Investigating energy harvesting technology to wirelessly charge batteries of mobile devices

By

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DECLARATION

I, Neetu Ramsaroop, declare that this dissertation represents my own work and has not been previously submitted in any form for another degree at any university or institution of higher learning. All information cited from published and unpublished works have been acknowledged.

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Esther D. Joubert Date

DEDICATION

To

My family and my supportive friends

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LIST OF ABBREVIATIONS

5G	Fifth Generation (Network)
A4WP	Alliance for Wireless Power
AC	Alternate Current
ASIC	Application – Specific Integrated Circuit
DC	Direct Current
EMF	Electromagnetic Frequency
EMI	Electromagnetic Interference
ESR	Equivalent Services Resistance
FCC	Federal Communications Commission
GHz	Giga Hertz
GSM	Global System of Mobile Communication
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial Scientific Media
kHz	Kilo Hertz
km	Kilometre
M&S	Modelling and Simulation
MHz	Mega Hertz
PCB	Printed Circuit Board
PMA	Power Matters Alliance
PRU	Power Receiving Unit
PTU	Power Transmitter Unit
QoE	Quality of Service

RF	Radio Frequency
RFID	Radio Frequency Identification
SWIPT	Simultaneous Wireless Information and Power Transfer
V	Volts
W	Watts
WBAN	Wireless Body Area Network
WiFi	Wireless Fidelity (Wireless Network)
WPC	Wireless Power Consortium
WPT	Wireless Power Transfer
WSN	Wireless Sensor Network

PUBLICATIONS FROM THE DISSERTATION

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ABSTRACT

Mobile devices have recently become powerful computing tools for aiding daily tasks. However, their batteries discharge quickly, even if they are not being used mainly because of the heavy computation tasks required by the multimedia applications that run on them. The swift turnover time on the battery life span is challenging as frequent charging is required to keep the device functioning. This is a major bottleneck because of the current energy optimisation crisis, user inconvenience due to constant charging of a battery and erratic nature of the electricity supply in some areas.

In the current research project, the primary aim was to explore the energy harvesting technology innovation of radio frequency to wirelessly recharge the batteries of mobile devices. This implied an alternative way of charging the batteries of mobile devices without the need for a physical charger to connect to an electrical outlet. Energy harvesting, which involves making use of free energy from the atmosphere is the most innovative energy efficient wireless charging technology because mobile devices are constantly transmitting radio signals. Radio signals are initially received from the atmosphere through an antenna. Thereafter, these signals are converted using a rectifier circuit, from alternating current into direct current which is then utilised to recharge the battery of a mobile device.

This research study adopted a mathematical modelling and simulation research methods. The model involved building an RF energy harvesting prototype. This prototype model displayed the limitations to be considered. The LTSpice simulation software was used to test the feasibility of combining diodes, capacitors and antenna type based on the limitations of the prototype model. The result of this research project demonstrates the building of a radio frequency harvesting circuit that can store a minimum load of 5mV that is required to charge the battery of a mobile device. Moreover, it has explained an alternative storage of the acquired energy using a supercapacitor compared to a mobile device battery.

CHAPTER 1

INTRODUCTION

The main aim of this research was based on exploring the energy harvesting technology theory to recharge mobile devices wirelessly. This inferred an alternative way of charging the batteries of mobile devices without the need for a physical charger to connect to an electrical outlet. Energy harvesting, which comprises making use of easily available energy is the most novel energy-efficient wireless charging technology because mobile devices are continuously transmitting radio signals.

The research initiative of wireless power transfer (WPT) and Radio Frequency (RF) harvesting had commenced with the beginnings of electrical power and involved the development of windmills, water mills and passive solar systems. The existence of electromagnetic radiation had started with research conducted by Heinrich Hertz by proving the presence of electromagnetic radiation and radio waves in his experiments from 1886 to 1888. His experiments proved the electromagnetic wave proliferation in open space by means of parabolic reflectors at equal ends of the structure that permitted the transmitting and receiving of radio waves. These experiments have several matches to the RF energy harvesting related work done in the current years. The preliminary idea of wireless power transmission based on the forecast and indication of radio waves originated in the end of the 19^{th} century (Escala, 2010) (Carlson, 2013).

