DEVELOPMENT OF STAND-ALONE FOUR SOURCES RADIO FREQUENCY ENERGY HARVESTER USING SINGLE ANTENNA FOR MOBILE PHONE CHARGING

BY

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MEng/SEET/2018/8334

DEPARTMENT OF TELECOMMUNICATION ENGINEERING
FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

JUNE, 2023

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING IN COMMUNICATION ENGINEERING

JUNE, 2023

DECLARATION

I hereby declare that this thesis titled: "Development of Stand-Alone Four Sources Radio Frequency Energy Harvester Using Single Antenna." is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

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MEng/SEET/2018/8334

FEDERAL UNIVERSITY OF TECHNOLOGY

MINNA, NIGERIA

SIGNATURE/DATE

CERTIFICATION

The research titled: "Development of Stand-Alone Four Radio Frequency Sources Energy Harvester Using Single Antenna" by: Abubakar, Mohammed Baba (MEng/SEET/2018/8334) meets the regulations governing the award of the degree MEng of the Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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ABSTRACT

Irregular Electrical Power Supply is a major challenge in many developing countries. The effort to harness alternative energy for low power electronic devices is an ongoing research work. In this thesis, energy propagated by Radio Frequency signals was converted to DC energy to charge a mobile phone. Due to the low power density of RF signals, this research combined four RF sources to give sufficient energy enough to charge a mobile phone. FM, TV, DSTV, and GSM signals were integrated and connected in parallel to a broadband antenna. To achieve this, energy from each RF signal wave was measured using an Agilent Spectrum Analyzer (N9342C, 100 kHz-7.0 GHz) for TV and FM signal strength measurements and a cell tower application for GSM signal strength measurement. To convert the captured RF signal to DC, an RF energy circuit was designed and constructed along with DC-DC boost converter. The output DC voltage for the minimum RF input power of 5dBm (3.16 mW) was 100% met at a distance of 255 meters away from the transmitter. However 5.79% of the required current was met.

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
ADS	Advance Design System
AM	Amplitude Modulation
DC	Direct Current
FM	Frequency Modulation
GSM	Global System for Mobile Communication
IEEE	Institute of Electrical and Electronic Engineering
PCE	Power Conversion Efficiency
RF	Radio Frequency
TV	Television
UE	User Equipment
UMTS	Universal Mobile Terrestrial Telecommunication System
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Node

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

There is a growing interest to harvest ambient energy for the operation of portable electronic devices or low power wireless sensors. RF energy harvesting can be used to partially/fully supply the energy required for the operation of portable electronic devices such as wireless sensors, cell phones, blue tooth devices, medical implants and hearing aid devices (Jabbar *et al.,* 2010). In an RF energy harvesting system, an antenna receives the incident RF signal, an impedance matching circuit maximizes the power transfer from the receiving antenna to the rectifier and a multi-stage rectifier converts the incoming RF signals to an output DC voltage.

A revolutionary growth in wireless technology attracts huge attention from research community to make a self-sustainable device feasible through Radio Frequency (RF) energy harvesting. It exploits ambient electromagnetic energy transmitted from different RF systems to remotely feed the electronic devices (Nintanavongsa *et al.*, 2012). Compared to other harvesting techniques, RF energy harvesting provides relatively predictable energy supply owing to the features of easy availability and less dependency on environmental variations. In general, most of the electronic devices are powered by batteries and this leads to some disadvantages such as larger size and weight of device, regular maintenance due to limited battery lifetime, this can become more difficult and more expensive when the device operates in severe or even difficult to access environment. Therefore, the ambient energy harvesting techniques will offer solution to the aforesaid problem. The energy existing in the natural environment is of many different kinds; each has a different power density in ambient environment and requires a suitable harvesting technique, such as solar energy (100mW/cm^2), thermal energy (60μW/cm^2), ambient RF energy (0.0002 – 1μW/cm^2), energy from vibration (200μW/cm^3) (Sangkil *et al.*, 2014).

High electromagnetic energy generated from radio frequency emitted by such sources contains electromagnetic energy that can be converted into DC (Direct Current) voltage using a rectifier voltage doubler circuit linked to the receiving antenna. This circuit system can convert the RF signal to DC power at distances over 100 meters. To maintain a sufficient supply of energy in midst of varying RF concentrations, a capacitor can be attached to the circuit system to output the required constant voltage (Le *et al.*, 2008).

In conventional RF energy harvesting systems, the extraction of RF power is realized by receiving an RF signal using an antenna, rectifying the RF signal to produce the desired DC for powering an external circuit or devi

There are two different methods of operation of RF energy. The harvest-use in which the energy harvested is immediately used by the device. In this case, the harvested energy must always be equal to or greater than the energy demand of the devices, or they will be unable to operate. The second method of operation, harvest-store-use, employs an energy storage unit like a rechargeable battery or a capacitor, which is charged whenever the supplied energy exceeds the energy demands of the device operation. In addition, the usage of a capacitor as an energy storage unit increases the efficiency of the system (Prusayon, 2012). In this research, several capacitors were used to accumulate more power from four different RF sources sufficiently to power mobile phones

1.2 Statement of the Research Problem

The mobile phone batteries need to be recharged from time to time after usage and one of the major problems in Nigeria today is irregular power supply. The alternative energy sources are the Solar, which is not always available and fossil fuel, which is capital intensive coupled with the greenhouse gas emission effect. However insufficient power supply affects functionality of mobile devices in terms of charging. In order to solve the problem without using fossils fuels, it is necessary to develop a compact, inexpensive system with the ability to recharge the batteries of the mobile devices. A viable solution to this, is to capture RF energy from external ambient sources that will be converted to a DC voltage suitable for charging mobile phones

1.3 Aim and Objectives

The aim of this research is to develop a Stand-Alone four sources Radio Frequency (RF) energy harvester using a wide band antenna. To achieve this, the following objectives were set:

i. Measure RF power from: Base station of a cellular communication, FM broadcasting transmitters, DSTV (Digital Satellite Television) and T V transmitter, using Cell Tower application and Spectrum Analyzer at Bida, Niger State, Nigeria
ii. Design RF energy harvester circuit that will harvest energy from four energy sources in (i) using a wide band antenna.
iii. Fabricate RF energy harvester designed in (ii)
iv. Test the fabricated RF energy harvester and compare the result with other related works.

1.4 Scope of the study

In this research, it designed and fabricated a stand-alone portable four RF sources energy harvester using single antenna. The four sources of energy that were considered are: base station of a cellular communication, , FM broadcasting transmitters, TV (VHF) and DStv (UHF) transmitter, with a target output voltage of 5V and current of 1A, for charging of mobile phones

1.5 Justification for the Study

This work will assist people who need to continuously charge their mobile phone, so long as the RF signal is available as well as providing power for low powered electronics devices such as wireless sensor network and wireless earphone.

1.6 Thesis outline

The rest of the thesis is structure as follows. Chapter two reviews components of Radio Frequency Energy Harvester and related literature on single band, double bands, triple bands and quad bands. Chapter three present the research system model and methodology. Chapter four presents and discusses the results of radio frequency signal strength field measurements and experimental result. Chapter five states the conclusion and recommendations of the research.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Preamble

The charge level of User Equipment (UEs) battery is paramount, for UEs to be active at all times. Often, the charge level of UEs batteries in developing countries, such as Nigeria cannot keep UEs active at all times, accrued to unstable electrical power supply to charge UE battery whenever the need arises. Researchers in a way to ensure that the charge level of UEs battery and other low power consumption electronic devices are charge at all times; they introduced alternative power supply source. One of the promising alternative means of power supply to UEs is the RF energy harvester. The conventional RF energy harvesting systems work by receiving an RF signal using an antenna, extraction of RF power and then rectifying this RF signal to produce the desired DC which is then conditioned to power an external circuit or device. This chapter reviews works on RF signals, RF energy harvesters, components of RF energy harvesters and existing RF energy harvesters.

2.2 Radio Frequency Signal

An RF signal is an electrical oscillation, with frequency ranging from 3 kHz to 300 GHz that contains both information and RF energy (Rosli *et al*. 2018; Clerck *et al.,* 2018). Table 1 presents summary of electromagnetic spectrum of RF signal that can be sourced from radio transmission (Amplitude and Frequency modulation) Television (TV) transmission and cellular communication nodes. An RF signal is transmitted or received using an antenna into space. The transmission lines of RF include wired medium (coaxial cables, parallel wire lines) and wireless medium (space).

Table 2.1: Classification of electromagnetic wave spectrum

Band Designation	Frequency	Wavelength	Example Uses
Extremely Low Frequency	3 – 30 Hz	100 –10mm	
Super Low Frequency	30 – 300 Hz	10 – 1 mm	Power lines
Ultra Low Frequency	300 – 3 KHz	1Mm100km	
Very Low Frequency	3 – 30 KHz	100 – 10 km	Submarine Communication
Low Frequency (LF)	30 – 300 KHz	10 – 1km	RFID
Medium Frequency (	300 – 3 MHz	1 m - 100 m	Amplitude Modulation broadcast
High Frequency (HF)	3 – 30 MHz	100 – 10m	Shortwave
Very High Frequency	30 – 300 MHz	10 – 1 m	(FM and TV broadcast
Ultra High Frequency	300MHz-3GHz	1 m- 10 cm	TV, WLAN and GPS
Super High Frequency	3 – 30 GHz	10 – 1 cm	Radar, Satellite Communication
Extremely High Frequency (EHF)	30 – 300 GHz	10 – 1 mm	Radar, Radio astronomy, point-to-Point high rate data links
Microwaves	1 – 300 GHz	30cm–1mm	
Millimeter wave	30 300 GHz	10– 1 mm	
Sub millimeter waves	>300 GHz	< 1mm	

(Source: Stutzman and Thiele, 2012)

The mathematical expression for converting from wavelength to frequency is presented in equation (1)

$$wavelength\ (\lambda) = \frac{speed\ of\ light\ (c)}{frequency\ (f)} \qquad (2.1)$$

2.2.1 Advantages and disadvantages of radio frequency signal application

The RF Signal can be used in various applications ranging from medical applications, radar for object detection, Satellite communication and microwave line of sight communication system. However, there are some situations where RF signals have insignificant radiation and sometimes affect life.

RF energy harvester is not without demerits. The common demerits are uncontrolled radiation of RF affects pre-adolescent children, pregnant women and elderly humans, It affects some of the fruits grown near the RF tower areas, and the areas near RF cellular towers have been observed with more lightening compared to other area

2.3 Radio Frequency Energy Harvesters

This process of collecting energy from other sources and converting it into electrical energy is called energy harvesting. RF energy harvester is an electronic device that collects RF energy using antennas, converts the RF energy into AC, then into DC using rectifiers and directly powers a low power electronic device (Wireless sensor nodes, and UE), and stores the excess direct current (DC) power in a battery or a super-capacitor for higher power low duty-cycle operations (Clerck *et al.*, 2018; Caselli *et al*., 2019). A UE can be on call or connected to the internet and still be charging its battery wirelessly using RF energy harvester (Rosli *et al*. 2018). The major electronic component of an RF energy harvester is a rectifier and an antenna; which is commonly referred to as Rectenna or RF-DC. The amount of energy harvested depends on distance from RF Source. So the network nodes can have clear differences in harvested RF energy (Lu *et al*., 2015).The working principle of an RF harvester is summarized using a block diagram presented in Figure 2.1.

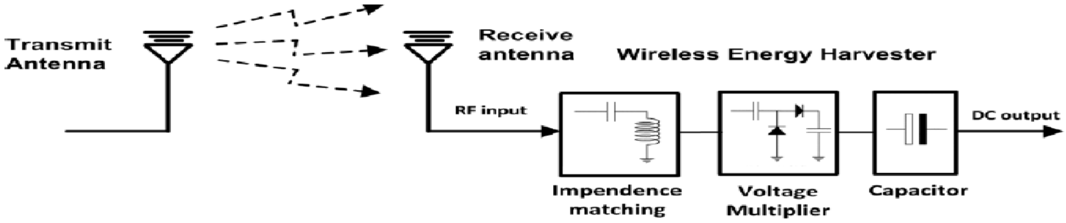

Figure 2.1: General block diagram of an RF energy harvester

The amount of energy that an RF harvester can receive is given by a combination of parameters including: the distance between transmitter and energy harvester, the frequency of RF signal, the power at which transmitter emits signal. The estimation of RF received power is given from the Friis equation presented in equation (2.2).

$$P_r = \frac{P_T\ G_t G_r \lambda^2}{(4\pi R)^2} \tag{2.2}$$

Where P_r stand for power at the receiving antenna (dBm), P_t is the output power of transmitting antenna (dBm), G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, λ is wavelength (m), and R is the distance between the antennas (m). The transmitted power level is very important for these systems.

The density of energy and the potential amount that can be harvested is larger in urban areas where most of those networks and transmitters operate, usually transmitting at higher power to cover the losses from the buildings (Pinuela *et al.*, 2018). RF energy harvesting sources can be classified as either dedicated RF energy sources or ambient RF sources (Lu *et al.*, 2015). Ambient RF energy typically covers transmission frequencies in the range 0.2 - 2.4 GHz, and is freely available from public communication services such as television (TV), GSM, Wireless Local Area networks (WLAN), and Wi-Fi. On the other hand, dedicated RF sources are on-demand supply and generally have high power density due to directional transmission, and it is used to power wireless nodes that require predictable and high amount of energy.

However, RF energy harvesters suffer from low power outputs and this is attributed to the unpredictable nature of the input power, the received signal is also prone to fluctuations by obstacles and bad weather and has a very low power density as compared to other sources. Nevertheless, a lot of researchers have investigated the possibility of harvesting power from RF sources that will be enough to drive commercial components such as wireless chargers, Wireless Sensor Node (WSN) and wireless earphone. The power density is given by equation (2.3).

$$P_d = \frac{P_t G_t}{4\pi D^2} \quad (2.3)$$

Where P_t is the transmitted power (dBm), G_t is the transmitted antenna gain and D is the distance between the transmit antenna and the rectenna (m) respectively.

Manufacturers looking to harvest energy through other means have to consider the following four factors: the device's power consumption; its usage pattern; its size; and the motion and vibration to which the device is generally subjected. RF energy harvesting is one of the most important energy harvesting methods.

The idea of RF energy harvesting, is to capture transmitted RF energy at ambient, convert it to DC voltage and use it directly for low power circuit or store it for later use. The concept to convert RF signals to DC voltage needs an efficient antenna with a rectifier circuit. The efficiency of RF energy harvesting depends on the efficiency of antenna which depends on its impedance and the rectifier circuit impedance. There is different design and circuit topology of an RF harvester, a typical example source from Caselli *et al*. (2019) is presented in Figure 2.2

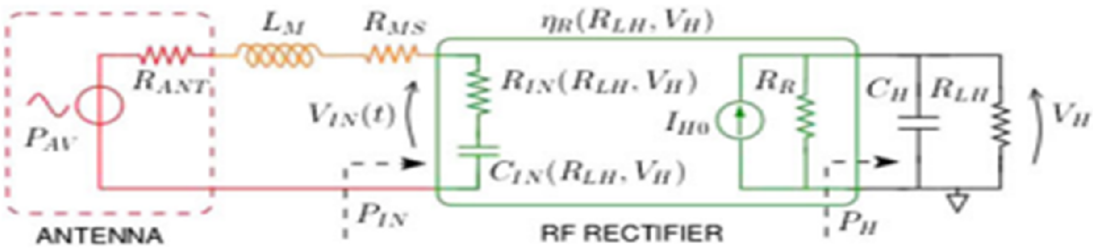

Figure 2.2: Circuit Diagram of an RF Harvester (Source: Caselli *et al.,* 2019)

From Figure 2.2, R_{ANT} stand for antenna resistance (Ω), P_{AN} stand for RF power collected by antenna (dBm), L_M represents the matching network inductance (H), R_{MS} represents matching network resistance, R_{IN} stand for input resistance in Rectenna (Ω), C_{IN} stand for capacitance of Rectenna (F), R_{LH} stand for load resistance of harvester (Ω). The harvested energy can be fed into low-power electronics directly using either wireless or wired medium.

The Power Conversion Efficiency (PCE) of an energy harvester is a Key Performance Indicator (KPI) which refers to the ratio of output dc power to input RF power. According to Danial *et al*. (2019); Sampe *et al.* (2019), equation (2.4) is used for computing PCE

$$eff\ (\%) = \frac{P_{out}}{P_{in}} = \left(\frac{V_{R_L}^2}{R_L}\right)\left(\frac{1}{P_{in}}\right) \times 100\ \% = \frac{V_{R_L}^2}{R_L P_{in}} \times 100\ \% \tag{2.4}$$

Where PCE $is\ eff\ (\%)$ in percentage, P_{out} stand for dc output power (dBm), P_{in} stand for input RF power (dBm), R_L stand for load resistance (Ω) and V_{RL} stand for voltage across load resistance (V).

The input power to an antenna can be computed using equation (2.5)

$$P_{in} = P_{tx}G_{tx}G_{rx}\left(\frac{\lambda}{4\pi d}\right)^2 \quad (2.5)$$

Where P_{in} (dBm) stand for antenna input power, P_{tx} stand for transmitter power (dBm), G_{tx} and G_{rx} antenna gain of transmitter and receiver respectively, λ represents wavelength of RF (m), d stand for distance between transmitter and receiver. The bulk energy loss in an RF energy harvester has to do with the RF-DC converter. Researchers have proposed different circuit design and topology to reduce the losses in the system.

2.4 Components of Radio Frequency Harvesters

Radio frequency harvester is a circuit that captured RF signal in free space and convert it to DC power. They harvest ambient RF energy and convert the harvested power into useful DC power. The design of an RF harvester requires an efficient antenna for maximizing the reception of the ambient RF signals; a matching network to match the antenna impedance with the complex load impedance composed of inductive and capacitive elements, in order to achieve the maximum power delivery from antenna to rectifier; and optimization of the rectifier circuit for RF to DC conversion.

