# Analysis of the Efficiency of RF to DC Conversion using an Energy harvesting device


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***Abstract*— In this paper, the waveforms from various modulated schemes like QAM, PAM, BPSK, QPSK and FSK are transmitted and the efficiency of radio frequency (RF) to direct current (DC) at the receiver is analyzed. The RF to DC power conversion is performed by the industrially manufactured energy harvesting device Powercast P2110B. A frequency 915 MHz is selected for the study of RF power conversion efficiency. The waveforms of various modulated schemes are generated by the Universal Software Radio Peripheral (USRP) device which is connected to a computer via Ethernet cable. The generation of RF signals is controlled using the LabVIEW software. The generated RF signals from the USRP module are received by the Powercast P2110B energy harvester device using rectenna (Yagi-Uda antenna). The influence of average input power level on the conversion efficiency is measured by monitoring the voltage at the output of RF-to-DC converter. It is observed that by selecting proper digital modulation scheme, efficiency of RF-to-DC converter can be improved. The analysis shows that BPSK scheme chosen for transmission provides better energy harvesting as compared to other modulation schemes.**



***Index Terms*— RF-DC conversion, modulated waveforms, Universal Software Radio Peripheral (USRP), RF Energy Harvester Circuit (RFHC)**


## I. INTRODUCTION

Energy harvesting is also known as ambient power or energy scavenging or power harvesting. It is the process of extracting the energy dissipated when transferred from transmitter to receiver. The energy transmitted and received can be of any form namely thermal energy, voltaic energy, solar energy, hydro electric energy, RF energy, wind energy, etc. The harvest of RF energy is quite different from harvesting other types of energy. The controllable and predictable nature of RF energy and its independency on environmental conditions differentiate this form of energy harvesting over other renewable resources. In wireless (RF) energy harvesting, electromagnetic energy from multiple sources received by an antenna, is converted into an electric energy and the converted energy is used as a power source for Other devices. There are different methodologies to harvest RF energy namely Simultaneous Wireless Information and Power Transfer (SWIPT) [1], [2], Wireless power transfer (WPT) [3], power splitter method, time reversal techniques, etc.

WPT is the transmission of electromagnetic energy without any physical wired connections [4]. In a wireless power transmission system, a transmitter device, driven from a power source, generates a time-varying electromagnetic field, which transmits power across space to a receiver device, which extracts power from the field and supplies it to an electrical load. Reception reliability and information transfer rates are traditionally used to analyze the performance of the wireless networks.

But, the source of RF energy is variable and unpredictable. This uncertainty leads to reduced RF – DC Conversion efficiency in energy harvesting circuits. Interestingly, the overall RF-to-DC conversion efficiency of the rectenna (Energy Harvester) is not only a function of its design but also of its input waveform [4]. This alternative, wireless power transmission (WPT) uses an intentional signal, transmitted to power up the receiver devices. Several works have proposed to improve the efficiency by selecting the most adequate waveform for transmission [5].

In [5], the OFDM, the White noise and the chaotic signal results in better RF – DC conversion efficiency when compared with one-tone signal. But most real-time communications employs the modulation schemes. The relationship between modulation schemes and the RF – DC conversion efficiency need to be analyzed.

The rest of the paper is organized as follows: The architecture behind the transmission of the modulation schemes are provided in Section II. Section III discusses about the hardware development of the energy harvester circuit. The description of the experimental setup is dealt in Section IV. The results obtained and the analysis on the performance of the harvester for the waveforms from various


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modulated schemes is done in Section V and finally Section VI concludes the overall work.

## II. TRANSMISSION SYSTEM ARCHITECTURE

A typical personal computer can be used for Wireless data transmission. NI-USRP is a software defined radio designed by the company National Instruments. The host computer which is connected to the USRP through an Ethernet cable allows the user to transmit or receive data. This is achieved by software named Laboratory Virtual Instrument Engineering Workbench (LabVIEW). It is system design and development software from National Instruments. The USRP 2920 kit is shown in Fig.1.


