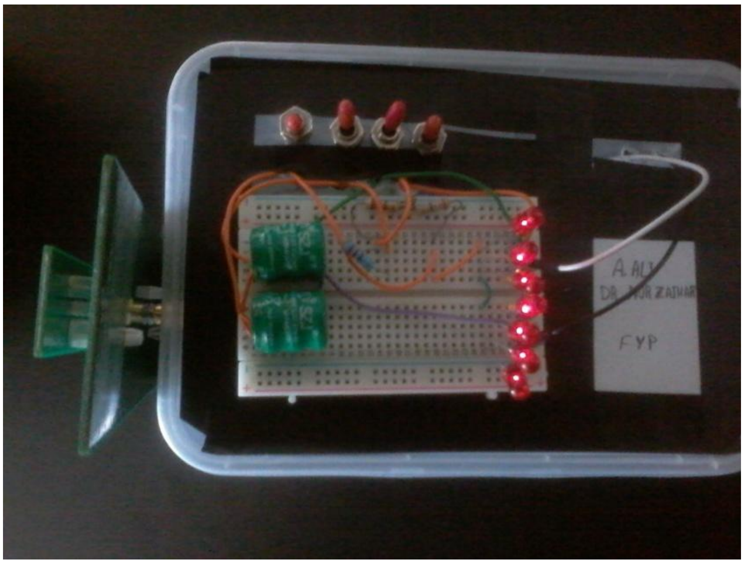


Figure 18: Mode IV

Table XIV: 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	

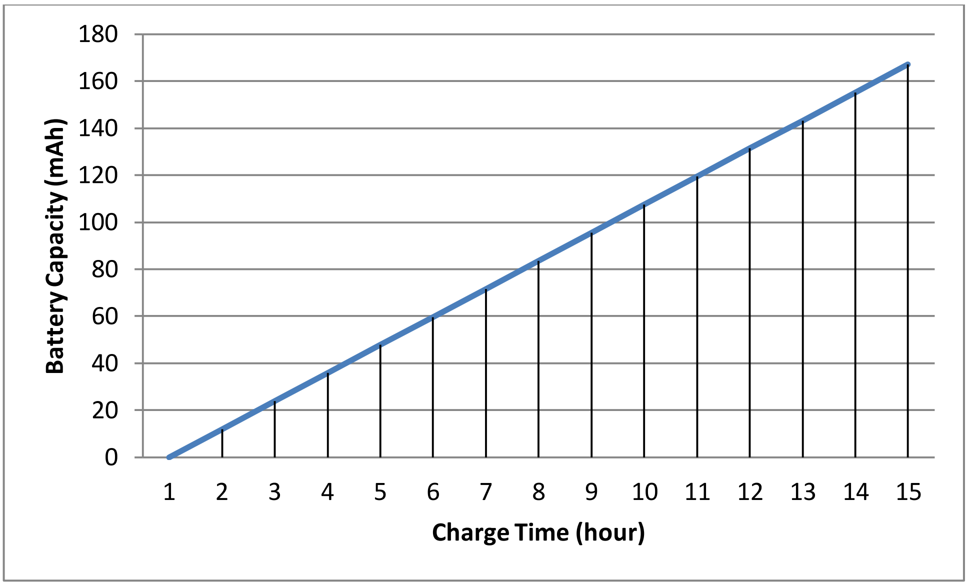


Figure 19: Charge Time Mode IV

4.2.5 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 **Figure 20** and **21**, and the measurements of the system are available in **Table XV**.