2.4.1 Radio frequency antennas

RF antenna plays a vital role in maximizing the reception of RF energy from the surrounding. It is defined by Institute of Electrical and Electronic Engineering (IEEE) as part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves (Stutzman and Thiele, 2012). The performance parameter of antenna is presented in Table 2.2.

Table 2.2: Performance parameters of antennas

S/N	Parameter	Description
1	Radiation Pattern, F(θ, Ø):	Angular variation of radiation around the antenna, including: directive single or multiple narrow beams, Omni directional and shaped of main beam
2	Directivity, (D):	Ratio of power density in the direction of the pattern peak to the average power density at the same distance from the antenna
3	Gain, (G):	Directivity reduced by the losses on the antenna
4	Polarization	The instantaneous electric field vector associated with the radiation from an antenna when transmitting. Antenna Polarization include: Linear, Circular and Elliptical
5	Impedance, $Z_{A:}$	The input impedance at the antenna terminals
6	Bandwidth:	Range of frequencies
7	System Considerations:	Mechanical considerations (size, weight, aerodynamics, vibration, positioning accuracy), environmental aspects (effects of wind, rain, temperature, altitude)
8	Special consideration for transmitting antennas:	Power handling, intermodulation, radiation hazards

(Source: Stutzman and Thiele, 2012)

2.4.2 Matching network

A matching network also called impedance transformer is constructed using lossless elements such as capacitor and inductor. It is placed between the antenna and rectifier sub-blocks of an RF energy harvester to maximize the power transfer from the antenna to the rectifying circuit. Maximum power transfer is achieved when load impedance (Z_L) is equals to complex conjugate of source impedance (Z_S^*). There are various matching circuits in use; but the common design is an L-section matching circuit presented in Figure 2.3, made up of capacitor, resistor and inductor.

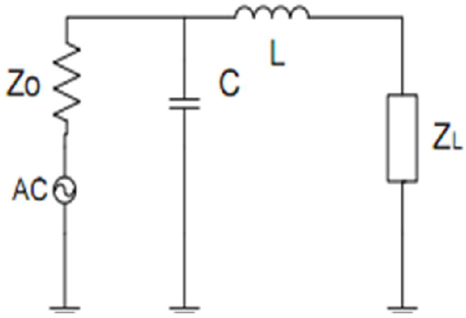

Figure 2.3: A matching network of an RF energy harvester

If the output voltage of the rectifier is lower than the operating voltage of the RF rectifier, the rectifier will not be able to operate. Thus, it is crucial to have adequate voltage levels at the antenna output and minimize losses due to mismatch of impedances between the antenna and rectifier. To serve this purpose, an L-matching network is proposed to be placed between the antenna and the rectifier to maximize power transfer between the antenna (source) and the rectifier (load).

The impedances of the source and the load are matched at the desired operating frequency, such that the impedances are complex conjugates of each other. The first step in the design of matching networks would be to find the input impedance of the load, to be matched to the output impedance of the source, typically 50 Ω.

2.4.3 Rectifier

A rectifier converts an A.C to D.C. There are single phase and three phase rectifier which could be half wave or full wave rectifier. Figure 2.4 presents a block diagram of type of rectifiers.

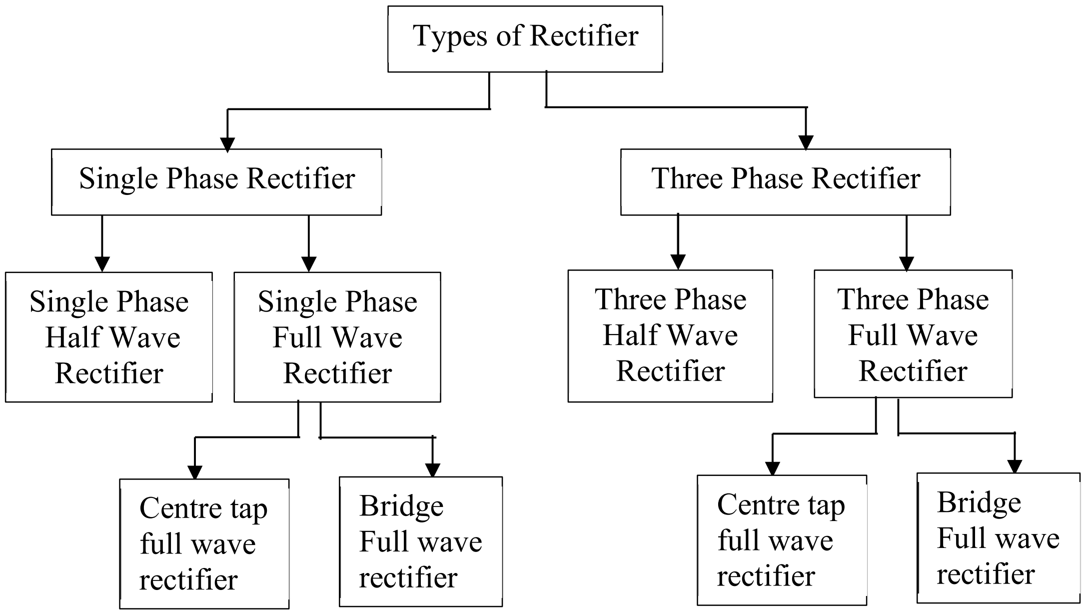

Figure 2.4: Types of rectifier

An RF harvester makes use of a single phase rectifier. A half wave rectifier makes use of a single diode to convert A.C to DC. Figure 2.5 and 2.6 present the schematic diagram of a single phase half wave rectifier and its waveform respectively.

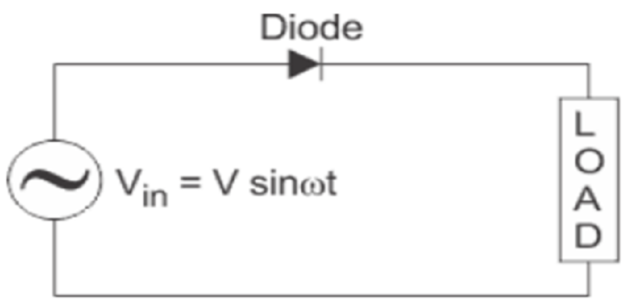

Figure 2.5: an illustration of a single phase half wave rectifier

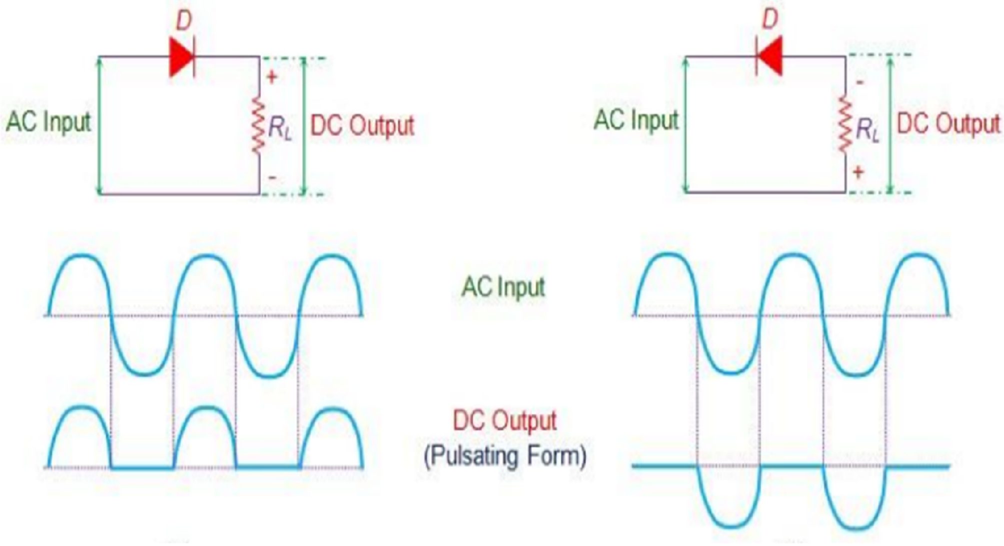

Figure 2.6: waveform of half wave rectifier

Figures 2.5 and 2.6 indicates that the half wave rectifier uses one diode to converts the positive phase of an input A.C to D.C output and the negative phase is truncated. Half wave D.C load current (I_{DC}^{HWR}), D.C load voltage (V_{DC}^{HWR}), Root Mean Square (RMS) load current (I_{rms}^{HWR}), and RMS voltage (V_{rms}^{HWR}) are computed using equation (2.9.1), (2.9.2), (2.9.3) and (2.9.4) respectively.

$$I_{DC}^{HWR} = \frac{1}{2\pi}\int_0^{\pi} I_m sinwt = \frac{I_m}{\pi} \qquad (2.9.1)$$

$$V_{DC}^{HWR} = \frac{V_m}{\pi} \qquad (2.9.2)$$

$$I_{rms}^{HWR} = \frac{I_m}{\sqrt{2}} \qquad (2.9.3)$$

$$V_{rms}^{HWR} = \frac{V_m}{\sqrt{2}} \qquad (2.9.4)$$

Full wave rectifier converts both the positive and negative pulses of an input A.C wave to a D.C wave at the same time. Figure 2.7 presents the circuit diagram of center tap, Figure 2.8 present bridge full wave rectifier and Figure gives the waveform of full rectification

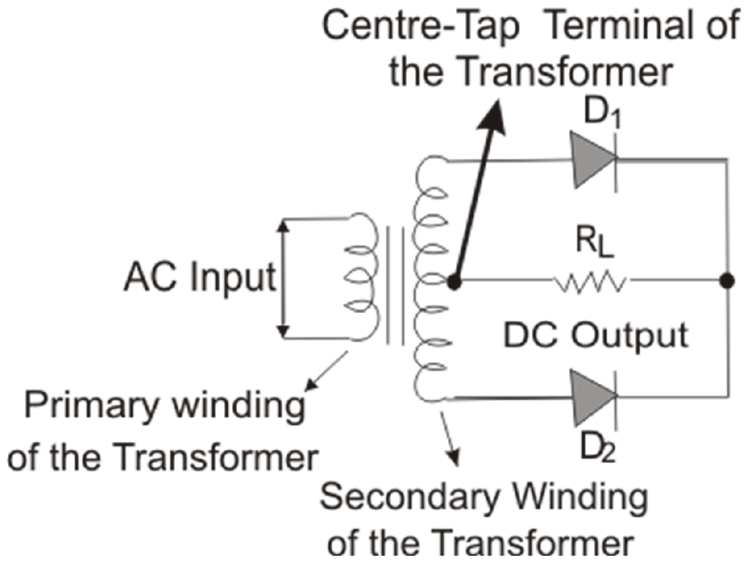

Figure 2.7: Centre tapped full wave rectifier

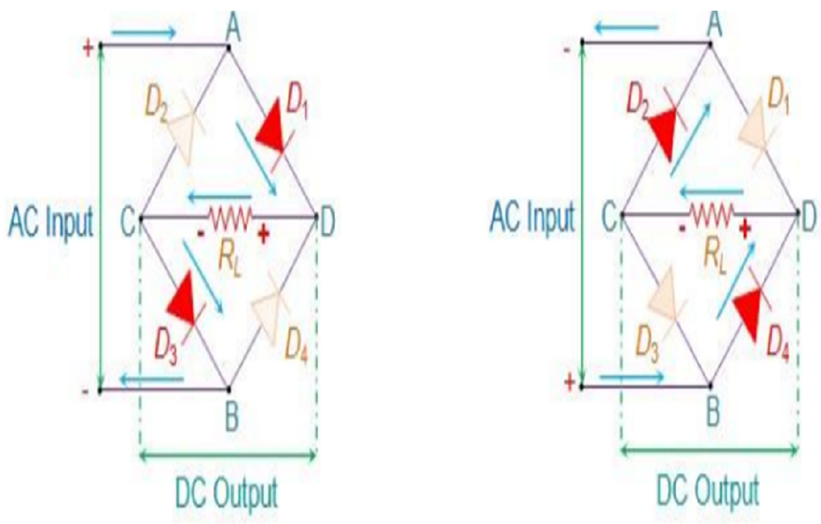

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Figure 2.8: bridge full wave rectifier

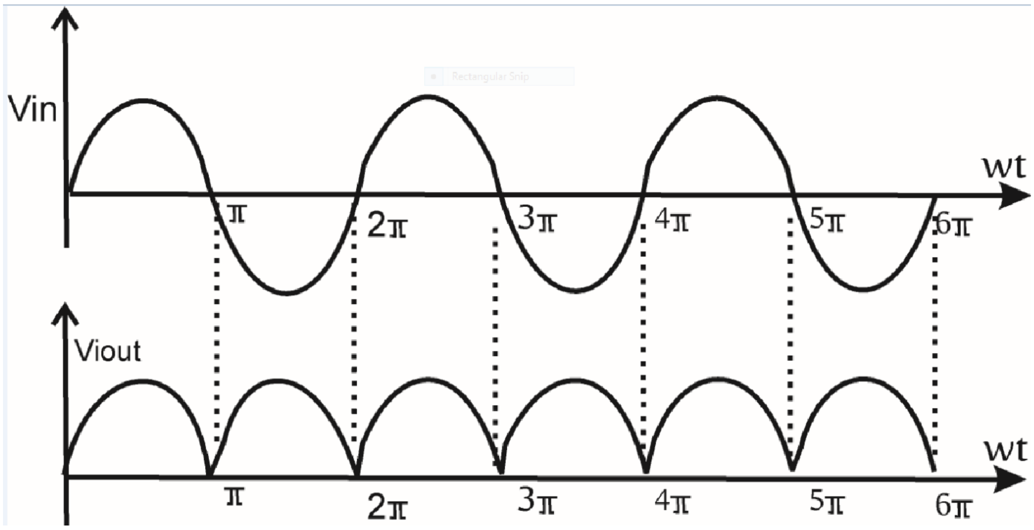


Figure 2.90: The waveform of full wave rectifier

D.C load current (I_{DC}^{FwR}), DC load voltage (V_{DC}^{FwR}), RMS current (I_{rms}^{FwR}), and RMS current (V_{rms}^{FwR}) of a full wave rectifier is compute using equation (2.9.5), (2.9.6), (2.9.7) and (2.9.8) respectively.

$$I_{DC}^{FwR} = \frac{1}{\pi}\int_0^{\pi} I_m Sinwt = \frac{2I_m}{\pi} \quad (2.9.5)$$

$$V_{DC}^{FwR} = \frac{2V_m}{\pi} \quad (2.9.6)$$

$$I_{rms}^{FwR} = \frac{I_m}{\sqrt{2}} \quad (2.9.7)$$

$$V_{rms}^{FwR} = \frac{V_m}{\sqrt{2}} \quad (2.9.8)$$

2.5 Review of Related Work

Several energy harvesting systems and their applications have been studied and presented in literature. The following are some of the related works in literature

2.5.1 Review of single-Band Radio Frequency Energy Harvester works

Zeng *et al.* (2017) presented "A Compact Fractal Loop Rectenna for RF Energy Harvesting". This paper presents the design and the fabrication of a compact fractal loop rectenna for RF energy harvesting. A high-efficiency rectifier is incorporated in the loop antenna to form a compact rectenna. Measured results indicate an efficiency of 61 percent, an output DC voltage of 1.8V across an output resistance of 12kΩ for a power density of $10\mu W/cm^2$ at 1.8GHz. That is, the RF source is GSM 1800MHz band. This output from the RF energy harvester was able to power a battery-less LCD watch at a distance of 10 meters from the GSM base station.

Similarly, Ankush *et al*. (2017) developed a system for Powering Future Mobile Phones through RF energy harvesting. The Author studied the revolutionized way Mobile phones are being charged and paving a way of charging the future mobile phones through RF energy harvesting. The measured RF power is emitted by the mobile phones operating at uplink i.e. GSM 900MHz band. The energy stored per day is 1.5 J, this amount of energy can be used to operate future mobile phones which have an inbuilt energy harvesting circuit. The measurement result obtained through the designed experimental RF Energy Harvesting prototype shows that it is possible to harvest RF energy from the mobile phones operating at uplink, that is, GSM 900MHz.

Also Leon-Gil *et al.* (2015) worked on an optimized Cockcroft Walton Voltage Multiplier RF energy harvesting for DC power from FM broadcasting. A new approach was developed which accurately predicts output impedance in optimizing the maximum power delivered to the load. To power up low power consumption devices based on Cockcroft Walton Voltage Multiplier, the output impedance of the system depends on the junction resistance and capacitance of the diode rather than the stage capacitance as formerly considered. The model was validated by comparing the result obtained with the ideal Cockcroft Walton Voltage Multiplier. It gives high output Voltage with relatively low current.

Likewise, Uzun (2016) worked on Single band RF Energy harvester which operates at GSM 900MHz band and Consists of a 2-stage Dickson voltage multiplier and L type impedance matching circuit; an efficiency of 45% at 0 dBm input power. The simulation results show that it can power low power sensor.

In considering the work of Timothy *et al*. (2020) titled enabling a Battery-Less Sensor Node Using Dedicated Radio Frequency Energy Harvesting for Complete Off-Grid Applications. The system was designed to provide complete off-grid Internet of Things (IoT) applications. To this end a power base station was designed which derives its power from solar PV panels to radiate the RF energy used to power the sensor node. A 12 element Yagi antenna was designed and optimized using the FEKO electromagnetic software. A step-up converter to step the voltage output of RF-DC converter circuit up to 3.3 V. The results obtained from the experiments performed showed that enough RF energy was harvested over a distance of 15 m to allow the sensor node complete one sense-transmit operation for the duration of 156 min. The Yagi antenna achieved a gain of 12.62 dBi and a return loss of -14.11 dB at 920 MHz. However the work was silent on conversion efficiency and output current

Similarly, Ahn (2015) developed RF Energy Harvesting and Charging Circuits for Low Power Mobile Devices. In this paper, a 4×4 rectenna of 2.13 GHz was developed for low power mobile devices. The rectenna element is a micro strip patch antenna with PTFT board of 10 di electric constant and 1.6 mm thickness that has a gain of 5.8 dBi.A step-up converter is operated with load at 0.7V to 5.5V. If the output current is 1.7mA, the conversion efficiency shows 80.9%. From the evaluated results of RF energy harvesting system, the low power mobile devices such as Zigbee when set at a distance of 12m from the transmitter can be operated.