Fig.1. NI-USRP 2920

The transmission of desired signal involves a series of steps which are given as follows in Fig.2.

- Initialize subVI – initialize a software reference to the NI-USRP hardware and check whether the connection between the host and the hardware is succeeded or not.
- Configure subVI – NI-USRP receiver parameters such as active antenna (whether TX or RX port is used), IQ rate (500 kHz), Carrier frequency (915 MHz), and the gain are set.
- Start subVI – It will initialize the acquisition of signal and this is where the desired signal is given after coding and modulation. Here, Modulation schemes like QAM, PAM, PSK, and FSK are used for transmission. The type of Modulation and the parameters like Samples per symbol, PN sequence order can be changed from the Block diagram as shown in Fig.3.
- Read subVI – It acquires a frame of IQ baseband signal samples from the USRP hardware and the IQ plot can be analyzed from the front panel.
- Stop subVI – It stops the acquisition of signal when the user stopped the code.
- Close subVI – This VI closes the software reference to the NI-USRP hardware.

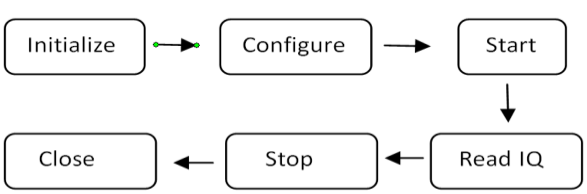


Fig.2. Steps involved in transmission

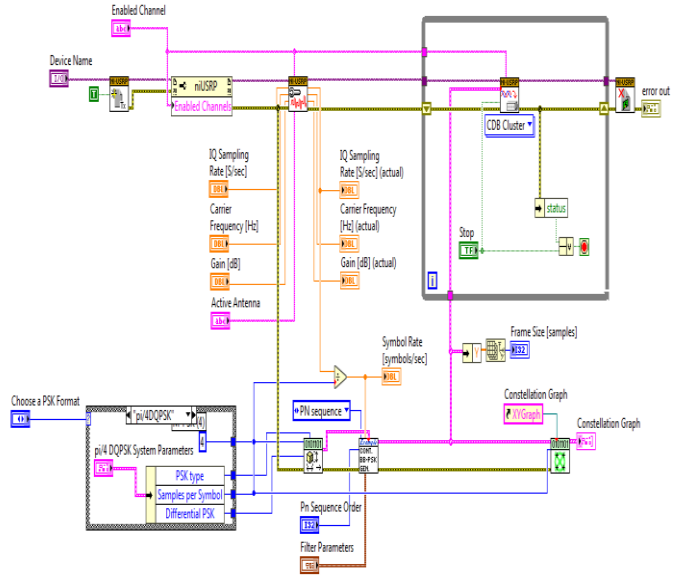


Fig.3. Block diagram for PSK transmission

## III. DEVELOPMENT OF ENERGY HARVESTING CIRCUIT

The Conversion of RF energy to DC is done by the Powercast P2110B Power harvester which is an RF energy harvesting device. Since it is housed in a compact SMD package, the P2110B receiver provides RF energy harvesting and power management for battery-free, micro-power devices. The device stores the converted DC power in a capacitor. When a charge threshold on the capacitor is reached, the P2110B enhances the voltage to set output voltage level and enables the voltage output. When the charge on the capacitor reduces to the low voltage threshold the voltage output is turned off. As in [12], [13] and [14], the prototypes of energy harvesters are built by various researchers.

Certain modifications in the values of resistors are done in [13] for the energy harvester used in this work. The DC output voltage from the P2110 is preset to 3.3V. However, it can be adjusted by adding an external resistor to increase or decrease the output voltage.