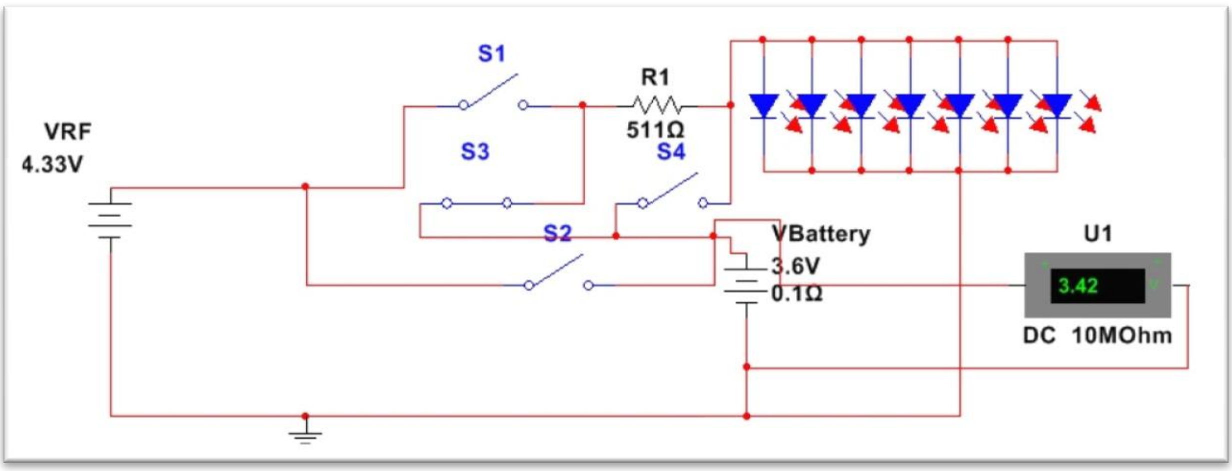


Figure 20: Mode V

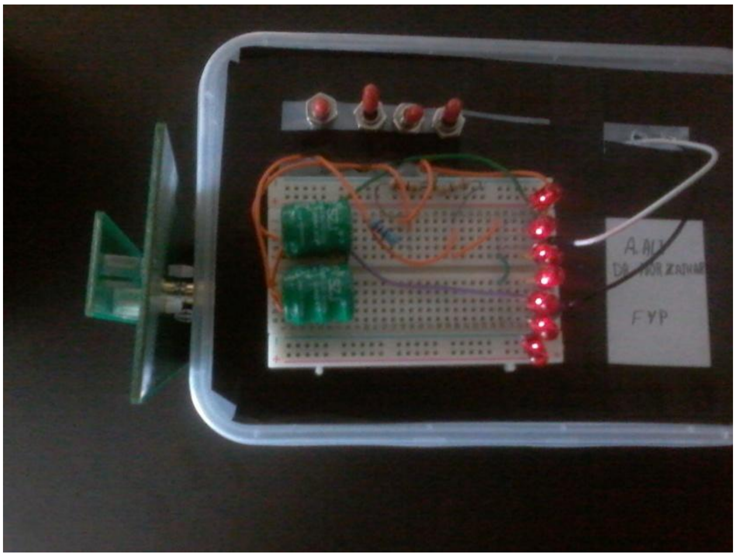


Figure 21: Mode V

Table XV: 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	

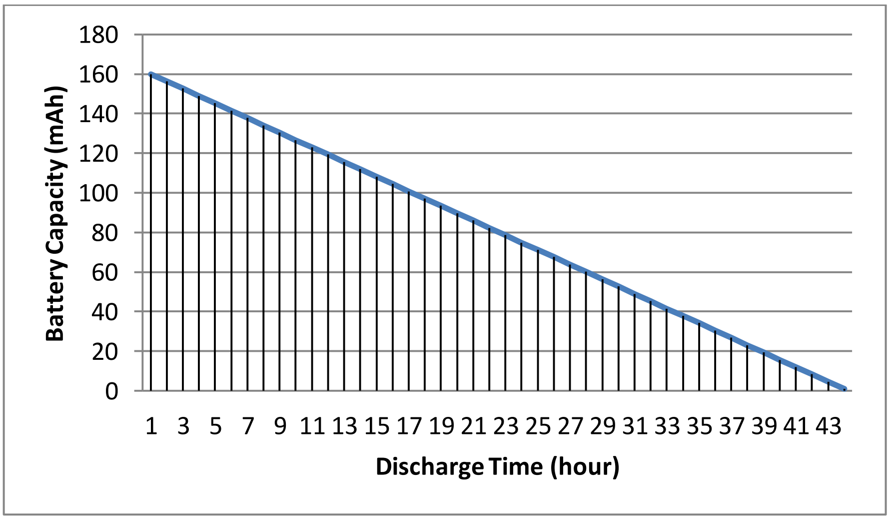


Figure 22: Discharge Time Mode V

4.2.6 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 **Figure 23** and **24**, and the measurements of the system are available in **Table XVI**.