Also, Jabbar *et al*. (2010): developed RF Energy Harvesting System and Circuits for Charging of Mobile Devices. Low series resistance Schottky diodes are most suitable for implementing the RF energy harvesting circuit due to its high forward bias current for a given voltage. This paper presents the CMOS based Villard voltage multiplier circuit to be compatible with CMOS processes. A modified form of existing CMOS based voltage doubler circuit is presented to achieve 60% increase in output power over traditional circuits at 0 dBm input power. The circuit can be used in RF energy harvesting and RF power transmission systems. The circuit parameters are set according to design and input power range from -10 dBm to 5 dBm. The circuit shows improved output power than the traditional CMOS circuit. Output voltage level can be increased using multiple stages of the multiplier circuit.

Daniel *et al.* (2018) work titled a design of ambient RF energy harvester with sensitivity of 21dBm and power Efficiency of a 39.3% using internal threshold voltage compensation proposed a reconfigurable RF- DC converter that used voltage cancellation and maximum power point tracking (MPPT) algorithm. The rectifier threshold voltage is controlled dynamically in the forward and reverse biased transistors. The positive half-cycle of proposed RF–DC converter reduces the voltage drop across the forward-biased transistors and minimizes the reverse leakage current during the negative half-cycle to increase the system power efficiency and to prevent the loss of energy stored in the prior stages. The RF harvester yielded a maximum efficiency of 39.3% at input power of -21 dBm and 900 MHz. The harvester was limited to 900 MHz only.

Likewise Yunas *et al*. (2020) did a comparative analysis on the performance of four antenna designs that were optimized at 5 GHz. The antennas were based on silicon substrates (Si-based antenna), Si-substrate with air cavity, glass-based micro-machine antenna and Duroid 5880 substrate. Their result indicated that glass-based micro-machine antenna had the smallest antenna size compared to the other three antennas. And the S_{11} loss parameter of the four antenna indicated that only Si-based substrate antenna has loss above the target of -10 dBm. The antennas were not simulated at other frequency apart from 5 GHz.

2.5.2 Review of Dual-Band Radio Frequency Energy Harvester works

Mouapi *et al.* (2017) presented a work titled "A new approach to design of RF energy harvesting system for wireless sensor networks". The authors set up an autonomous wireless sensor network powered by RF energy through a RF energy harvesting system which they designed with the goal to minimize return loss between 2.3GHz and 2.6GHz as well as maximize the DC output voltage of the RF energy harvesting system. The WSN was deployed 800 meters from the base station. The result indicates that at 0 dB input power, a 1.85 V output voltage was obtained. Maximum conversion efficiency of 49 percent was achieved. The results also indicate the possibility of using electromagnetic waves as an alternative energy source, but could be improved upon by using GSM 900MHz band.

Likewise Zakaria *et al.* (2013) worked on a planar dual-band monopole antenna which operates at 915MHz and 1800MHz for GSM band application. Simulation of the design and implementation is done and the measured results are better than the simulation value. The monopole antenna achieves good return loss at frequencies of 915 MHz and 1800 MHz with bandwidth value of 124.2 MHz and 196.9 MHz with gain 1.97dB and 3dB, respectively.

The work of Danial *et al*. (2019) titled CMOS RF Energy Harvester With 47% Peak Efficiency Using Internal Threshold Voltage Compensation considered a single stage complementary metal oxide semiconductor (CMOS) RF energy harvester based on IVC technique, to harvester energy from of 0.902 and 2.45 GHz frequency bands. They used two matching networks for the dual frequency band. Their results at 0.902 GHz within the input power ranges of -9 to 10 dBm gave more than 20% power conversion efficiency

(PCE). At 2.45 GHz RF band, it had the maximum PCE of 27.1% at 20 dBm, and more than 11% PCE within input power range of -2 to 15 dBm. The PCE was below 30%.

Likewise Wang and Negra (2014), a novel tri-band RF rectifier was designed for wireless energy harvesting on frequencies of 1050 MHz, 2050 MHz and 2600 MHz to achieve a 10mW and it has the ability to harvest RF energy from the corresponding operating frequencies sources. The Rectifier was designed and fabricated on a Rogers RO4003CTM substrate. Here in this work, several stages of rectifiers were used to give higher output voltage.

Similarly, Natasha *et al.* (2019) work titled "design constraint of a radio frequency energy harvesting. In this paper, the Author first studied antenna, its types and properties and finally discussed in details the matching network, its types and rectifier circuit of single and seven stages voltage multiplier were designed and simulated. Generally, the output of the rectifier is not sufficient enough to be used for low power applications and ended the paper with detailed explanations of DC-DC converter for boosting the output of the rectifier

Also, Borges *et al*. (2014) RF energy harvesting circuit was specifically developed for GSM bands (900/1800) and a wearable dual-band antenna suitable for possible implementation. Besides, a wearable dual-band printed circuit antenna with gains of the order of 1.8-2.06dBi and 77.6-82% efficiency capable of harvesting electromagnetic energy from the GSM (900/1800) frequency bands, the authors also simulated the behavior of a 5-stage Dickson voltage multiplier for power supply for an IRIS sensor node. Three prototypes for the 5-stage Dickson voltage multiplier with matching impedance were proposed and experimentally characterized. Results show that all three prototypes can power the IRIS sensor node for RF received powers of -4dBm, -6dBm and -5dBm, and conversion efficiencies of 20, 32 and 26%, respectively. Very good results but using lossy material as stub matching and FR4 lead to low efficiency.

Likewise, Hoang *et al.* (2014) two efficient compact dual-band antennas for RF energy harvesters were proposed. The first is a Printed-IFA for GSM bands with 1.3dBi gain at 900 MHz band and 3.2dBi gain at 1800MHz band; and the second antenna is a quasi-Yagi for Wi-Fi bands with 5.7dBi gain at 2.45 GHz band and 5.9dBi gain at 5.3 GHz band. The proposed antenna's size is $\lambda./6 \times \lambda./5.5$ and it achieves 1.3dBi and 3.dBi at 900MHz and 1800MHz bands, respectively.

Similarly, Sun *et al*. (2016) worked on a dual-band rectenna using broadband Yagi antenna array for ambient RF power harvesting. A new rectenna with broadband quasi-Yagi array antenna and a dual-band rectifier has been designed to harvest the ambient RF power of GSM-1800 and UMTS-2100 bands. The measured output DC voltage was between 300 to 400 mV when measured in the ambience. But usage of Yagi Antenna Array makes device very large and needs to be used in radiation direction only. Multi stage rectifier can be used to satisfy required voltage for other applications

Also, Khansalee *et al.* (2014) proposed a dual-band rectifier to support the RF energy harvesting at 2.1 GHz and 2.45 GHz that are UMTS-2100 and Wi-Fi operating frequencies, respectively. In order to harvest at both frequencies, the input matching of the rectifier was designed to provide the high conversion efficiency at both frequencies; also, a high sensitivity Schottky diode was selected to be a small signal detector for the rectifier circuit. The simulation and experimental results were compared and discussed.

Likewise, Agrawal (2017)-Proposed a dual-band RF energy harvesting circuit using 4^{th}order dual-band matching network. The circuit comprises of4^{th} order dual-band impedance matching and a single-series circuit with one double diode; both are integrating into a compact shape to occupy a small area. It can be extended to *n* number of the frequency band by using only $2 \times n$ matching elements. To validate the designed method experimentally, a prototype of a dual-band rectifier is fabricated for two public telecommunication bands (GSM-900 and 1800). The meander line and the open stub are used to reduce the circuit complexity and sensitivity arising due to lumped elements. A good agreement is obtained between the simulation and the measurement. The measured results show that the proposed rectifier circuit exhibits the conversion efficiency of 25.7 and 65% for an input power of −20 and 0dBm, respectively. In addition, diode nonlinearity which affects the performance of the rectifier in terms of impedance matching was also investigated

Also Rosli *et al.* (2018) RF energy harvester comprised of rectifier (RF - AC), DC – DC converter, and voltage regulator, that was implemented in 0.13 µm CMOS technology. The DC-DC converter (made up of charge pump and ring oscillator) was to boost input voltage. Their result indicated a regulated output voltage 1.25 V at RF frequency range of 900 MHz and 2400 MHz, input RF power of -16.48 dBm, and load resistance of 50Ω. The DC – DC converter boosted inputted 370 mV from rectifier into high output voltage of 1.75 V, that was regulated into 1.25 V. The output voltage cannot power mobile phones.

Sampe *et al*. (2019) proposed an RF harvester that operated at 1.8 GHz and 2.5 GHz frequency band using an antenna they referred to as rectifying antenna, simulated using Computer Simulation Technology Microwave Studio (CST-MWS) software. The simulation results obtained in their worked were 1.35 V and 1.8 V at RF input power of -25 dBm and -20 dBm respectively. And the PCE of the RF-DC converter at 1.8 GHz and 2.5 GHz was 59.51% and 45.75% respectively

2.5.3 Review of Triple-Bands Radio Frequency Energy Harvester works

Muncuk *et al.* (2018) - worked on- "Multi-band Ambient RF Energy Harvesting Circuit Design for Enabling Battery-less Sensors and IoTs". In this paper, the authors first studied the characteristics of ambient RF signals in particular locations. Then they designed and fabricated a RF energy harvester that receives ambient RF energy from LTE 700MHz, GSM 850MHz and ISM 900MHz bands. The output power obtained could power sensors with current consumption of 45µA.

Keyrouz *et al.* (2013) designed a multi-band simultaneous RF energy harvesting system and was simulated, at 800MHz, 900MHz and 2.45 GHz as shown in Figure 2.9.1. A voltage multiplier is used to rectify the captured radio frequencies and to decrease the rectifier impedance in order to match it to a 50 Ω antenna. The combined system achieved 15% more efficiency when compared to single-frequency RF harvester. The simulated results were presented but there was no practical implementation of the rectifier circuit.

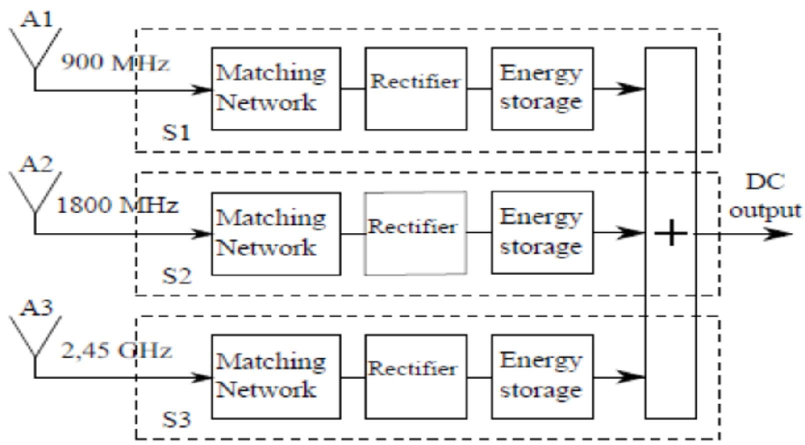


Figure 2.9.1: Multi-band simultaneous RF energy harvesting system.

Likewise Mrnk *et al*. (2016) in their work titled "The RF Energy Harvesting Antenna Operating in Commercially Deployed Frequency Bands: A Comparative Study", studied the performance of four basic antenna designs. They include the patch antenna, slot antenna, modified inverted F antenna and dielectric resonator antenna. Their performances were compared based on reflection co-efficient, efficiency, radiation patterns and dimensions. The frequency range of interest in this work is 0.8GHz to 2.6GHz that is covering the frequencies of operation in GSM, UMTS and Wi-Fi. All the four antennas proved to be effective for RF energy harvesting within the frequency range of interest except that further miniaturization is required for them to be used in wireless sensor networks and mobile wearable devices.

2.5.4 Review of Quad-Bands Radio Frequency Energy Harvester works

Similarly, Kuhn *et al*. (2015), designed a rectenna with four-RF band for RF energy harvesting to be used in wireless sensor network. The architecture has been designed to cover GSM (900-1800), UMTS, and Wi-Fi bands. The fabricated prototype shows an 84%

of RF-to-DC conversion efficiency at 0 dBm input power set on each of the four RF branches. The efficiency of all RF sources is high compared to a single band rectenna. Here in this work, we propose to use several stages of rectifier that will lead to higher output voltage which will be suitable for applications required.

Likewise Sunanda *et al*. (2022) worked on design of a Highly Efficient Wideband Multi Frequency Ambient RF Energy Harvester. The highly efficient quad-band RF harvester is proposed for ambient RF energy harvesting. The highly sensitive full-wave rectifier circuit is intended to strengthen the low power sensitivity. A broadband multi-frequency self-complementary log-parodic antenna is also installed in an ambient setting to improve the RF signal's receiving power. -20 dBm input RF power from 0.9 GHz to 2.6 GHz. The calculated dc rectification efficiency is about 52 percent at -20 dBm. Measurement in an ambient RF setting shows that the proposed harvester is able to harvest dc energy at -20 dBm up to 0.678. As shown in figure 2.9.2, a complete quad-band rectifier topology, a highly efficient quad-band RF harvester was proposed for ambient RF energy harvesting. A novel impedance matching network was introduced with novel broadband rectifying components to better align the usable RF signals with comparatively lower RF power density levels. The highly sensitive full-wave rectifier circuit was intended to strengthen the low power sensitivity. A broadband multi-frequency self-complementary log-parodic antenna is also installed in an ambient setting to improve the RF signal's receiving power.
Table 2.3 shows a summary of previous works relevant to the study

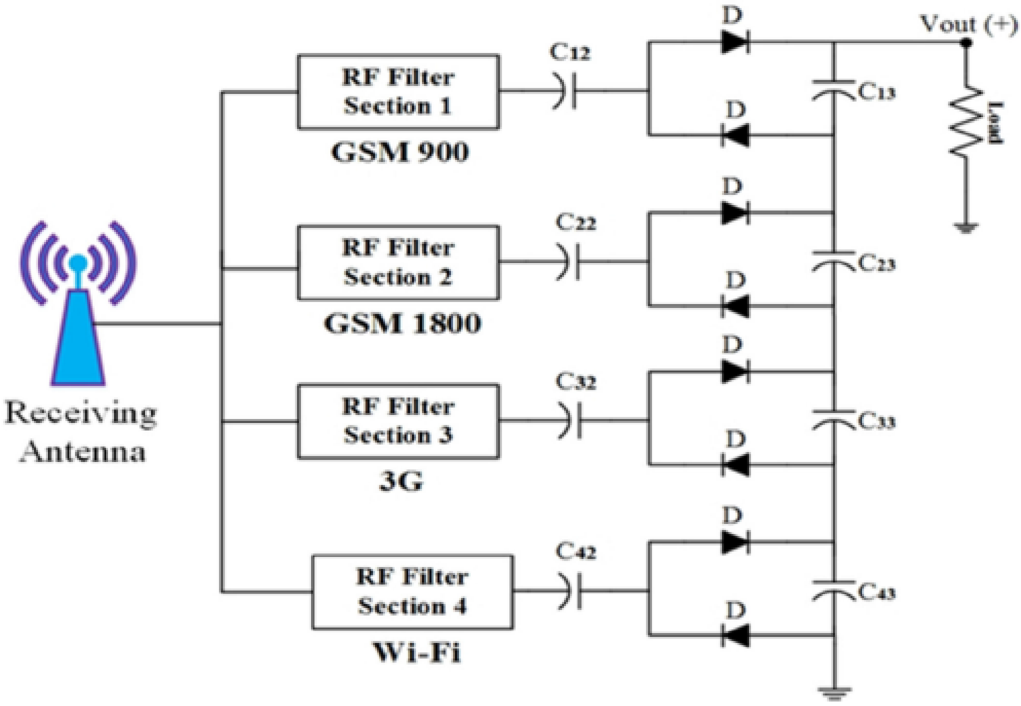


Figure 2.9.2: A complete quad-band rectifier topology (Sunanda *et al.,* 2022)

2.5.5 The Research Gap

This research is standalone four sources radio frequency energy harvester using single antenna for mobile phone charging. Due to low power density of RF signal, RF energy from four different sources were combined and boosted by joule thief boost converter to give a sufficient power that drives a mobile phone.

Table 2.3 shows a summary of previous works relevant to the study. It is presented in a format consisting of an author, year, title, weakness and strength. In most of these literatures, current generated were silent on and those mentioned were relatively low though there is always voltage generated by the system. This is due to the low power density of RF signals.