To decrease the output voltage, place a resistor calculated by the following equation from $V_{SET}$ to $V_{OUT}$. The voltage can be set to a minimum of 2.0V.

$$R = \left[1M\left(V_{out} - 1.21\right)\right] / \left(3.32 - V_{out}\right),\ M = 10^{6} \qquad (1)$$

To increase the output voltage, place a resistor calculated by the following equation from $V_{SET}$ to GND. The voltage can be set to a maximum of 5.5V.

$$R = 1.21M / \left(V_{out} - 3.32\right) \qquad (2)$$

From the above mentioned calculations, the values of the resistors are obtained and the circuit is designed as shown in Fig.4.

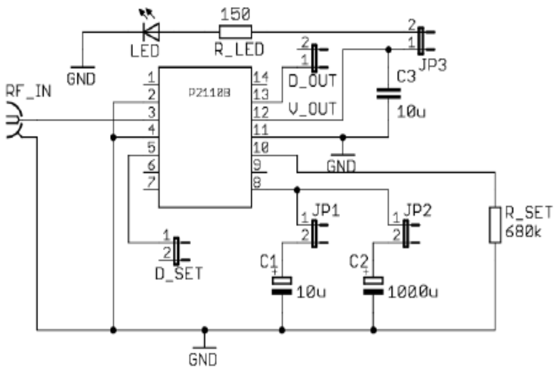


Fig.4. Circuit diagram of energy harvesting circuit [12]

The circuit given in Fig.4. is developed using the respective hardware components and is shown in Fig.5.

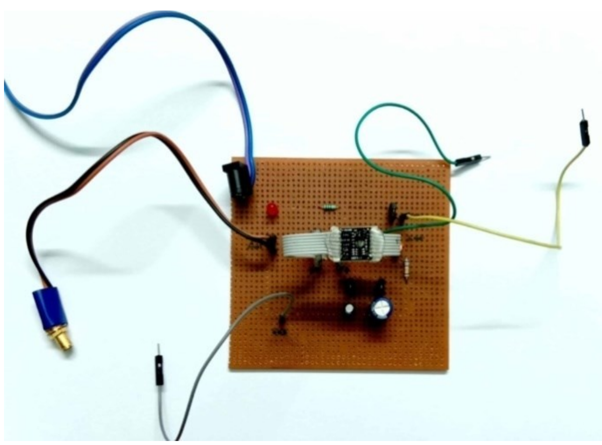

Fig.5. Hardware model of the circuit diagram

After the development of the hardware model, a Yagi-Uda antenna is to be connected to the SMA connector to receive the generated RF signals. An adapter of 5V/1A is connected to the adapter mount provided for power supply. The positive terminal of the adapter is given to pin 5 of the energy harvester module and negative terminal is grounded along with pins 2 and 4. A multimeter is required to measure the energy harvested in terms of voltage. The positive terminal of the multimeter is connected to pin 13 and the negative terminal is grounded along with pins 2 and 4.

## IV.DESCRIPTION OF EXPERIMENTAL SETUP

With the help of the harvester circuit designed in Fig.5. And the LabVIEW programs for different modulated signals, the energy harvested from waveforms of different modulated schemes is measured. Five different modulated schemes have been chosen namely 16-QAM, PAM, BPSK, QPSK and FSK. As in [12], the experimental setup is made as shown in Fig.6.

The Signal Processing laboratory and Image Processing laboratory of Thiagarajar College of Engineering, Madurai are chosen where the seven different locations for measuring

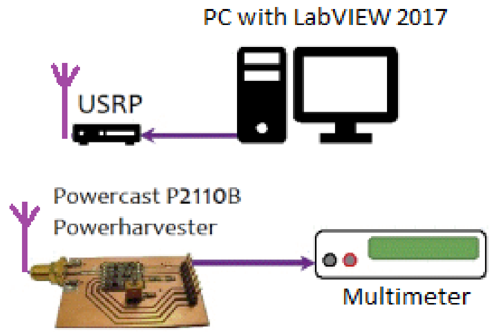


Fig.6. Experimental setup

Harvested energy are considered. The modulated signals are transmitted from a particular system connected to USRP which is labeled as Tx in Fig.6. The energy harvested during the reception of those signals are measured using the EH circuit placed at seven different locations labeled as R1, R2… R7 in Fig.7. These locations are at different distances and different angles from the transmitter.