During the latter part of the 19th century, the concept to transmit electrical energy amid dual points devoid of a physical connection to a source of power was marked by Nikola Tesla, as an “all-surpassing importance to man” (Tesla, 1905). Tesla expanded on experiments conducted by Heinrich Hertz, by creating the Tesla coil in 1891, which included an air gap between the primary and secondary coil and an iron core that was flexible enough to be moved to various locations in or out of the coil (Cooper, 2015). The coil was linked to a high pole of 200ft with a 3ft diameter sphere at its top. The Tesla coil required about 300kW of power, it reverberated at 150 kHz and the RF probability at the upper domain touched 100MV. This experiment had failed due to the result of the entire transferred power being dispersed in every direction per 150 kHz radio waves and the wavelength was 21km (Brown, 1984).

He further demonstrated wireless lighting by electrostatic induction in 1891, via two long Geissler tubes similar to neon tubes within his hands. Tesla expanded on the Tesla coil experiments with inductive and capacitive coupling to transmit power utilising alternate current (AC) voltages (Tesla, 1891). He attempted to develop a wireless lighting system based on near-field inductive and capacitive coupling and conducted a series of public demonstrations where he lit Geissler tubes (gas filled tubes) and incandescent light bulbs diagonally to the stage he was on. The conducted experiments failed in applying WPT systems for commercial use, but the energy transmitted from the oscillators was functioning at 150 kHz to light two light bulbs. The reason the experiments were unsuccessful was that the conveyed energy radiated in various directions at 150 kHz in which the wavelength was 20 km with low efficiency (Carlson, 2013). Based on the experiments, patents and contributions of Tesla towards electrical engineering, he served as a vice-president of the American Institute of Electrical Engineers from 1892 to 1894, the forerunner of the modern-day IEEE, along with the Institute of Radio Engineers (Corum and Corum, 2012).

Advances in producing high power microwaves originated in the 1930s with 1-10GHz radio waves being accomplished through the discovery of the magnetron and the klystron, established initially in Great Britain. This has produced enhancements in radar technology, though there was no focused deliberation towards using this technology in power transmission. This could only be possible World War II (Escala, 2010). The contributions of this technology were completed by Goubau, Schwering and others that established microwave power can be conveyed through efficiencies pending hundred percent via a beam waveguide involving either lenses or reflective looking glass (Tesla, 1904; Degenford, 1964).

The microwave power transmission (MPT) study and advances was originally started by Brown (1984). He announced the word and established on the rectenna meaning rectifying antenna. The initial rectenna was produced in 1963 and operated using 2-3

GHz, resulting in 50 percent output at 4W DC (direct current) and 40 percent at output 7W DC separately. Proceeding the rectenna, he prospered in MPT investigations based on the wired helicopter in 1964 and then in 1968 the free-flied helicopter. He further attempted to escalate the combined effectiveness with 2.45 GHz microwaves in the 1970s (Brown, 1984).

Recently, researchers have experimented with microwave transmission of power in domestic environments. At much lower power levels, short range wireless power transmission is now common place in passive Radio Frequency Identification (RFID) systems, which derive their energy using inductors, capacitors or radioactively from the tag reader (Arazia, 2002; Finkenzellar, 2003).

Researchers have explored the possibility of extracting power from the magnetic fields from high-voltage power lines (Giordano, 1998). The majority of these methods utilises a current transformer in transforming the magnetic fields to usable current. Currently smartphones and other mobile Internet devices have become pervasive, companies continually add features into each new device. The progressing generations of these devices are able to do more things faster. Due to advanced technologies like 4G and processor enhancements from Moore's Law, users have access to web content faster and run applications and games formerly only operational on desktops and laptops (Titcomb, 2016).

Titcomb (2016) further explained the limited research conducted on the battery. The Lithium-ion battery has not changed considerably since it was first promoted by Sony in 1991. Smartphones are being relied on for important transactions and the functionality of these devices is limited to the battery. In the last decade, though, the smartphone period has rendered existing battery technology distressingly insufficient. All this processing power takes a toll on the lifespan of the mobile device battery. The ultimate situation would be for battery technology to be kept up to date or in keeping with the processing power of the mobile devices. During the early 2000s, mobile phones would last days on end without being charged (Titcomb, 2016).