Table 2.3: Summary of Literature Review

S/N	Author/Year	Title	No of band	Techniques	Strength/Weakness
1	Leon-Gil *et al.* (2015)	Single band RFEH system from FM Broadcasting Band	Single-Band	An optimized Cockcroft Walton Voltage Multiplier	High output Voltage/ Relatively low current
2	Mrnka *et al.* (2016)	The RF energy harvesting antennas operating in commercially deployed frequency bands	Dual-Band	CST Microwave Studio	All the four antennas proved to be effective for RF energy harvesting/Further miniaturization is required for them to be used in wireless sensor networks
3	Mouapi *et al*. (2017)	A new approach to design of RF energy harvesting to enslave wireless sensor networks	Dual-Band	LEACH protocol, ADS	Higher efficiency status for wireless sensor networks
4	Kuhn (2015)	Multi band stuck RF Energy harvester	Quad-Bands	Four RF band was designed and simulated	Higher efficiency status for wireless sensor networks
5	Zakaria *et al*. (2013)	Dual-band monopole for RF energy system	Dual-Bands	Agilent ADS 2009 simulator	Good output/ Distance limited to narrow band
6	Wang & Negra (2014)	Novel Tri Band RF Rectifier design for wireless energy harvesting	Triple-Band	Fabrication of a rectifier circuit on R04003 CTM substrate	10 mW/ At short distance
7	Muncuk *et al*. (2018)	Multi-band Ambient RF energy harvesting circuit for enabling battery-less sensor and IoT	Triple - Bands	Agilent ADS	Could power sensor/Relatively low current
8	Natasha *et al*. (2019)	Design constraint of RF energy harvester	Dual-Bands	Simulation	Details on characteristics and different antenna construction and

					matching network/ No practical implementation
9	Zeng *et al*. (2017)	A compact fractal loop rectenna for RF energy harvesting system	Single-Band	Higher efficiency antenna incorporated in loop antenna	61 % efficiency, 1.8V and can power LED/Obtained at a short distance
10	Ankush *et al.,* (2017)	Powering feature mobile phones through RF energy harvesting	Single-Band	Designed experimental RFEH prototype	Good output power for charging a future mobile phone/ Cannot charge an Android phone
11	Berges *et al*. (2014)	RF energy harvesting circuit for GSM band (900/1800) MHz	Dual-Bands	Dickson voltage multiplier	Very good DC output/Low efficiency due lossy material and FR4 Stub Matching
12	Uzun (2016)	Design implementation of RF energy harvesting system for powering electronic devices	Single-Band	Two stages Dickson voltage multiplier	Powered low sensor/Low efficiency
13	Sun *et al*. (2016)	Dual band rectenna using broad band Yagi array antennas	Dual-Bands	Simulation	Good output voltage/ Yagi antenna array makes the device very large
14	Agrawal (2017)	A dual band RF harvesting circuit using 4^{th} order dual band matching network	Dual-Bands	Simulation of a rectifier circuit and its prototype was fabricated	It reduces circuit complicity/ Diode nonlinearity affects the performance of the rectifier in terms of impedance matching
15	Jabbar *et al*. (2010)	RF energy harvesting system and circuit for charging of mobile devices	Single-Band	Villard voltage multiplier	Higher efficiency in terms of output power
16	Danial *et al*. (2018)	Design of RF to DC Conversion Circuit for Energy Harvesting in CMOS 0.13-μm Technology	Single-Band	Simulation	Boosted low input voltage, though the output voltage gotten was still below 5V.

17	Rosli *et al.* (2018)	Design of RF to DC Conversion Circuit for Energy Harvesting in CMOS 0.13-µm Technology	Dual-Bands	CMOS technology	Had reconfigurable RF-DC converter. Based on only 900 MHz frequency
18	Danial *et al*. (2019)	CMOS RF Energy Harvester With 47% Peak Efficiency Using Internal Threshold Voltage Compensation	Single-band	Simulation	Had low threshold voltage and PCE below 30%
19	Sampe *et al* ,(2019)	Architecture of an efficient dual band1.8/2.5 GHz rectenna for RF energy harvesting.		simulated using Computer Simulation Technology Microwave Studio (CST-MWS) software	Gave high PCE of 59.7%, but the output voltage of the simulation was below 5V.
20	Yunas *et al*. (2020)	Design and Fabrication of Glass based MEMS Patch Antenna for Energy Harvester	Dual-bands	Simulation	Identified better material for small antennas for 5GHz, but did not consider other frequency range
21	Timothy *et al*. (2020)	Enabling a battery-less Sensor Node Using a Dedicated RF Energy Harvester for Complete Off-Grid Application	Single-band	RF system was designed and antenna Was simulated using FEKO software	Good output voltage that can power a sensor node but silent on power conversion efficiency and current
22	Ahn (2015)	Developed RF Energy Harvesting and charging circuit low power Mobile Devices	Dual-band	Simulation	The simulated result shows high output voltage with very low output current
22	Sunanda *et al*. (2022)	Highly Efficient Wide-Band Multi Frequency Ambient RF Energy Harvester	Quad-Bands	A prototype RF harvester wasconstructed	The system harvested and gives an output voltage 0,678 V and PCE of 52 but salient on output current

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 Research Materials and Tools

The electrical components used for the fabrication of the RF energy harvester include capacitors, resistors, schottky diode (FR 107 and IN 4148), antenna (Broadband antenna), transistors, ferrite core, battery, printed circuit board, capacitors (fixed and variable), inductance, Jumper wires and soldering lead. While the hardware tools used include: soldering iron, dell laptop, spectrum analyzer for measuring RF power, multi-meter for measuring output voltage, current and power of energy harvester and the software tools used include: avenza map, epicollect5 and cell tower.

The targeted RF signal from the study area, Bida, Niger State comprised of RF from FM broadcasting transmitter, Television transmitter, and mobile base station transmitters. The summary of the targeted RF signal are presented in Table 3.1

Table 3.1: Targeted RF Sources

S/n	RF sources	Frequency band (MHz)	Distance from ref. point Km
1	FM Radio Broadcasting Station	88-108	6.15
2	TV Broadcasting Tower	170-300	6.25
3	DSTV	450-952	Nil
4	GSM Base Station	900-2100	Several

3.2 Research Method

The design, and fabrication of four sources RF energy harvester using single antenna was executed in stages; starting with the design that gave the required components and lastly a prototype was fabricated. The test results of the fabricated RF energy harvester were compared with some other related works. The four source RF energy harvester using single antenna starts with measuring collected RF power, matching the collected RF power, rectifying AC input to DC and boosting the DC output of rectifier using DC-DC converter and then regulating the boosted DC voltage to 5Volts. A single broadband antenna is used which covers the frequencies of interest. The Gang capacitor was incorporated to act a frequency selector to select the frequencies corresponding to the frequencies of the targeted RF sources. RF-DC converter circuit was designed using a low resistance Schottky diode, FR 107 due its desirable characteristics of having a very low threshold voltage ranging from (0.2-0.4) mV. The output of the rectification was combined to yield more power sufficiently that drove the DC converter (joule thief) which is self-regulated system required to give a stable output voltage. The block diagram of RF energy harvester is presented in Figure 3.1.

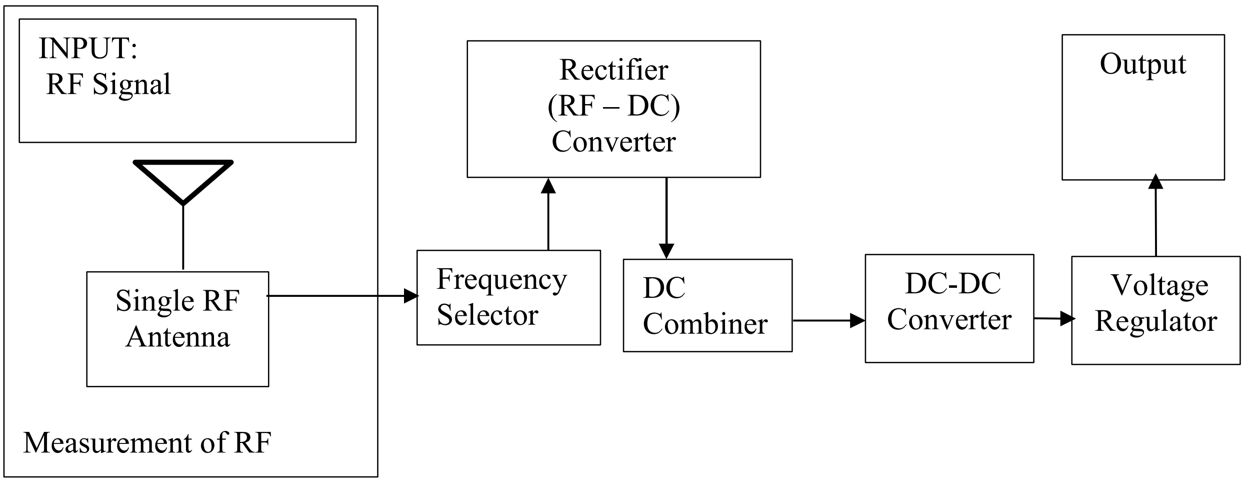


Figure 3.1 Block diagram of four-source RF energy harvester using single antenna processes

The model used in this work consists of an antenna. Frequency Selector, Matching Network, Rectifier circuit and DC-DC converter and each plays a significant role in the system as shown in Figure 3.2

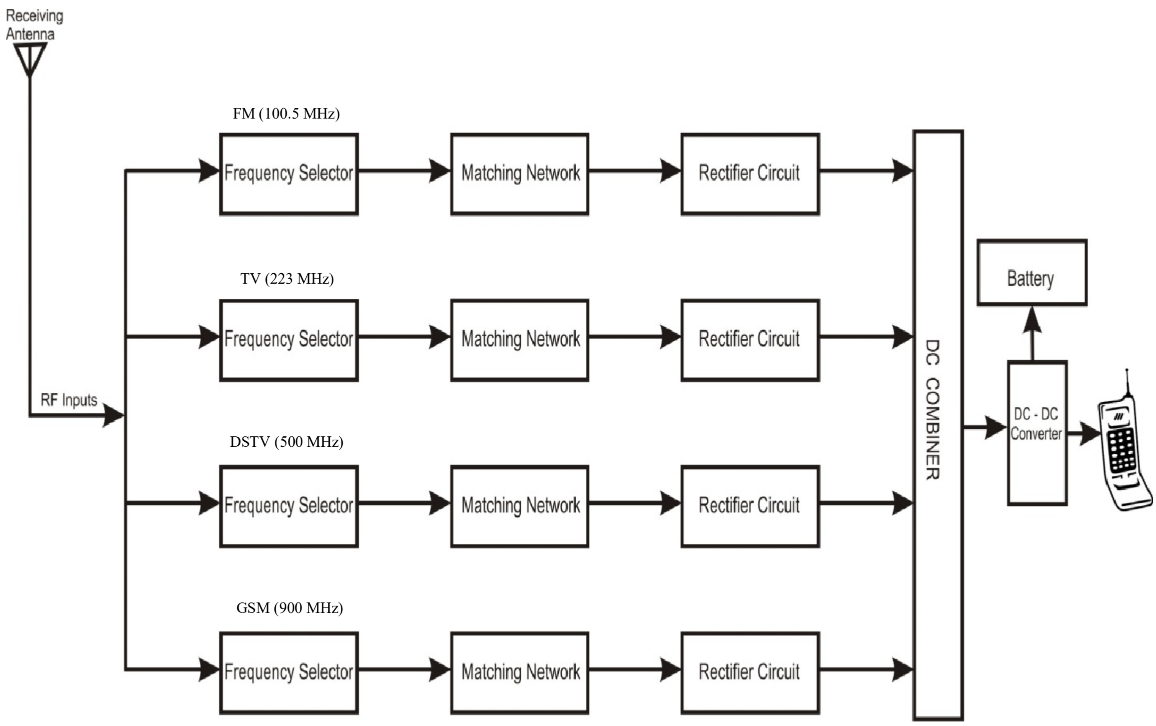


Figure 3.2: The model for four source RF Energy Harvester using single antenna

A wide band antenna of frequency range of 45 MHz to 1GHz was used to capture the RF signals within the frequency bands and selected by the frequency selector as shown in Figure 3.3 for maximum transfer of power to the rectifier circuits by the matching networks. The outputs of the rectifiers were combined to give a voltage sufficient to trigger the DC-DC converter for the required output voltage which can either be used directly or store for later use.

3.3 Design

3.3.1 Preliminary design assumptions

i. **FR 107** schottky diode was used because it is an universal high frequency diode with low threshold voltage

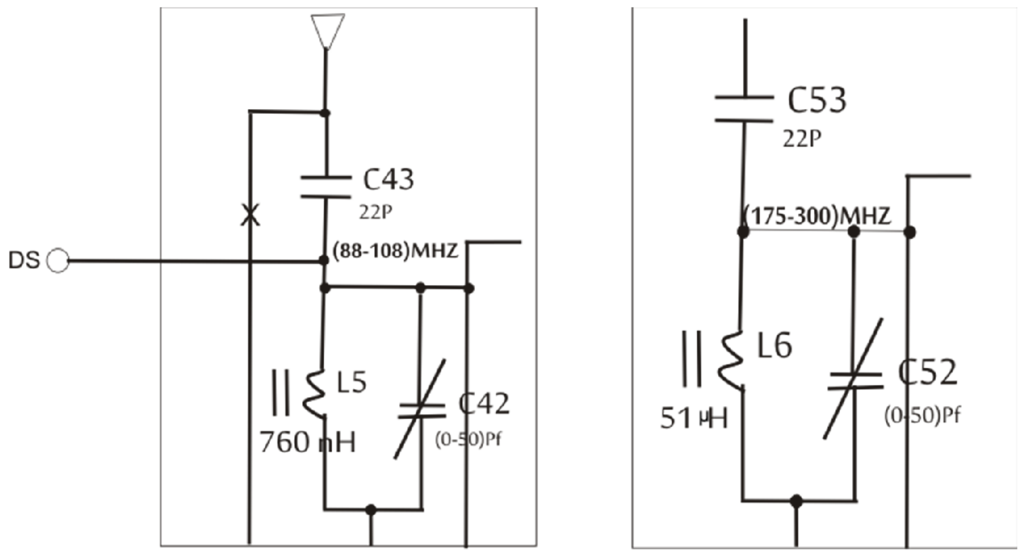
ii. **(0-50)pF capacitor** was selected in the designing of frequency selector circuit

iii. **22pF capacitor** was selected from CSRB20G10L00 datasheets, it's no polarized capacitor used to prevent interference between selected frequency and the other

iv. An electrolytic capacitor with a capacitance of C = 47 μF was chosen.

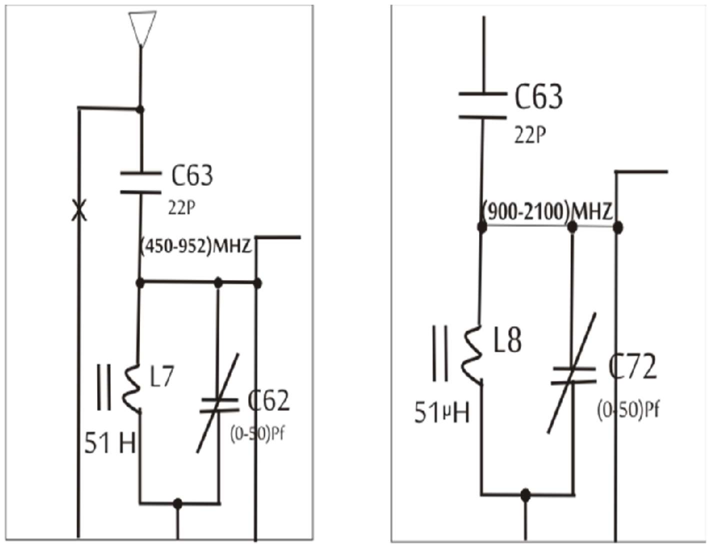
v. From the PR6003-T diode datasheet, in4148 was chosen.

3.3.2 Frequency selection circuit



(a) (b)

Figure 3.3: Circuit diagram of (a) FM (88-108) and (b) TV (175-300) frequency selector network



(c) (d)

Figure 3.4: Circuit diagram of (c) DStv (450-952) MHz and (d) GSM (900-2100) MHz frequency selector network

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (3.1)$$

$$C = \frac{1}{4\pi^2 f^2 L} \qquad (3.2)$$

$$L = \frac{\mu NA}{l} \qquad (3.3)$$

Where f, L and C stands for frequency selected, inductance, capacitance, N is the number of turns, l is the length of wire and . The higher the inductance and capacitance the lower the frequency selected by the frequency selector. The lower the inductance and capacitance the higher the frequency selected by the frequency selector.

3.3.3 Design calculations

3.3.3.1 *Frequency Selection Circuit*

Using equation (3.4) for computing an inductance

$L = \frac{\mu N A}{l}$ (3.3)

FM data

N = 20, L = 0.046m = 46 x 10^{-3}m, A = 0.7cm^2 = 0.7x 10^{-4}m = 7 x 10^{-5}m^2

μ = $4\pi 10^{-7}$N/A

Inductor (L) = $\frac{\mu N^2 A}{L}$

L = $\frac{4\pi\ X\ 10^{-7}\ X\ 20^2\ X\ 7X10^{-5}}{46\ X\ 10^{-3}}$

L = $\frac{4\pi\ X\ 2800X10^{-12-(-3)}}{46}$

L = $\frac{35{,}190X10^{-9}}{46}$ = $\frac{35190X10^{-9}}{46}$ = $760X10^{-9}$ $= 760nH$

For GSM

N = 30, μ = $4\pi 10^{-7}$N/A, A = 9x10^{-5}m^2 , L = 2 x10^{-3}m

L = $\frac{\mu N^2 A}{L}$

L = $\frac{4\pi\ X\ 10^{-7}\ X\ 30^2\ X\ 9X10^{-5}}{2\ X\ 10^{-3}}$

L = $\frac{4\pi\ X\ 8100X10^{-12}}{2\ X\ 10^{-3}}$

L = $\frac{102{,}00X10^{-9}}{2}$ = $51000X10^{-9}$ $= 51X10^{-6}$ = 51μH

For TV

N = 35, μ = $4\pi 10^{-7}$N/A A = 11x10^{-5}m^2 , L = 3.35 x10^{-3}m

L = $\frac{\mu N^2 A}{L}$

L = $\frac{4\pi\ X\ 10^{-7}\ X\ 35^2\ X\ 11X10^{-5}}{3.35\ X\ 10^{-3}}$

L = $\frac{169785X10^{-12}}{3.35\ X\ 10^{-3}}$

L = $51\ X\ 10^3\ X10^{-9}$ $= 51X10^{-6}$ but $\mu =\ 10^{-6}$ L = 51μH

For DSTV

N = 37, μ = $4\pi 10^{-7}$N/A A = $17x10^{-5}m^2$, L = $5.75\ x10^{-3}$m

L = $\frac{\mu N^2 A}{L}$

L = $\frac{4\pi\ X\ 10^{-7}\ X\ 37^2\ X\ 17X10^{-5}}{5.75\ X\ 10^{-3}}$

L = $\frac{293240X10^{-12}}{5.75\ X\ 10^{-3}}$

L = $50998\ X10^{-9}$ = $51\ X\ 10^3\ X10^{-6}$ L = 51μH

Four frequency selectors were used to select frequency ranging from 87 – 108 MHz, 175 – 300 MHz, 450 – 962 MHz, and 900 – 2100 MHz, to capture RF from FM broadcasting stations, television stations and GSM cellular communication networks.