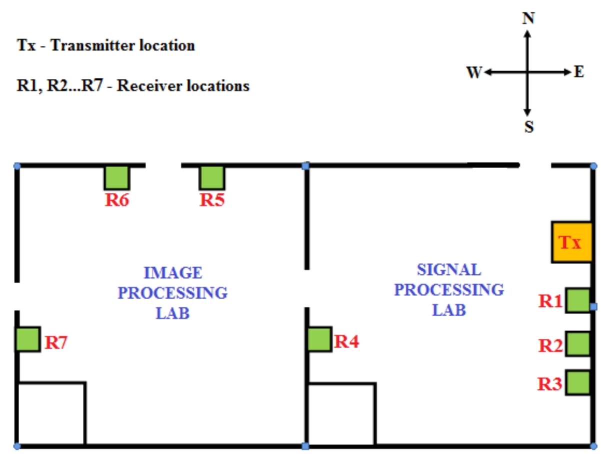


Fig.7. Map showing the locations where the transmit and receive antenna are placed

Fig.8. clearly shows the location of the transmitter Yagi-Uda antenna connected to the USRP 2920 and the locations of the receiver Yagi-Uda antenna connected with the designed energy harvester circuit.

Fig.8. Experimental setup with the transmitter and receiver at a Distance of 1.5 meters

In order to analyze the readings taken in terms of power, the measured voltage is converted into power using the formula,

$$P = V^2 / R$$

Where $P$ is power, $V$ is voltage and R is resistance equal to 150 Ohm (R_LED)

## V.RESULTS AND DISCUSSIONS

The signals of various modulated schemes namely QAM, PAM, PSK (BPSK, QPSK) and FSK are generated according to the architecture explained Section II using LabVIEW software. The signals are transmitted and received through USRP at a carrier frequency of 915 MHz.

Figures 9, 11, 13, 15 and 17 shows the parameters set at the transmitter and the constellation diagram for 16-QAM, PAM, BPSK, QPSK and FSK signals.