Hence, this chapter defines the concept of energy harvesting and elaborates on the energy harvesting methods to charge mobile devices. The idea of an alternative storage of energy compared to the mobile device battery is also stated. The identification of the approaches used to charge mobile devices wirelessly will then lead to the statement of the research problem at the root of this research, followed by the formulation of the study's aim and objectives, as well as its rationale and limitations. The chapter ends with an outline of the other chapters of the dissertation.

1.1 PROBLEM STATEMENT

Current developments in the design of mobile devices joined with improvements in the combination of wireless access and networks, have made mobile devices exceptionally prevalent. These devices offer convenience and offer services including communication, computation, personal information management, and Internet access. Mobile devices such as personal digital assistants, laptops with wireless access and mobile cell phones are becoming pervasive. As the practicality and abilities of these mobile devices have surged, their energy consumption supplies also increase (Markopoulou et al, 2005).

Wireless data services rely on a constant source of power to operate and this increased demand for power leads to the problem of battery depletion (Ku et al, 2016). Three issues arise with the use of mobile devices:

a) Firstly, a mobile device battery needs constant charging and this is seen as a major problem in the absence of an electrical outlet or charging cables.
b) Secondly, if the mobile device is being charged this poses an inconvenience to the user since the device cannot be used during that time.
c) Additionally, with the current energy crisis and restricted electricity supply in certain areas frequent charging is limited.
d) Finally, wireless devices have moderately slow developments in rechargeable battery technology.

Based on the issues mentioned, it is vital to investigate a fresh method of power supply by reducing the use of fossil fuels while accumulating more renewable energy sources in wireless communications and networking associated with mobile devices.

1.2 STUDY OBJECTIVES

This work investigates Radio Frequency (RF) harvesting. It makes sense to hypothesise that some of the identified limitations encountered by harvesting RF energy to charge a mobile device were taken into account when developing the RF harvesting circuit and was considered during the testing stages; hence the aim of this study was to wirelessly charge mobile devices using RF energy harvesting. This aim is further articulated by the hereby listed research objectives:

a) To investigate approaches that can be used to charge mobile devices wirelessly.
b) To implement a wireless charging system based on radio frequency harvesting.
c) To evaluate test results of the implemented wireless charging system to prove charging of a mobile device based on device distance and battery size is possible.

The above research objective can be translated into the following research questions:

- **Research Question 1**: What approaches can be used to charge mobile devices wirelessly?
- **Research Question 2**: How can the wireless charging system be implemented based on radio frequency harvesting?
- **Research Question 3**: How to evaluate the test results of the implemented wireless charging system with a mobile device based on distance and mobile device battery size?

The section below describes the method implemented to achieve the above-mentioned objectives, factors and tools used to comprehend the aim.

1.2.1 Methodology

RF harvesting is a fairly new technology and constant research on different approaches pertaining to the field of RF harvesting is still ongoing. Previous studies, related work and technical documents were relied upon in creating this thesis.

In order to provide necessary background for this work, preliminary study of the RF harvesting concept is done. This provides useful information on various approaches of the concept such as benefits, challenges, trends and models used for this work.

This is followed by specific literature study and review of the research problem. The literature study gives adequate insight into what is expected in terms of input and output. Thereafter, a discussion is presented on the method used, prototype and simulation tool chosen for investigating the effectiveness of the RF harvesting concept. Then, the different components are compared using the simulation software and circuit layouts are investigated until desired result is achieved.

1.2.2 Simulation Tool

The methodology adopted for this research is based on mathematical modelling and simulation. The energy harvesting circuit was created as a prototype model. The initial prototype highlighted the findings and limitations to be considered for future design. LTSpice simulation software was used for the dimensioning and correct interpretation of the individual components of the circuit.

Various mathematical formulae were applied to calculate the amount of power that could be generated from the prototype and the simulation circuit. The simulation software demonstrated the behaviour of the different components and circuit layouts for effective RF energy harvesting.