The first frequency selector was designed to capture RF ranging from 87 – 108 MHz from FM broadcasting stations using $760nH$ and variable capacitor with capacitance ranging from $0 - 50\ pF$, the capacitance require to select 87 MHz and 108MHz frequency will be compute using equation (3.3).

$$C_{88\ MHz} = \frac{1}{4 \times (3.142)^2 \times (88 \times 10^6)^2 \times (760 \times 10^{-9})} = 0.0656\ pF$$

$$C_{108\ MHz} = \frac{1}{4 \times (3.142)^2 \times (108 \times 10^6)^2 \times (760 \times 10^{-9})} = 0.0426\ pF$$

The second frequency selector was designed to capture RF ranging from 175 – 300 MHz from TV (VHF) broadcasting stations using $51\ \mu H$ and variable capacitor with capacitance ranging from $1 - 50\ pF$, the capacitance require to select 175 MHz and 300 MHz frequency will be compute using equation (3.3).

$$C_{175\,MHz} = \frac{1}{4 \times (3.142)^2 \times (175 \times 10^6)^2 \times (51 \times 10^{-6})} = 0.0162\,pF$$

$$C_{300\,MHz} = \frac{1}{4 \times (3.142)^2 \times (300 \times 10^6)^2 \times (51 \times 10^{-6})} = 0.00552\,pF$$

The third frequency selector was designed to capture RF ranging from 450 – 952 MHz from TV (UHF) broadcasting stations using $51\,\mu H$ and variable capacitor with capacitance ranging from $0 - 50\,pF$, the capacitance require to select 450 MHz and 952 MHz frequency will be compute using equation (3.3).

$$C_{450\,MHz} = \frac{1}{4 \times (3.142)^2 \times (450 \times 10^6)^2 \times (51 \times 10^{-6})} = 0.00245\,pF$$

$$C_{952\,MHz} = \frac{1}{4 \times (3.142)^2 \times (952 \times 10^6)^2 \times (51 \times 10^{-6})} = 0.000548\,pF$$

The fourth frequency selector was designed to capture RF ranging from 900 – 1200 MHz, using $51\,\mu H$ and variable capacitor with capacitance ranging from $1 - 50\,pF$, the capacitance require to select 900 MHz and 2100 MHz frequency will be computed using equation (3.5).

$$C_{900\,MHz} = \frac{1}{4 \times (3.142)^2 \times (900 \times 10^6)^2 \times (51 \times 10^{-6})} = 9.8\,pF$$

$$C_{1200\,MHz} = \frac{1}{4 \times (3.142)^2 \times (1200 \times 10^6)^2 \times (51 \times 10^{-6})} = 9.345\,pF$$

3.3.4 Rectifier circuit

The RF-to-DC rectifying circuit is a voltage rectifier based on the zero-bias FR 107 Schottky diode. This at last was selected for rectification purposes because of its shorter transit time when compared with PN diodes as well as for its low threshold voltage. The low turn-on voltage is required because the diode will not operate with bias and consequently will not operate in the steepest region of the IV curve (Pinuela *et al*., 2013). The RF-to-DC rectifier shown in Figure 3.5

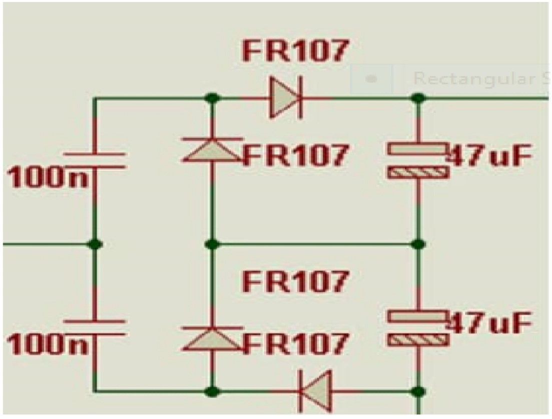


Figure 3.5: Circuit diagram of a rectifier circuit

3.3.5 Low voltage boost converter

Ferrite core inductors were selected due to its low losses. In practical implementation of the converter, four low voltage rating transistors 2N5551 were placed in parallel and supplied current to the four ferrite core inductors laid on the rod through different RF sources as shown in Figure 3.6. The inductors saturated to resonate and compensate other sources with little or no signal for more current; it boosts up output voltage slightly to 1.435V and sum up current flowing from each section. The other part is also a joule thief boost converter circuit which consists of diode (in 4148) from PR6003-T diode datasheet, a LED and two 1.1V li-ion batteries connected in parallel. It boosted 1.435 V to 5.008V. The LED served as an indicator for the system reception, with an USB port for charging phone directly or stored in battery for later used. The low voltage boost converter is shown in Figure 3.6. Also Figure 3.7 which is the circuit diagram of four sources RF energy harvester using a single antenna to capture RF signal from four sources and convert it in to DC for mobile phone charging

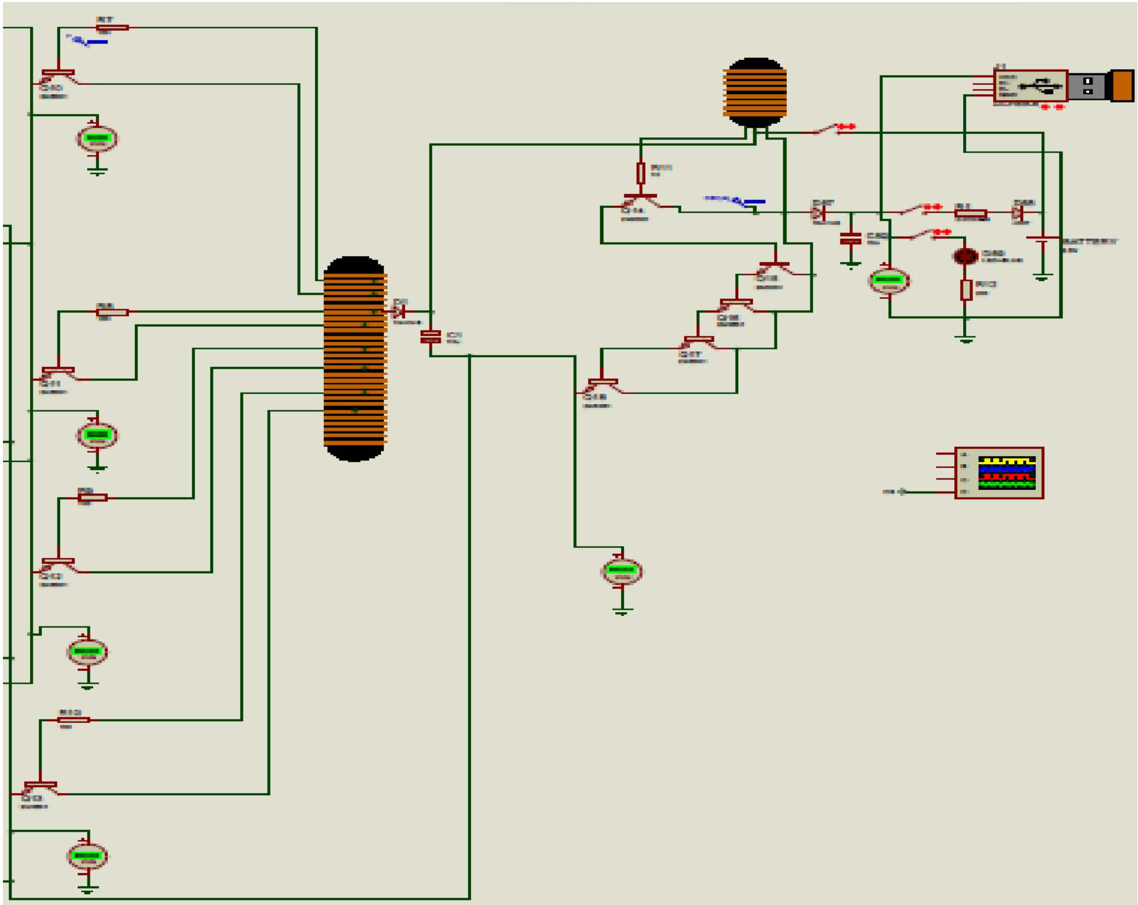


Figure 3.6: Low voltage boost converter

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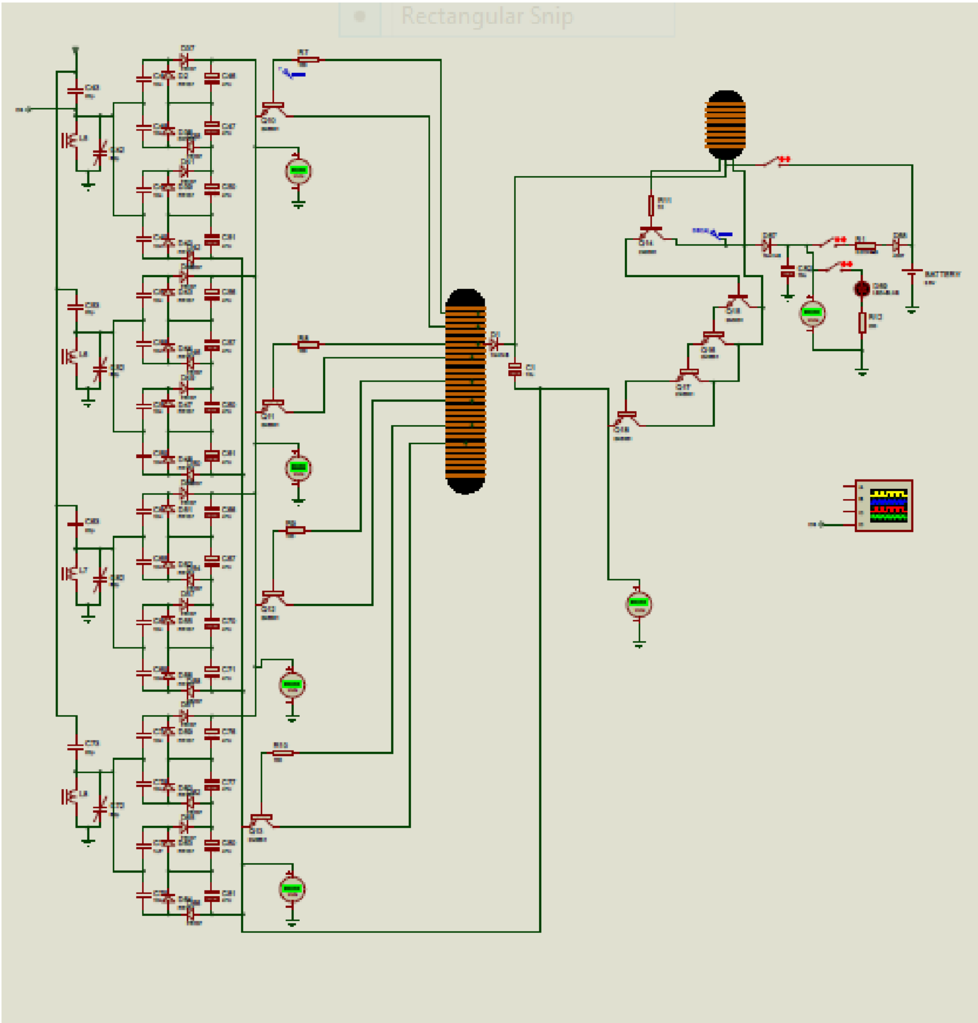


Figure 3.7 Circuit diagram of four-source RF energy harvester using single Antenna

The system flow chart is presented in Figure 3.8

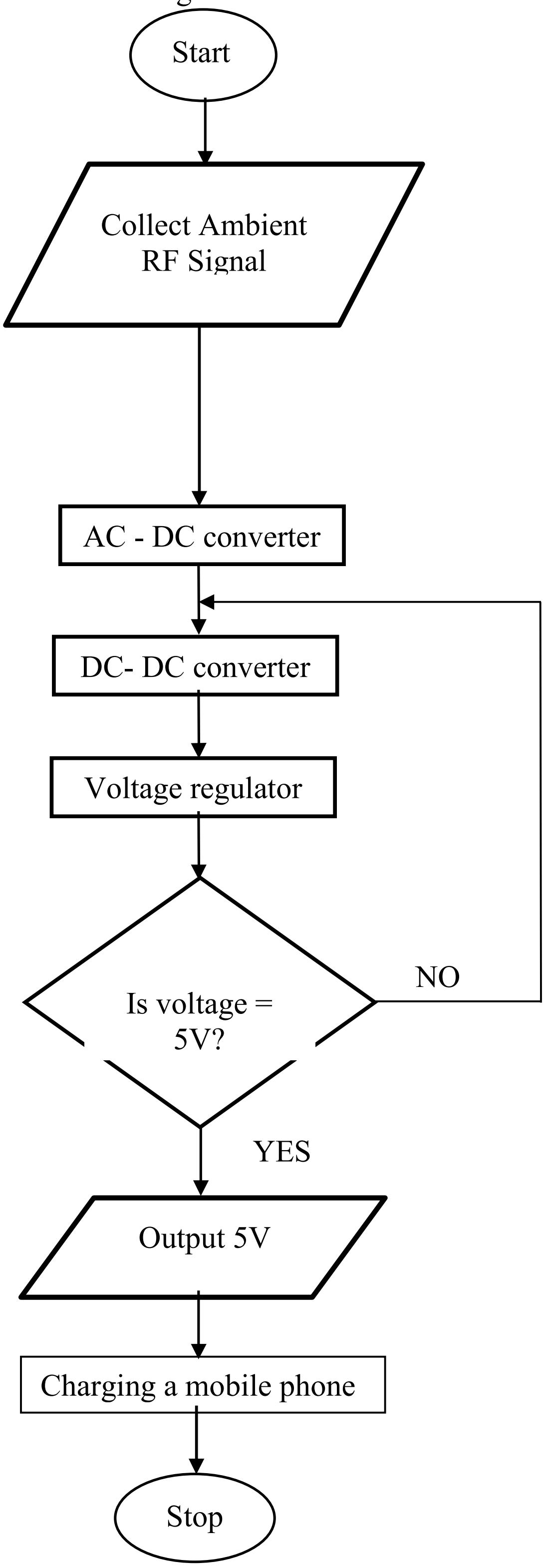


Figure 3.8 Flowchart of the RF energy harvester using single antenna

3.4 RF Measurement

Both hardware and software components were used in taking the measurements of signal strength of the targeted radio frequency sources

The Agilent Spectrum Analyzer was the hardware component used for the measurement of TV and FM signal strength while the Cell tower application was the software used for taking measurement of GSM signal strength.

In order to determine the available RF energy, a wideband antenna for RF energy harvesting coupled to handheld spectrum analyzer was used to take the measurements of TV and FM signal strength in Bida town. During the measurements the antenna was rotated in all the angles of elevation and the spectrum analyzer was set to "max hold" to ensure that the maximum instantaneous power level inside the band of interest is captured.

The antenna in this system functions as a transducer which converts electromagnetic energy into electrical energy. The losses in the antenna and in the transmission feed lines are primary responsible for power loss between the input and the output of the receiving antenna. Losses due to discrepancy between impedances degrade the performance of the receiving antenna further which reduces the antenna output power and voltage which is computed using equations (3.4) and (3.5) respectively.

$$P_{Antenna} = \frac{(V_{Antenna})^2}{2R_{Antenna}} \tag{3.4}$$

$$V_{Antenna} = \sqrt{2 \times P_{Antenna} \times R_{Antenna}} \tag{3.5}$$

Where $V_{Antenna}$ stand for voltage of antenna, $R_{Antenna}$refers to resistance of antenna, and $P_{Antenna}$ stands for antenna power. Figure 3.9 shows the block diagram of the Spectrum Analyzer set up as used to measure input RF power.

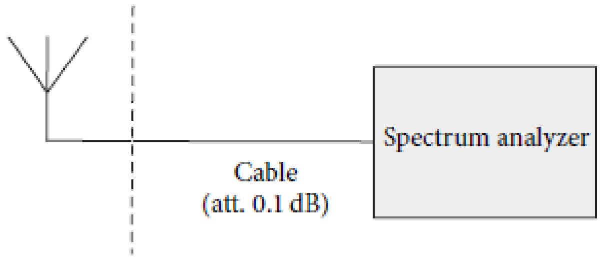


Figure 3.9: Block Diagram of the Spectrum Analyzer set up

The broadband antenna of (45-900) MHz was connected to the Spectrum Analyzer through a cable in order to measure the FM and TV signal strength as demonstrated in Figure 3.9

Firstly, the Spectrum Analyzer was powered ON and the frequency of 88 MHz was entered as the start frequency and 108 MHz as the stop frequency. At every 2 km away from FM broadcasting transmitter, a measurement was taken at a frequency of 100.5 MHz up to a distance of 6.15 km to the reference point (Electrical Engineering Complex Federal Polytechnic Bida, Niger State).

Secondly, the frequency of 170 MHz was entered as the start frequency and 300 MHz as the stop frequency. At every 2 km away from TV broadcasting transmitter, a measurement was taken at a frequency of 223 MHz up to a distance of 6.25 km to the reference point.