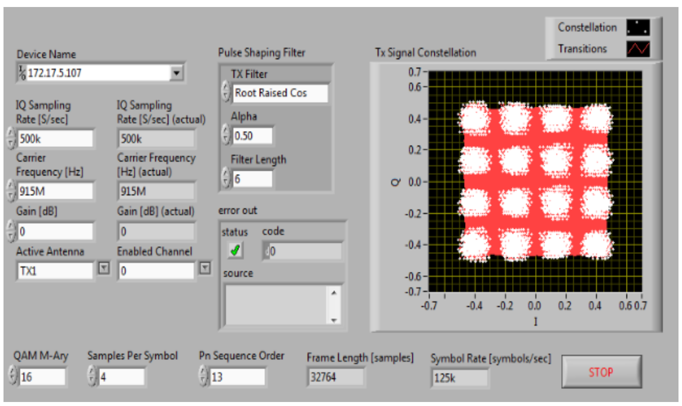


Fig.9. 16-QAM transmitter

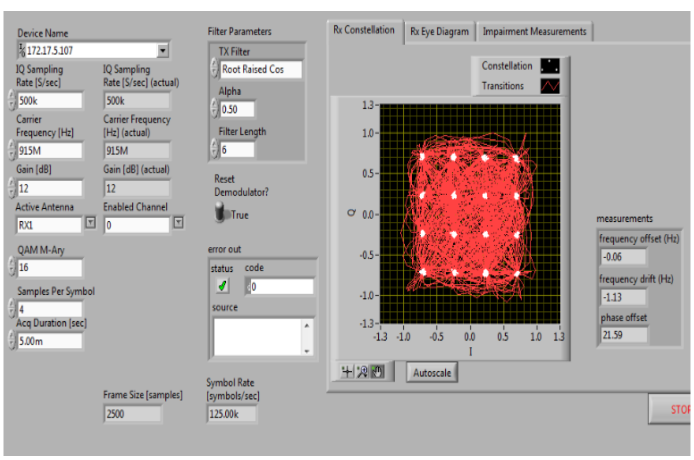


Fig.10. 16-QAM receiver

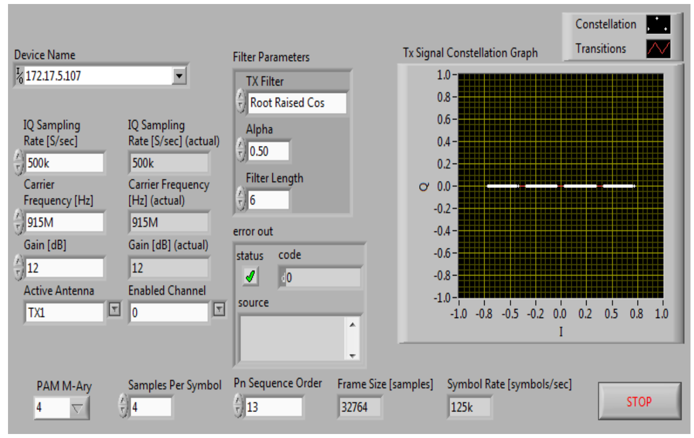


Fig.11. PAM transmitter

Figures 10, 12, 14 and 16 show the constellation diagram of the received 16-QAM, PAM, BPSK and QPSK signals when received using NI-USRP.