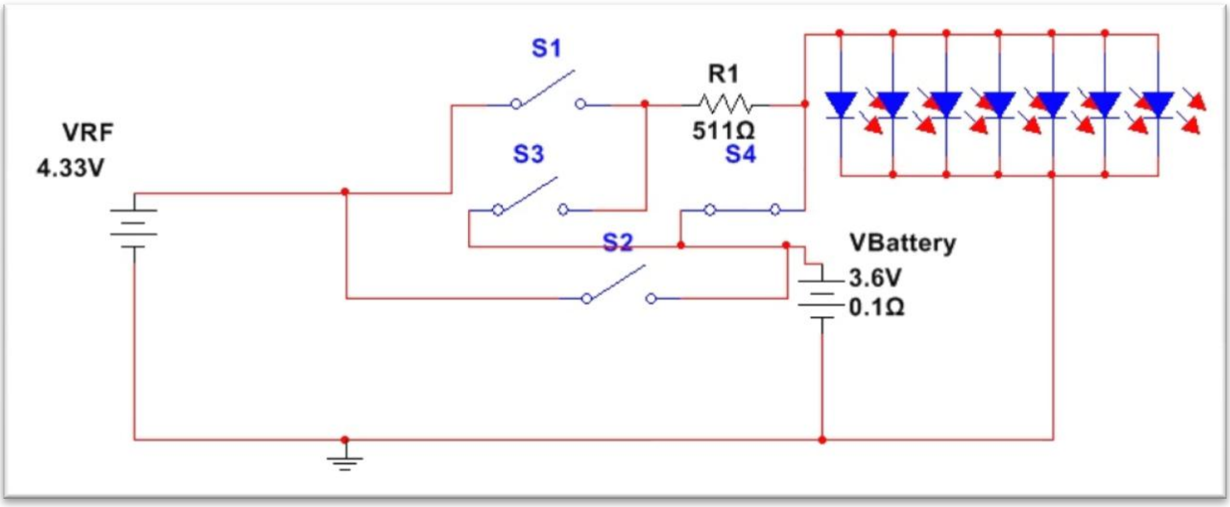


Figure 23: Mode VI

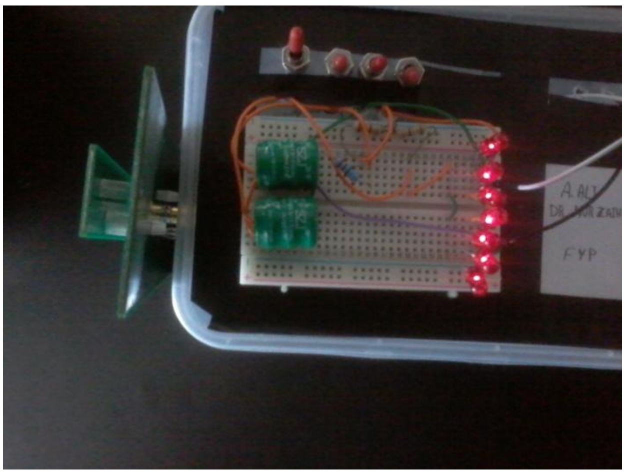


Figure 24: Mode VI

Table XVI: 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	

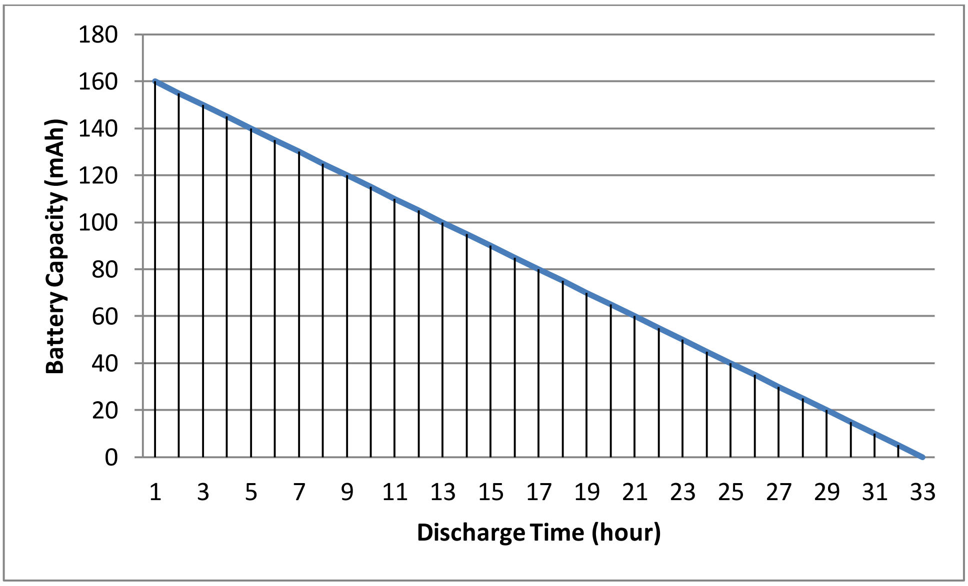


Figure 25: Discharge Time Mode VI

4.3 Designing a larger-scale Li-Fi system

According to the measurements of the system, especially at the Mode II, the battery charging mode, we can easily notice that the maximum achieved power is 54 mW, while the maximum power drawn by the Li-Fi system was 16.2 mW, meaning that the system can supply a load that is more than three times larger than this system with the same specifications. In order to do that, further research needs to be done.

Chapter 5
Conclusion and Recommendation

5.1 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 to be installed on a prototype made from plastic to make the outer shape for it. Furthermore, the system was able to achieve 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. The RF energy harvesting system, as mentioned in the results, can be able, so far, to power up a Li-Fi device that has a power consumption requirement of 54 mW efficiently.

5.2 Recommendation

As for now, the P2110-EVB has been purchased from Powercast in order to convert the energy from Radio Frequency to electrical energy. Further designs and designing a microchip with the same properties as the P2110 Powerharvester receiver is recommended in order to reduce the cost by designing and manufacturing the prototype and the harvester instead of purchasing it.

Also, researches can be done to increase the output power of the circuit by increasing the input frequency or by decreasing the losses of the power inside the circuit.

One more step is to try to depend on 3G (2100 MHz) and 4G (1800/2600 MHz) instead of the normal GSM/2G that is being used now (900 MHz) to eliminate the dependency on the TX91501 915MHz transmitter [12].

One last recommendation is that a modified design can be done in order to create a larger-scale Li-Fi device that has a power consumption of 54 mW using the same equipment and procedures that have been already used in this project.

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