1.3 CONTRIBUTIONS

The contributions of related research towards RF energy harvesting mostly focused on sensor networks based on the quantity of harvested energy. The main contribution of this research is the introduction of RF energy harvesting circuit that is able to power a mobile device battery and the basic principles of this innovative concept was explained. A prototype proves the theory of RF energy harvesting to be possible. Simulation software demonstrates the effectiveness of the components in the circuit and discusses the special considerations for the layout of the circuit. The contributions of this research are summarised below:

- Firstly, the theory of RF energy harvesting is proven using a prototype circuit that was based on the Tesla Air circuit.
- Secondly, the capacitor was seen as an alternative to the battery of the mobile device concerning the storage of the harvested energy, based on the lifespan and not consisting of chemicals like the battery.
- Thirdly, the effectiveness of the different components was investigated using the simulation software.
- Further the circuit layout was studied using different mathematical formulae to calculate voltage loss, antenna type, half-wave and full-wave rectifier circuits for maximum energy harvested.

1.4 MOTIVATION

The evolution of energy harvesting originated from the windmill and the water wheel. Researchers had investigated methods to store the energy from heat and vibrations for many decades. The main driving force behind the search for innovative energy harvesting devices is the need to power sensor networks and mobile devices without batteries. The energy harvesting concept is also motivated by the need to address the issue of climate change and global warming.

RF wireless power holds vast potential for replacing batteries or increasing their lifespan. Especially in critical situations, this much needed innovation would be most useful. Wireless ad-hoc networks would benefit the most from this innovation since these networks are battery-powered and are mostly deployed in critical environments such as military zones, hostile, hazardous, flooded areas and in emergency health care situations where it is almost impossible to replenish the batteries (Modupe, Olugbara, Ojo and Modupe, 2013).

The application of power harvesting technologies, devices and equipment can become self-sustaining pertaining to the energy required for operation, thereby obtaining an unlimited operating lifespan resulting in the demand for power maintenance becoming negligible.

The disposal of battery waste is currently a critical problem. The bulk of these batteries is dumped in landfills, resulting in the pollution of the land and water directly below. It seems the most effective solution for reducing battery waste is to avoid using them. Applying the RF harvesting concept will assist in reducing the dependency on batteries, which will ultimately have a positive impact on the environment. Moreover, the process of harnessing electromagnetic energy will not generate waste as it is a clean energy source.

1.5 OUTLINE OF THE DISSERTATION

The research study is RF harvesting related exploration. An adequate understanding of the technology concepts and standards is fundamental to perform such thorough study. Knowledge of the specifications and requirements for functionality and performance of the RF harvesting prototype is equally important to know if the technology implementation satisfies the conditions for charging a mobile device. Therefore, this dissertation provides an extensive overview of concepts in RF harvesting before delving into theory, mathematical simulation and testing the prototype.

The layout of this dissertation is as follows. Chapter 2 reviews literature in the field, as well as a review of existing implementations, and ends with the research questions. Chapter 3 describes the research methodology used in computer engineering, testing, study approach and analysis used. Chapter 4 provides an explanation of the findings in the research, including the design and any modifications to the prototype as a result of the testing feedback. Then Chapter 5 provides a conclusion to the study in this dissertation and considerations for future work.

1.6 SUMMARY

With the increasing use of mobile and computing devices, the problem of energy (battery) consumption is a rising issue. There is limited work being explored for addressing RF energy harvesting exclusively for mobile devices; majority of the studies are more or less concentrated on low powered devices like sensors. Studies towards powering up mobile phones are few to find.

This chapter has introduced the concept of Radio Frequency harvesting, the different types of harvesting methods with the associated limitations and the benefits and drawbacks of RF harvesting. RF harvesting as a means for charging mobile devices contact and wire free is singled out as the focus of this study on the basis of convenience and RF harvesting using free energy. One of the main points of this chapter is the formulation of the aim and objectives of this study to examine the motivation of using RF harvesting as a source of electrical energy in the charging of mobile devices. The next chapter is dedicated to the first objective of this study of the different RF harvesting approaches that have been used to charge mobile devices.

CHAPTER 2

LITERATURE REVIEW

This chapter presents an overview of energy harvesting methods and approaches used to charge mobile devices. Energy optimisation is presented and related research is explained. The different energy charging techniques are briefly explained. The concept of RF harvesting is expanded on. The key approaches and specifications pertaining to RF harvesting are clarified in this chapter. The specifications and previous studies for this innovation are few to mention and various aspects of the specifications are still being reviewed. Abiding to the length of the dissertation, this chapter provides a brief introduction to the RF energy harvesting and dwells only on key aspects of the concept relating to mobile charging.