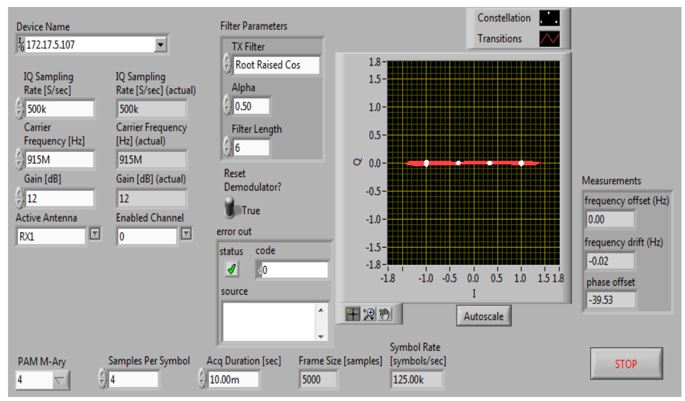


Fig.12. PAM receiver

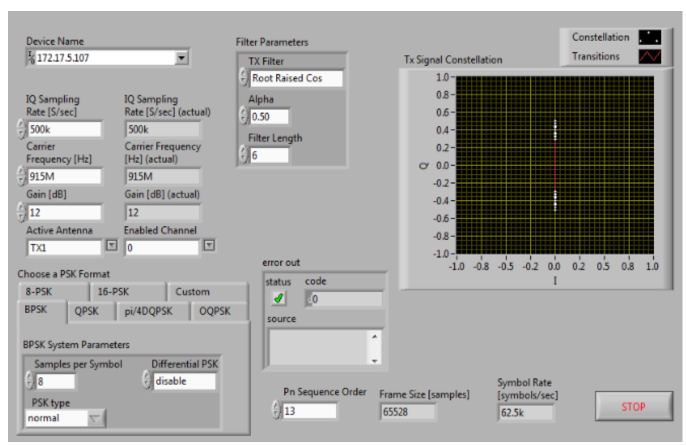


Fig.13. BPSK transmitter

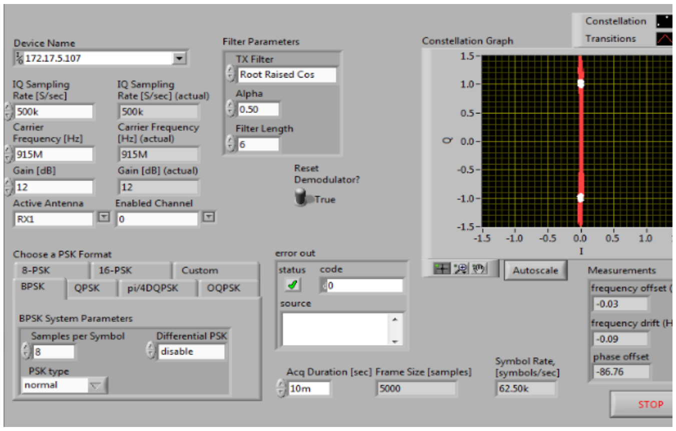


Fig.14. BPSK receiver

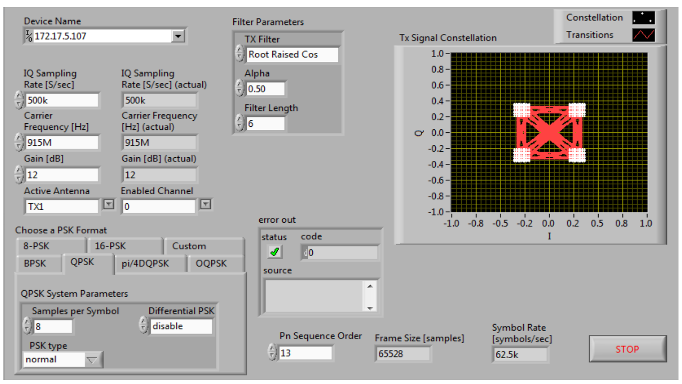


Fig.15. QPSK transmitter

From the constellation diagrams above it is quite clear that the transmitter and receiver waveforms are similar and the harvested energy measurement is done by replacing USRP module by energy harvesting circuit at the specified locations as in Fig.7. Fig.18 shows the reading of the multimeter for the receiver at a distance of 1.5 meters from the transmitter. The voltage measured is converted to power and the readings are tabulated for each modulated signal.

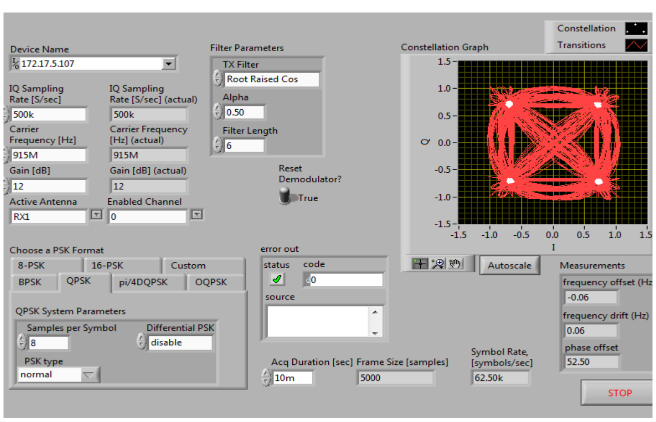


Fig.16. QPSK receiver

Table 1,2,3,4 and 5. Give the harvested power measured at different locations for 16-QAM, PAM, BPSK, QPSK and FSK signals respectively.