The measurements of signal strength of GSM signal was taken across Bida town using a mobile app (Cell tower app, an Avenza map) and Epicollect5. The measurement was taken at every 0.5km, 1km and 1.5km away from each GSM base station across Bida, Niger State.

3.5 The Comparison Matrix used for Performance Evaluation

The comparison matrix used for the performance evaluation of the developed four sources (quad band) Radio Frequency Energy Harvester is to compare the results obtained from testing and measurement of newly constructed quad band RF energy harvester with the result of other quad band related work.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Results

The distribution of the targeted RF sources at different locations in Bida Niger State is shown in Figure 4.1. Also the distribution of TV and FM stations across Bida and the measured power in dBm at a distance of 6.15 km and 6.25 km for every 2 km to the reference point is shows in Figure 4.2

The measurements of GSM signal strength, there are twenty eight Mtn base stations, eleven Airtel base stations, ten Glo base stations and six 9Mobibe base stations distributed across Bida with measured power in dBm at a distance of 0.5 km, 1 km and 1.5 km away from each base station as shown in Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6

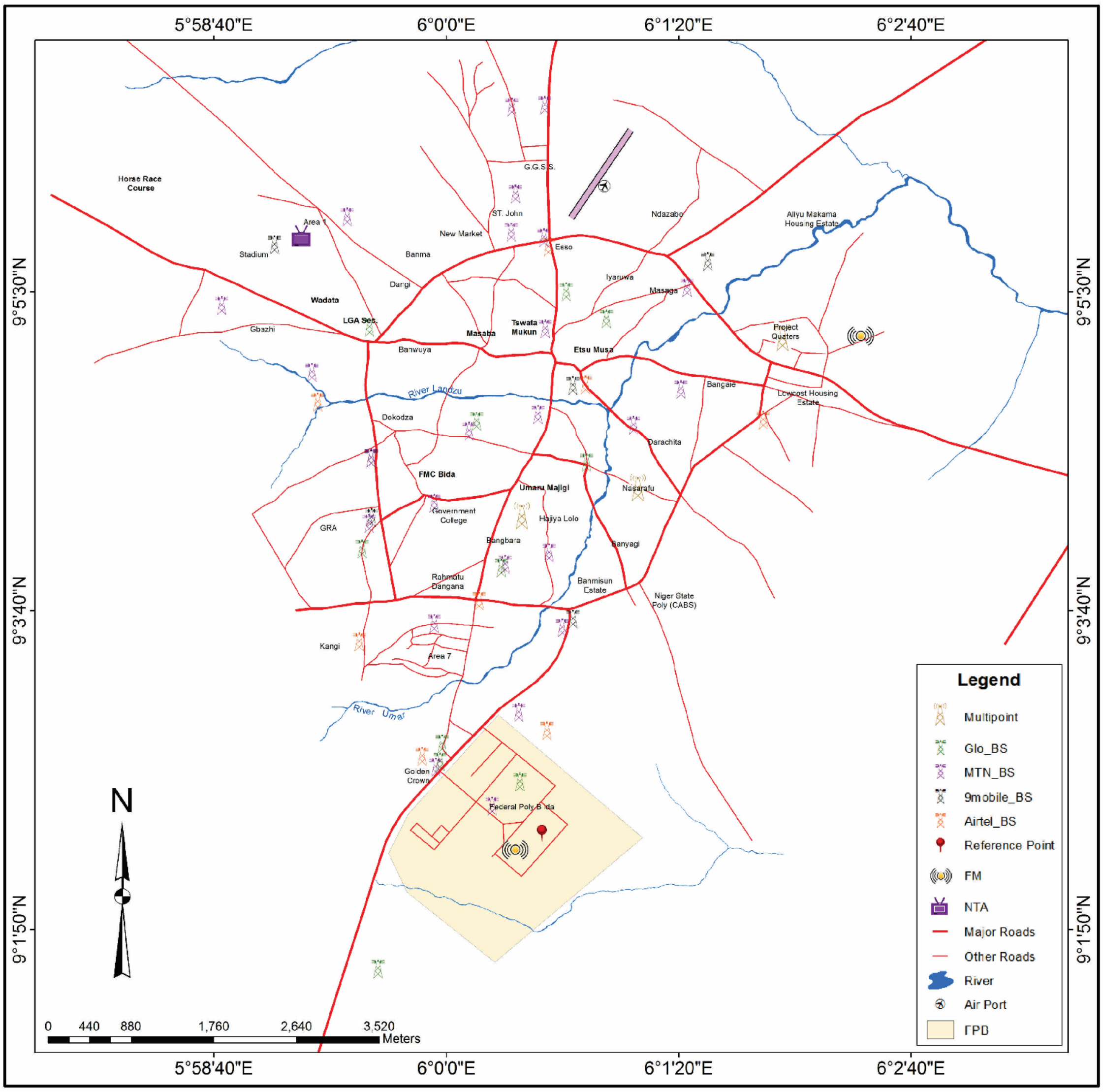


Fig. 4.1: Map showing the distributions of the targeted RF sources in Bida

The map of Bida showing the distribution of all the targeted RF sources across Bida, Niger State. There two FM stations, one TV station and fifty six GSM mask in Bida

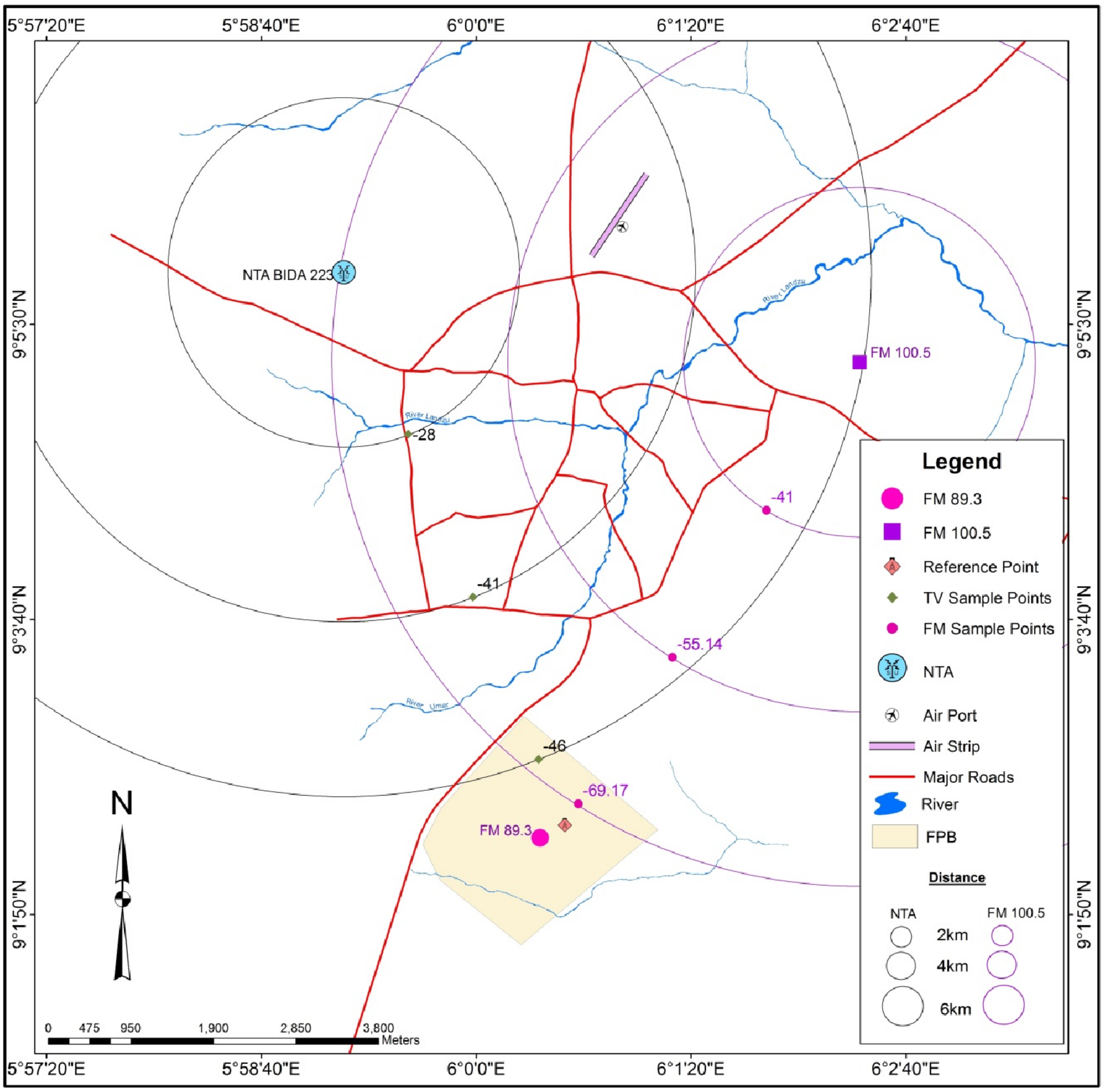


Fig. 4.2: The distribution of TV and FM stations in Bida with measured power in dBm

The Figure 4.2: show the distribution of TV and FM stations across Bida and their measured power in dBm at a distance of 6.15 km and 6.25 km to the reference point

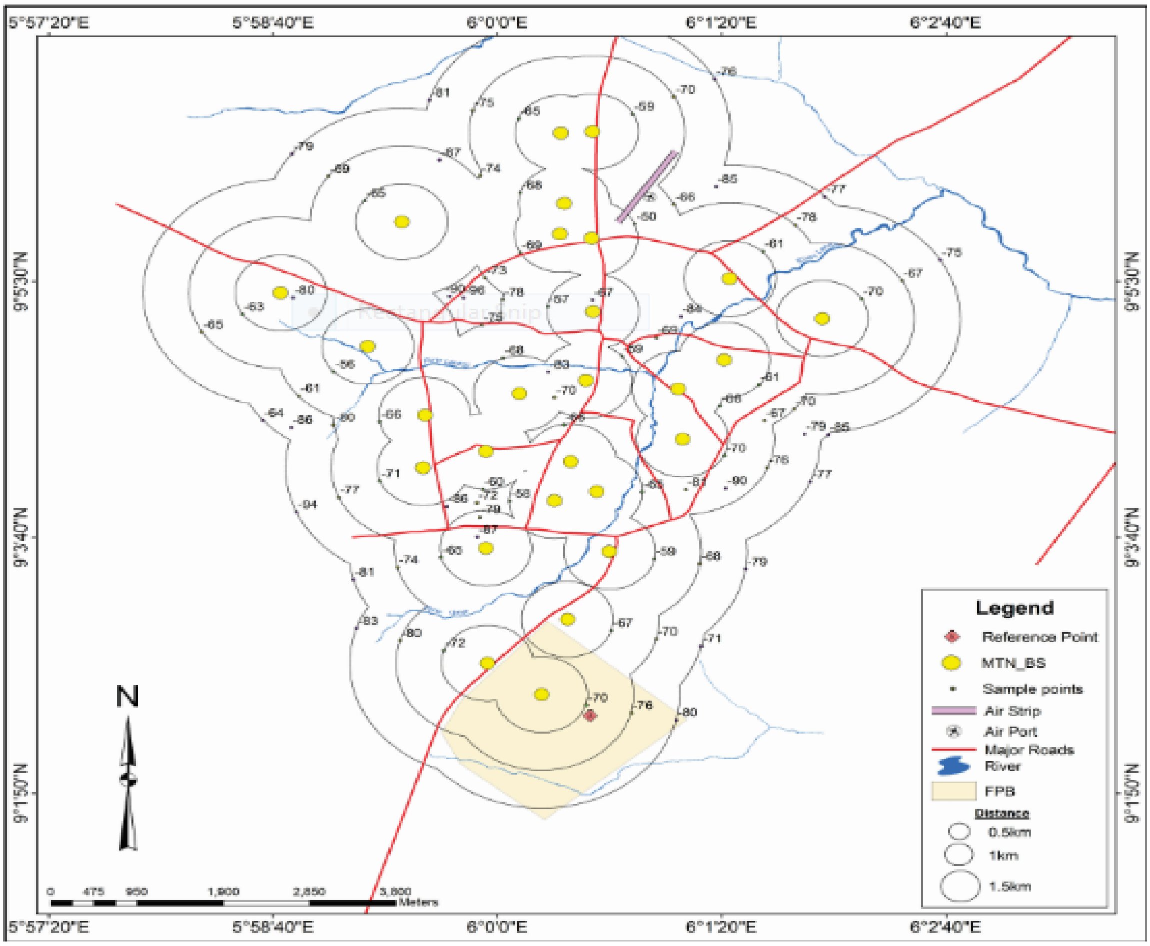


Fig. 4.3: The distributions of Mtn base stations in Bida with measured power in dBm

The Figure 4.3 shows twenty eight Mtn base stations distributed across Bida with measured power in dBm at a distance of 0.5 km, 1 km and 1.5 km away from each base station

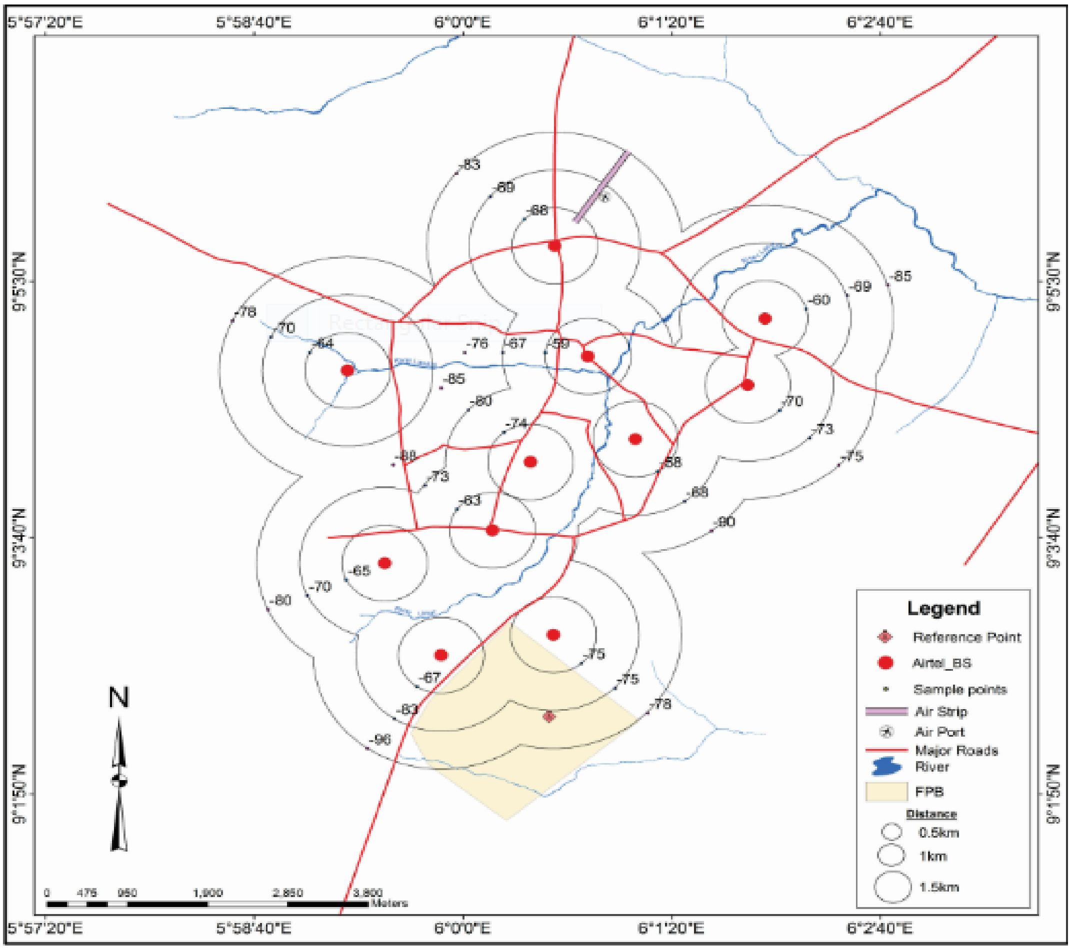


Fig 4.4: The distributions of Airtel base stations in Bida with measured power in dBm

The Figure 4.4 shows eleven Airtel base stations distributed across Bida with measured power in dBm at a distance of 0.5 km, 1 km and 1.5 km away from each base station.