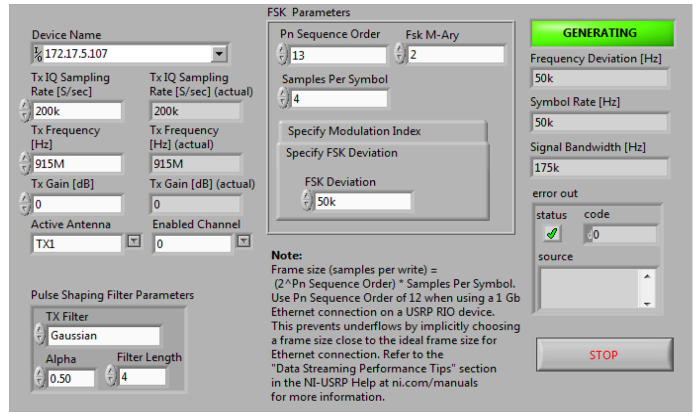


Fig.17. FSK Transmitter

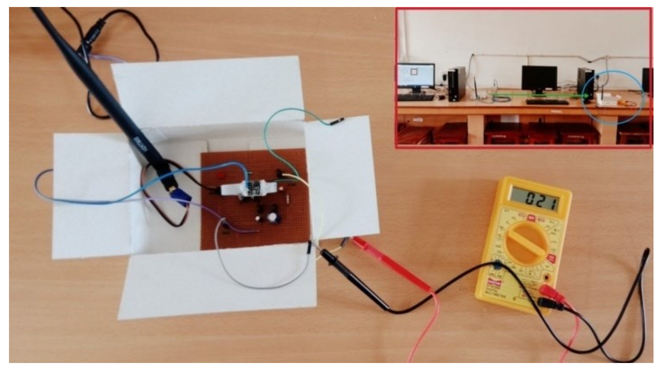

Fig.18. Measurement of voltage at a distance of 1.5m for QPSK signal

| Location no. | Distance of the location from the transmitter (in metres) | Angle of the location from the transmitter (in degrees) | Mea-sured voltage (mV) | Harvest-ed power P=V²/R (μWatts) (R = 150 ohm) |
|---|---|---|---|---|
| R1 | 1.5 | 0 | 190 | 240 |
| R2 | 2.5 | 0 | 170 | 192 |
| R3 | 4 | 0 | 150 | 150 |
| R4 | 7 | 55 | 120 | 96 |
| R5 | 9 | 100 | 100 | 66 |
| R6 | 11.5 | 110 | 90 | 54 |
| R7 | 13.5 | 60 | 80 | 42 |

TABLE 1. POWER HARVESTED FOR 16-QAM SIGNAL

It can be clearly understood from tables 1, 2, 3, 4, 5 and Fig.18. That on increase of the distance of the receiver, the harvested power is found to be decreasing. Thereby, the harvested power is inversely proportional to the distance of the receiver from the transmitter.

Fig.19. shows the graph displaying the variations of The power harvested with respect to the distance of the receiver from the transmitter. From the graph, it can be inferred that when FSK signals are transmitted, the power harvested is very low when compared to the transmission of other modulated schemes. The 16-QAM and PAM are observed to have nearest readings of harvested energy other than the first and last positions of the receiver. The transmission of BPSK signals is found to be highly efficient with a maximum harvested power of 322µ Watts with the receiver at 1.5 meters from transmitter. Even at the farthest distance considered (13.5 meters), it is found to harvest 0.54 Watts of power which is comparatively higher than that of all other modulated schemes. However at certain positions of the receiver, the transmission of QPSK signals are also found to harvest a power equal to that of BPSK signals.

| Loc-ation no. | Distance of the location from the transmitter (in meters) | Angle of the location from the transmitter (in degrees) | Measured voltage (mV) | Harvested power $P=V^2/R$ (µWatts) (R = 150 ohm) |
|---|---|---|---|---|
| R1 | 1.5 | 0 | 180 | 216 |
| R2 | 2.5 | 0 | 160 | 170 |
| R3 | 4 | 0 | 150 | 150 |
| R4 | 7 | 55 | 120 | 96 |
| R5 | 9 | 100 | 100 | 60 |
| R6 | 11.5 | 110 | 80 | 42 |
| R7 | 13.5 | 60 | 70 | 32 |

TABLE 2. POWER HARVESTED FOR PAM SIGNAL

| Loc-ation no. | Distance of the location from the transmitter (in meters) | Angle of the location from the transmitter (in degrees) | Meas-ured voltage (mV) | Harves-ted power $P=V^2/R$ (µWatts) (R = 150 ohm) |
|---|---|---|---|---|
| R1 | 1.5 | 0 | 220 | 322 |
| R2 | 2.5 | 0 | 200 | 266 |
| R3 | 4 | 0 | 180 | 216 |
| R4 | 7 | 55 | 150 | 150 |
| R5 | 9 | 100 | 120 | 96 |
| R6 | 11.5 | 110 | 110 | 80 |
| R7 | 13.5 | 60 | 90 | 54 |

TABLE 3. POWER HARVESTED FOR BPSK SIGNAL

| Loc-ation no. | Distance of the location from the transmitter (in meters) | Angle of the location from the transmitter (in degrees) | Measured voltage (mV) | Harvested power $P=V^2/R$ (µWatts) (R = 150 ohm) |
|---|---|---|---|---|
| R1 | 1.5 | 0 | 210 | 294 |
| R2 | 2.5 | 0 | 200 | 266 |
| R3 | 4 | 0 | 170 | 192 |
| R4 | 7 | 55 | 150 | 15 |
| R5 | 9 | 100 | 120 | 96 |
| R6 | 11.5 | 110 | 100 | 66 |
| R7 | 13.5 | 60 | 80 | 42 |

TABLE 4. POWER HARVESTED FOR QPSK SIGNAL

| Loc-ation no. | Distance of the location from the transmitter (in meters) | Angle of the location from the transmitter (in degrees) | Measured voltage (mV) | Harvested power $P=v^2/r$ (µWatts) (r = 150 ohm) |
|---|---|---|---|---|
| R1 | 1.5 | 0 | 170 | 192 |
| R2 | 2.5 | 0 | 150 | 150 |
| R3 | 4 | 0 | 130 | 112 |
| R4 | 7 | 55 | 100 | 66 |
| R5 | 9 | 100 | 90 | 54 |
| R6 | 11.5 | 110 | 80 | 42 |
| R7 | 13.5 | 60 | 60 | 24 |

TABLE 5. POWER HARVESTED FOR FSK SIGNAL

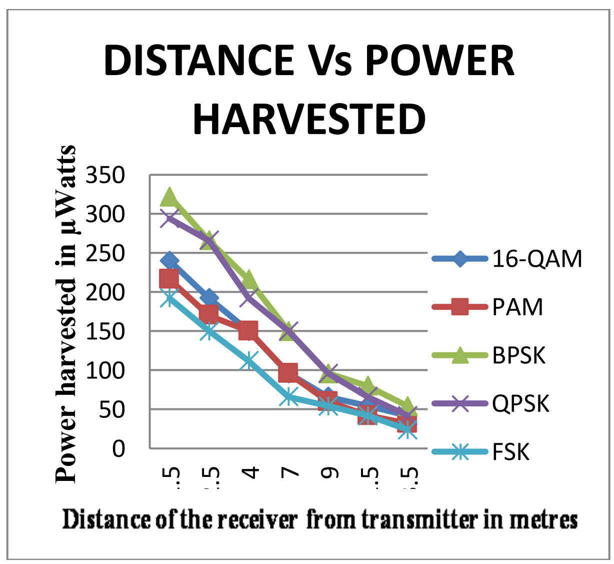


Fig.19. Graph showing the variations in the power harvested

## VI. CONCLUSION

In this paper, LabVIEW block diagrams for transmitting various modulated signals is discussed. On successful transmission of those signals using USRP, the energy harvested for each modulation scheme is measured. It is done by the circuit which employs the energy harvester module P2110B. The output of energy harvested is in terms of voltage which is converted into power for the purpose of analysis. Inferences are made on power harvested and is observed that the harvested power is inversely proportional to the distance of the receiver from the transmitter. The transmission of BPSK signals is found to provide high energy efficiency than that of other modulated signals.

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