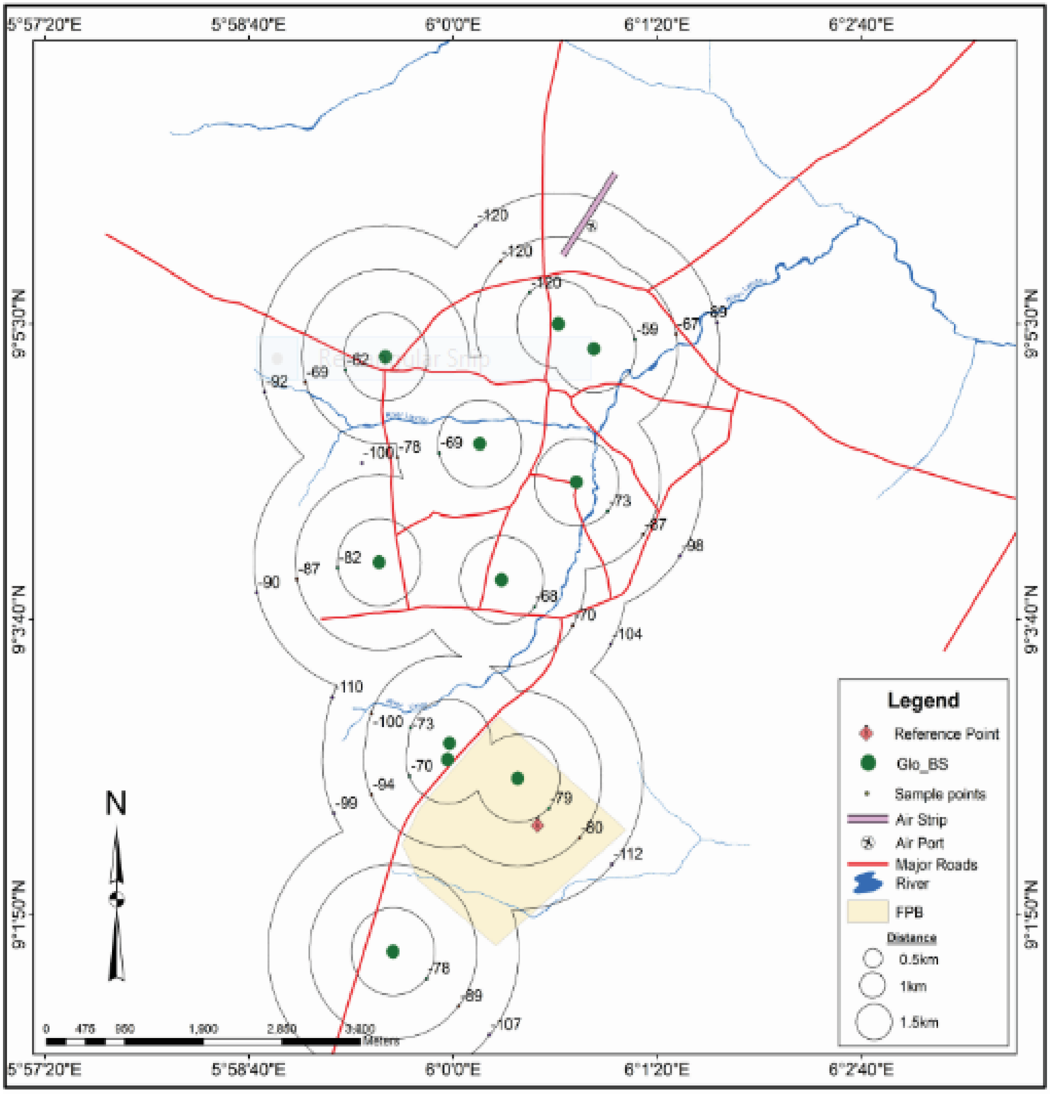


Fig. 4.5: The distributions of Glo base stations in Bida with measured power in dBm

The Fig. 4.5 shows ten Glo base stations distributed across Bida with measured power in dBm at a distance of 0.5 Km, 1 km and 1.5 km away from each base station

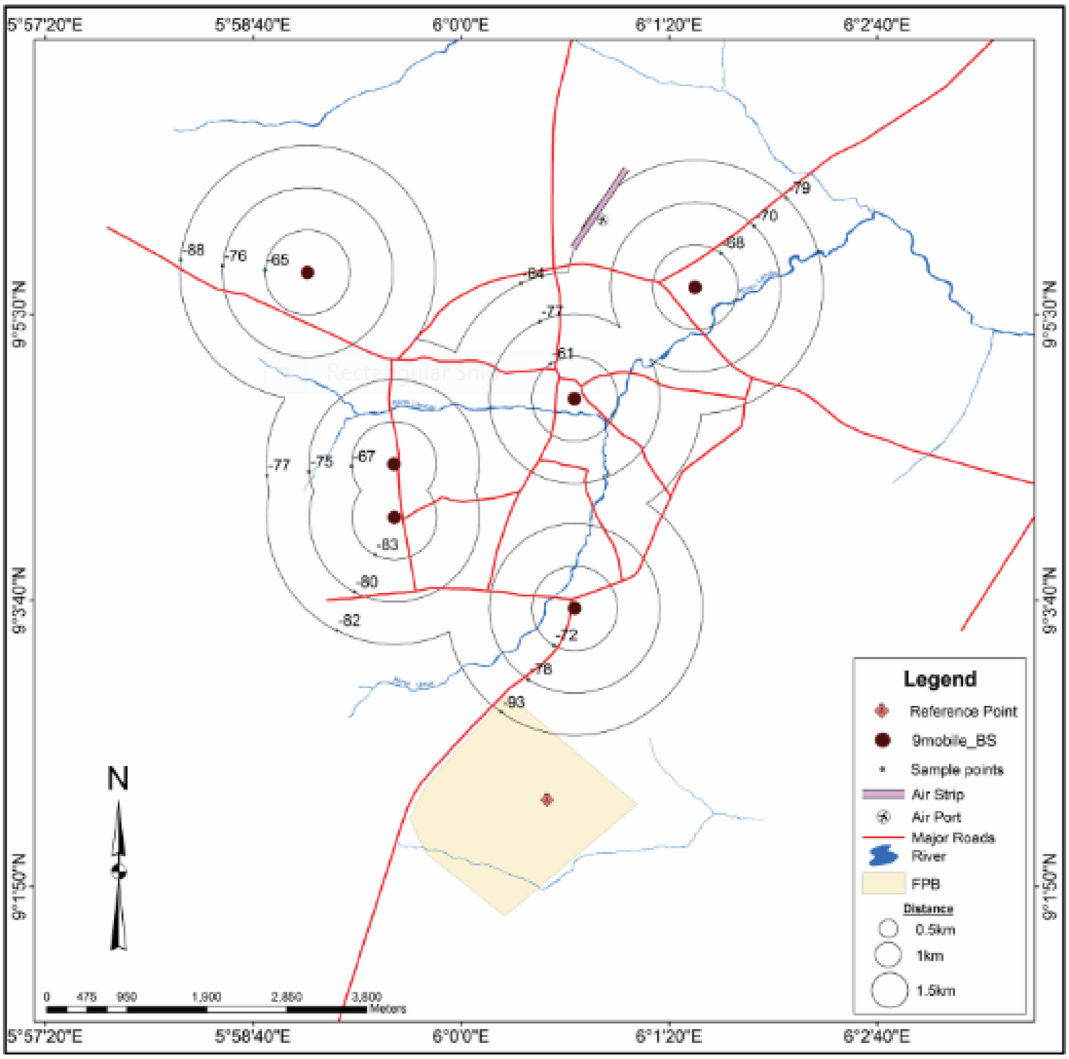


Fig. 4.6: The distributions of 9Mobile stations in Bida with measured power in dBm

The Fig. 4.6 are six 9Mobile base stations distributed across Bida with measured power in dBm at a distance of 0.5 km, 1 km and 1.5 km away from each base station

A bar graph of measured power (dBm) of FM and TV signal strength against distance (Km) is shown in Figure 4.7. It is an upside down Figure due the negative values of the measured signal strength

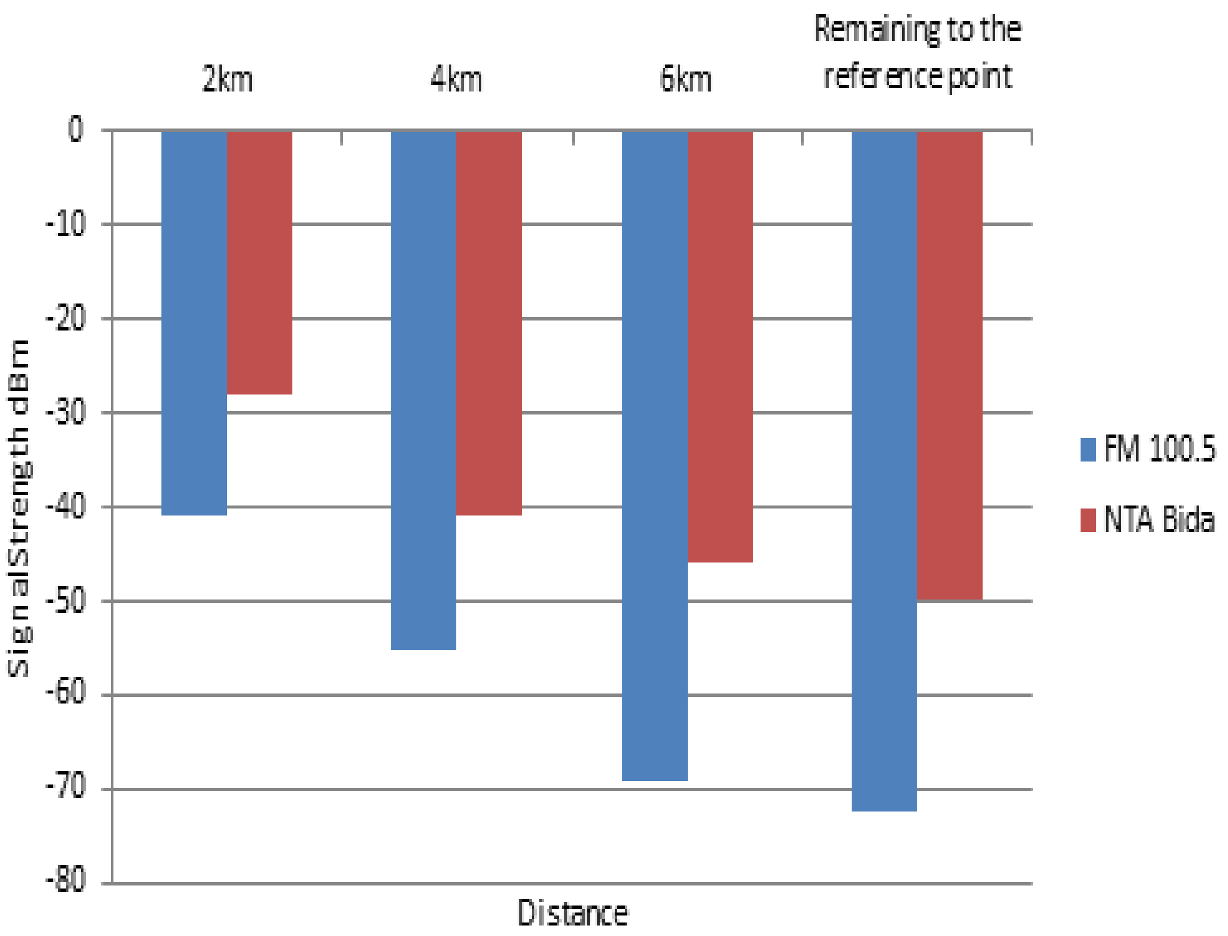


Figure 4.7: The measured power in (dBm) of FM and TV signal against distance (Km)

From Figure 4.7, it is obviously shows that TV signal gives better power than the FM signal.

A component bar graph of measured GSM signal strength (dBm) against distance (Km) is shown in Figure 4.7. It is an upside down Figure due the negative values of the measured GSM signal strength

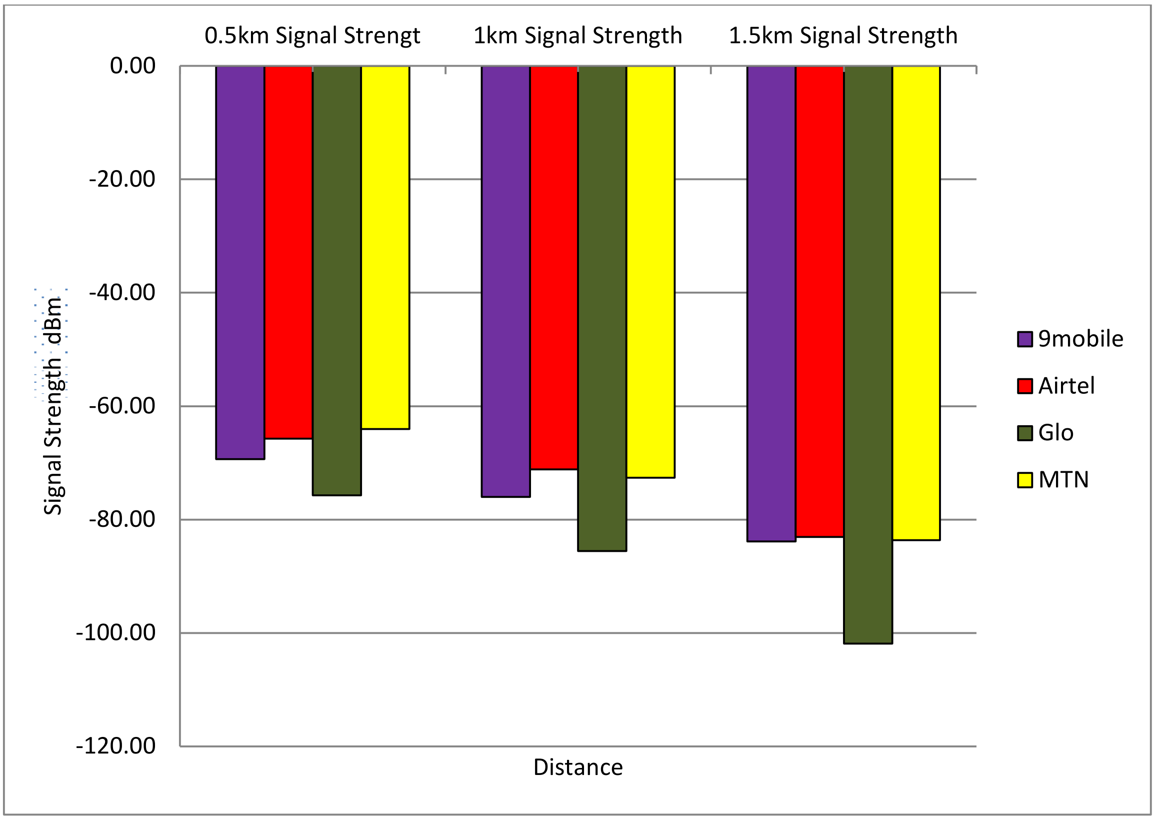


Fig.4.8: The component bar chart shows the average GSM signal strength against distance (Km)

From Fig. 4.8, it is cleared that MTN have better signal strength followed by Airtel, Glo and 9Mobile. There measurement results were obtained at 0.5km, 1km and 1.5km respectively

4.3 Discussion of Results

The FM and TV signal strength measured, TV yielded better results at various high distances (2 km, 4 km, 6 km, 6.15 km and 6.25km) away from the tower to the reference point (Electrical Engineering Complex Federal Polytechnic Bida, Niger State) for which the measurements were taken . Also, from measurement results obtained for GSM, it was revealed that MTN have better signal strength followed by Airtel, Glo and 9Mobile. There measurement results were obtained at 0.5km, 1km and 1.5km respectively

The output voltage and current obtained during testing and measurement of the newly constructed four sources Radio Frequency Energy Harvester for charging a mobile phone (An android phone) was 5.008 V and 57.9 mA. The Voltage and current requirement for charging an android phone conveniently is 5 V and 1A respectively. The required voltage (5.008 V) was gotten during testing and measurement of newly constructed harvester at a distance of 255 meters away from FM tower for an RF input power of 5 dBm with relatively low current of about 57.9 mA for a power of 0.294 W against the required 5 W. Hence the system could not charge a mobile phone with a challenge of relatively low current but conveniently powered red LED of 1.8 V 20 mA for a power of 0.04 W. Similarly, Table 4.1 shows the comparison between this work and other related works, clearly indicating relatively low currents in some works and salient on current in other works due to its low nature in RF energy harvesting system. The harvested current poses a big challenge for achieving the aim of charging a mobile phone though the required voltage was 100% met.

Table 4.1: Comparison between the constructed RF Energy Harvester with a related quad band work

Author/Year	No of bands	Frequency bands (GHz)	RF input power (dBm)	Power Conversion Efficiency (%)	DC Voltage (V)	Current (mA)	Distance (m)	Remark
Sunanda et al. (2022}	Quad Bands	**0.9, 1.8, 2.12 and 2.4**	**-20**	**52**	**0.678**	**N/A**	**N/A**	Overcome the poor conversion efficiency
New Work	Quad Bands	**0.9, 0.1005, 0.223 and 0.45**	**5**	**94**	**5.08**	**57.9**	**255**	Lighted LED

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusion

The chapter discussed about the methodology for the design of the research Four Sources RF Energy Harvester that used single wide band antenna to capture the available RF signal from the ambient environment. The field measurement of RF signal strength was carried out across Bida town for each of the four targeted RF sources and good results were obtained.

The collected RF signal by the wide band antenna was selected by Frequency Selector for the targeted RF sources and rectified by the rectifying circuit. The output voltage gives 5.08 V with a current of 57.9 mA. The system can conveniently powered LED but could not power mobile phone due to the relatively low current of 57.9 mA

5.2 Recommendations

The following were recommended for future research on several sources RF energy harvesting system

i. More attention should be given on how higher current can be generated
ii. In selecting a broad band antenna, a passive Yagi antenna of wider frequency range in order of Giga hertz should be used for appropriate coverage of all frequencies of interest

5.3 Contribution to knowledge

The development of standalone four sources radio frequency energy harvester as met up the voltage requirement for charging mobile phone (an android phone) with a minimum RF input power of 5 dBm gives an appreciable output voltage of 5.08 V with a power conversion efficiency of 94 %.

REFERENCES

Agrawal, C.A, (2017). A Dual-Band RF Energy Harvesting Circuit Using 4th Order Dual-Band Matching Network, *Cogent Engineering Electrical & Electronic Engineering/ Research Article,* https://doi.org/10.1080/23311916.2017.1332705

Ahn C., (2015) Development of RF Energy Harvesting and Charging Circuits for Low Power Mobile Devices, *Recent Researches in Circuits, Systems, Control and Signals*

Ankush J., Peer M. & Bohara V. (2017) Powering Future Mobile Phones through RF Energy Harvesting. *International workshop on Ant Colony Optimization*

Borges, L. M., Barroca, N., Saraiva, H. M., Tavares, J., Gouveia, P. T., Velez, F. J, & Gonçalves, R. (2014). Design and Evaluation of Multi-Band RF Energy Harvesting Circuits and Antennas for WSNs. *Paper presented at the Telecommunications International Conference (ICT)*, 21, 78 – 105.

Caselli, M., Tonelli, M. & Boni, A., (2019) Analysis and Design of an Integrated RF Energy Harvester for Ultra Low-Power Environments. *International Journal on Circuit Theory Applications,* 47, 1086–1104.

Clerck B., Zhang, R., Schober, R., Ng, D. W. K., Kim, D. I., & Poor, H. V. (2018). Fundamentals of Wireless Information and Power Transfer: From RF Energy Harvester Models to Signal and System Designs. *IEEE Journal on Selected Areas in Communications,* 37(1), 4 – 33.

Danial, K., Seong, J. O., Khuram, S., Deeksha, V., Zaffar, H. N. K., Young, G. P., Minjae, L., Keum, C. H., Youngoo, Y., & Kang-Yoon, L., (2019) A CMOS RF Energy Harvester with 47% Peak Efficiency Using Internal Threshold Voltage Compensation. An *IEEE Microwave and Wireless Components Letters* 29(6), 415 - 417

Danial, K., Hamed, A., Sang-Yun, K., Zaffar, H.N.K., Syed, A.A.S., Young, G.P., Keum, C.H.I., Youngoo, Y., Minjae, L., & Kang-Yoon, L. (2018). A Design of Ambient RF Energy Harvester with Sensitivity of 21 dBm and Power Efficiency of a 39.3% Using Internal Threshold Voltage Compensation. Journal of energies. *Energies* 11(5), 1258

Hoang, M. H., Phan. H. P., Van Hoang, T. Q., & Vuong, T. (2014).An Efficient Compact Dual Band Antennas for GSM and Wi-Fi Energy Harvesting. *International Conference of Advanced Technologies for Communications (ATC)*

Jabbar, H., Song, Y. S., & Jeong, T. T., (2010) RF Energy Harvesting System and Circuits for Charging of Mobile Devices. *IEEE Transactions on Consumer Electronics*, 247-253.

Keyrouz, S., Visser, H., & Tijhuis, A.(2013).A Multi-Band Simultaneous Radio Frequency Energy Harvesting. *European Conferenceon Energy Harvesting*, 7,25-52

Khansalee E., Zhao Y., & Nuanyai, K., (2014) High Frequency Rectifier for RF Energy Harvesting Systems. *International Conference on Information Technology and Electrical Engineering (ICITEE),* 7

Kuhn, V., Lahuec, C., Seguin, F., & Person, C.(2015). A Multi-Band Stacked RF Energy Harvester. *IEEE Transactions on Microwave Theory and Techniques, 63*(5), 1768-1778.

Le, T., Mayaram K. & Fiez, T. (2008) Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks. *IEEE Journal of Solid-State Circuits, 43*(5), 1287-1302.

Leon-Gil, J.C., Perales-Cruz, L., Licea-Jimenez, S.A. Pérez Garcia & J. Alvarez-Quintana (2015) *RF energy scavenging system for DC power from FM broadcasting based on an optimized Cockcroft–Walton voltage multiplier*, Journal of Electromagnetic Waves and Applications, 29:11, 1440-1453

Lu, X., Wang, P., Novato, D., Kim, D. I.,& Han, Z. (2015). Wireless Networks with RF Energy Harvesting: A Contemporary Survey*, IEEE Communications Surveys & Tutorials*,(17)2, 757 -789.

Mrnka, M., Vasina, P., Kufa, M., Hebelka, V., & Raida, Z. (2016). The RF Energy Harvesting Antennas Operating in Commercially Deployed Frequency Bands: A Comparative Study, *International Journal of Antennas and Propagation Volume 2016, Article ID 7379624, 11 pages http://dx.doi.org/10.1155/2016/7379624*

Mouapi, A., Hakem, N., & Delisle, G. Y. (2017). A new approach to design of RF energy harvesting system to enslave wireless sensor networks. *ICT Exp*

Muncuk U., Kubra A., Jayesh D., and Kaushik R. Chowdhury, (2018) Multi-band Ambient RF Energy Harvesting Circuit Design for Enabling Battery-less Sensors and IoTs. *DOI 10.1109/JIOT.2018.2813162, IEEE Internet of Things Journal*

Natasha A. S., Kishore K. U., Ram P. G. and Sahu R. (2019) Design Constraints of an Radio Frequency Energy Harvesting *An International Research Journal of Engineering and Technology (IRJET), 6(6)*

Nintanavongsa, P., Muncuk, U., Lewis, D., & Chowdhury, K. (2012). Design Optimization and Implementation for RF Energy Harvesting Circuits. *IEEE Journal on emerging and selected topics in Circuits and Systems, 2*,24–33.

Pinuela, M., Mitcheson, P. D. and Lucyszyn, S., (2018) Ambient RF energy harvesting in urban and semi-urban environments, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 61, No. 7, pp. 2715-2726, .

Prusayon, N. (2012). Design Optimization and Implementation for RF Energy Harvesting Circuits. IEEE. *Journal of Emerging and Selected Topics in Circuits and Systems*, 2 (1), 24 – 33.

Rosli, M. A. Murad, S. A. Z., Norizan, M. N., & Ramli, M. M. (2018) Design of RF to DC Conversion Circuit for Energy Harvesting in CMOS Technology *Electronic and Green Materials International Conference* 4(1) 265 – 271.

Sampe J, Yunus, N .H.M., Junas, J., & Pawi, A.(2019) Architecture of an efficient dual band 1.8/2.5 GHz rectenna for RF energy harvesting. *Telkomnika*, 17(6), 3137 – 3144.

Sangkil Kim, R. Vyas, J. Bito, K. Niotaki, A. Collado, A. Georgiadis, M. M. Tentzeris, (2014). Ambient RF Energy Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor Platforms, *Proceedings of the IEEE*, (102), 11, 1649-1666

Sunanda R. Jun-Jiat T., , Mardeni B. R., Tanvir A., Abbas Z. K. and Mahmud P. M. A (2022) design of a Highly Efficient Wideband Multi-Frequency Ambient RF Energy Harvester https://www.researchgate.net/publication/357672830 and DOI: 10.3390/s 22020424

Sun H., Guo Y., & Miao H. (2016) A Dual-Band Rectenna Using Broadband Yagi Antenna Array for ambient RF power Harvesting. An IEEE antenna and wireless propagation letter. Vol. 12

Stutzman W.L., & Thiele, G.A. (2012) *Antenna theory and design* John Wiley & Sons.

Timothy M., Stephen S. O., Adnan M. A., and Gerhard P. H. (2020) Enabling a Battery-Less Sensor Node Using Dedicated Radio Frequency Energy Harvesting for Complete Off-Grid Applications. *Council for Scientific and Industrial Research \ (CSIR), Pretoria 0184, South Africa*

Uzun, Y. (2016) Design and Implementation of RF Energy Harvesting System for Low-Power Electronic Devices.*Journal of Electronic Materials*, 1-6

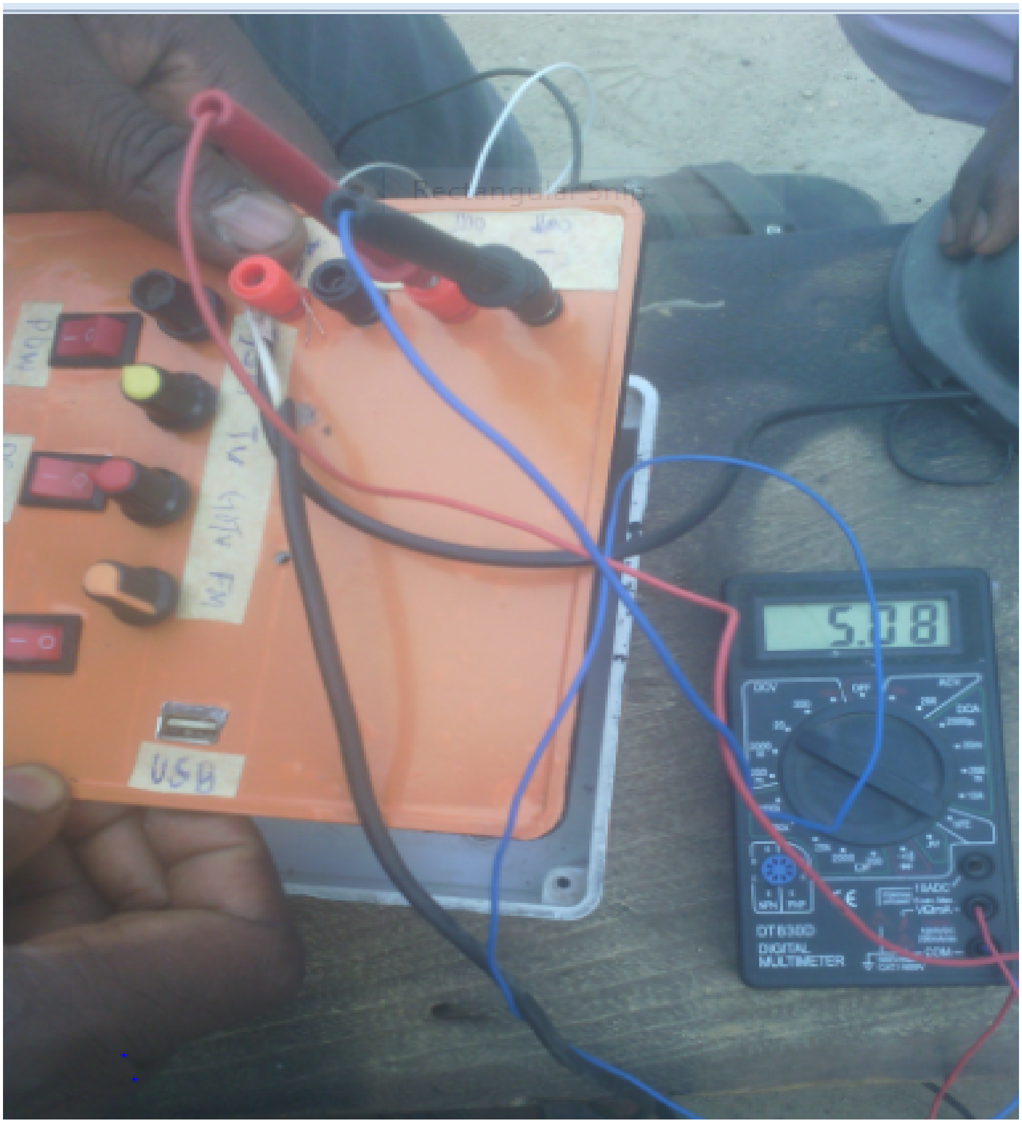
Wang D. & Negra, R. (2014).Novel Tri-Band RF Rectifier Design for Wireless Energy Harvesting. *Microwave Conference.* 56 – 90.

Yunas, J., Yunus, N. H. M., Sampe, J., & Nandiyanto, A. B (2020) Design and Fabrication ofGlass based MEMS Patch Antenna for Energy Harvester. *IEEE International Conference on Power and Energy (PECon),* 362 – 365.

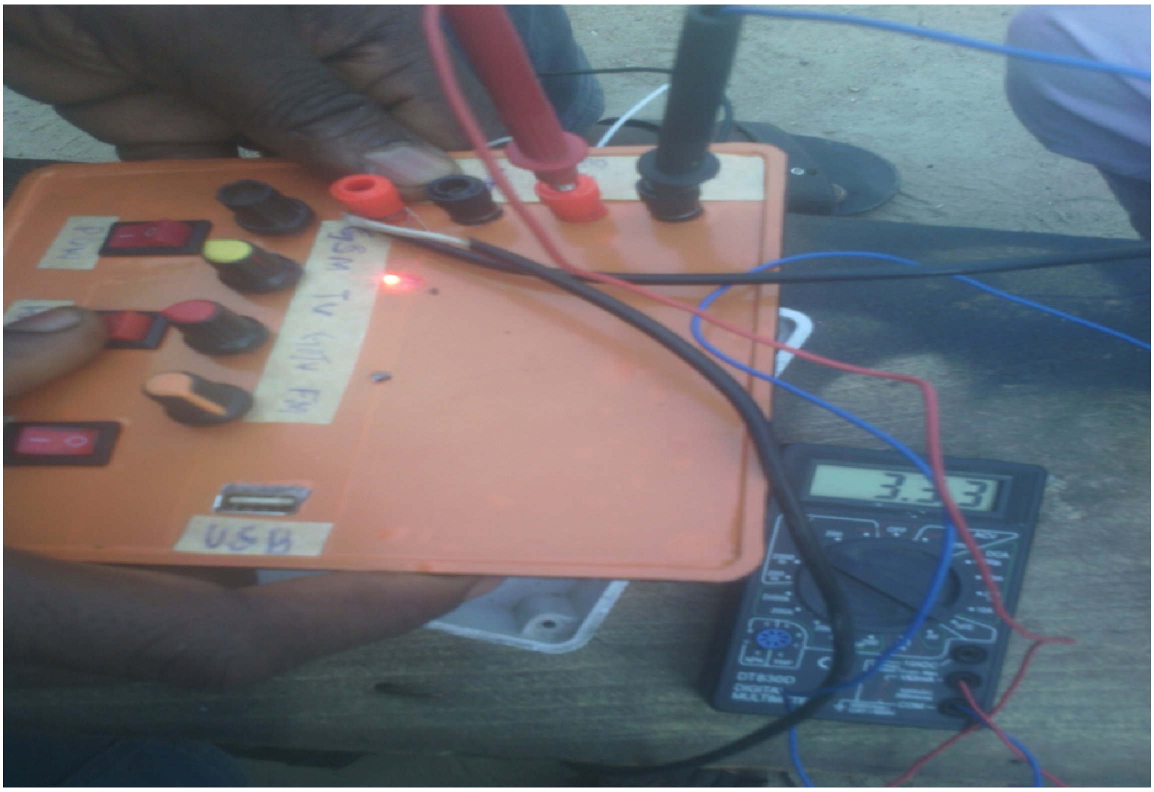
Zakaria, Z., Zainuddin, N., Aziz, M. A., Husain, M., & Mutalib, M., (2013) Dual-band Monopole Antenna for Energy Harvesting System *Paper presented at the Wireless Technology and Applications (ISWTA)*, 2013 IEEE Symposium

Zeng, M., Andrenko, A. S., Liu, X., Li, Z., & Tan, H. Z. (2017). A Compact Fractal Loop Rectenna for RF Energy Harvesting. *IEEE Antennas and Wireless Propagation Letters*, *16*, 2424–2427

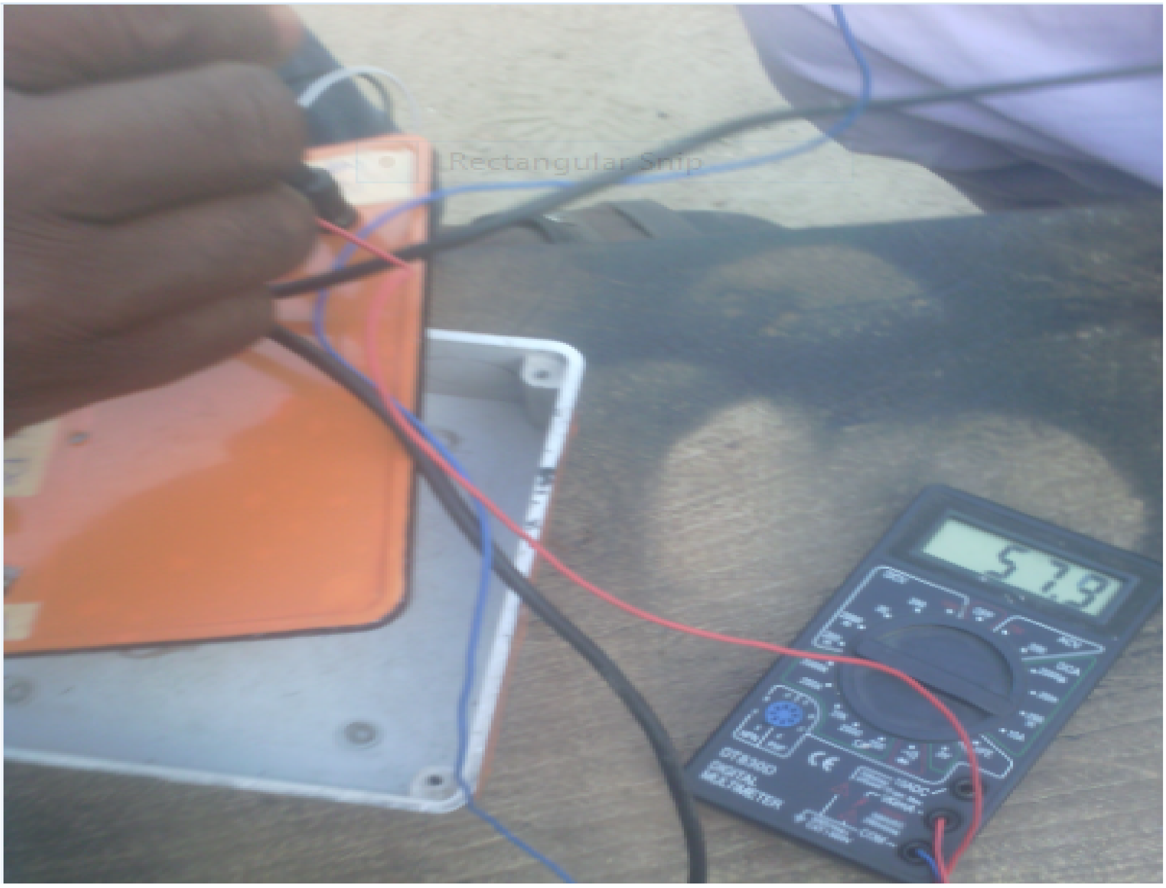
APPENDICES



Appendix A: The tested output voltage of the constructed RF energy harvester on no load



Appendix B: The tested output voltage of the constructed RF energy harvester on load



Appendix C: The tested output current of the constructed RF energy harvester in order of mA

Appendix D: Constructed Four Sources RF Energy Harvesting System

Appendix E: Internal arrangements of the components on PCB