2.1 ENERGY OPTIMISATION

Energy optimisation is evident using many different techniques, approached and methods. Related studies have explained the methods energy can be scavenged and used. Modupe et al (2013) explains the use of a genetic algorithm enhances more energy saving in the ad-hoc network compared to equivalent and adaptable grid model. The results of this study further elaborate on prolonging the lifespan of the battery used in the ad-hoc network. This research is investigating an alternative to the battery by using a supercomputer as an energy storage medium.

Many researches concentrated on optimising the harvested RF energy because presently it is limited to power viable loads. Research conducted by Sim et al (2010) investigated the possibility of enhancing the power harvested by the RF harvester by enhancing the structure of the antenna, this study comprised the use of dual antenna designs and assessed the power production from each design in a soil wireless sensor network. The initial antenna design focused on a low profile folded shorted patch antenna (ESPA) and the second design focused on an altered ESPA assembly. They used a steadfast transmitter to stream microwave energy at frequencies of 867 MHz and 2.45 GHz to the sensor nodes, the harvester produced power levels of 1.5-

2.2mW. This charge is substantially high from an RF harvester, nonetheless the use of a dedicated transmitter caused the harvested power to be much less than the power transmitted, and this resulted in the efficiency actually being low.

Bouchouicha et al (2010) examined the power densities from broadband and narrowband systems, their research included exploring the effect of the antenna and load on the harvested energy. The results of their research established that the energy harvested from the broad and narrow band systems was limited to directly pass charge to a low power device, however the energy could be stored in a capacitor or a micro battery, and their research further concluded that the selection of load and antenna had an influence on the harvested energy owing to impedance matching.

Harrist (2004) conducted research on an RF energy harvester to charge a mobile phone. The research was based on charging a capacitor using a charge pump with a peak detector circuit. A quarter wave whip antenna with a seven stage voltage doubler was used with the output capacitor. RF energy was harvested from a 915MHz signal transmitted from a dedicated transmitter.

Simulation software SPICE, was used to conduct optimisation of the circuit constants. The software permitted the user to enter a range of values for a specified factor and then stipulates the value of growth for each of the factors, this enables the user to identify the range of values that will produce high output power. The study indicated that the increase in the number of stages results in an increase in the output voltage, then the voltage calmed once the number of stages was six, any further stage caused a decrease in the output voltage and this can be clarified by the fact that the voltage gain becomes slightly as the number of stages reaches six. Adding surplus stages will ingest power without having any result of the output voltage. The harvester was verified on the following two phones, a Nokia 3570 requiring 1.26W to charge the battery, and a Motorola V60i requiring 2.36W to charge the battery. The harvester was capable to power the phones for a limited time and then was unsuccessful at sustaining the required power levels owing to little energy output levels, however the harvester was successful at recharging the batteries when the phones were switched off. The study was capable of demonstrating that the harvester could halve the charging period of the mobile phone batteries. This study was conducted in 2004, phone designs and features have changed from 2004 till date, and there is a much needed innovation to RF energy harvesting to charge these mobile device batteries today.

Arrawatia et al (2006) explored the viability of harvesting energy from a cell tower in the frequency band of 900 MHz, the focused cell towers were distributing a CDMA signal. The research used a broadband electromagnetically coupled Square microstrip antenna (SMSA). The research produced favourable results, the harvester was able to yield voltages of 0.87V when a single stage voltage doubler was used and 2.78V when six stage voltage doublers were used. The outcome of using Schottky diodes on the circuit was also studied, the research also established that the voltage levels improved considerably when Schottky diodes were used, this can be credited to their low threshold voltage of 230mV. This research was conducted about ten years ago, again, there has been too many advancements to the mobile phone industry now.

2.2 ENERGY HARVESTING

Energy harvesting entails scavenging ambient energy from motion, heat, light, electromagnetic radiation and other sources and this offers an appealing green energy alternative to power mobile devices (Rincon-Mora, 2011). Related studies pertaining to energy harvesting included providing energy to wireless sensor networks (WSN), Internet of Things (IoT) and is currently ongoing.

WSN is defined as a set of sensor nodes liable for sensing a somatic occurrences, and advancing their surveillance to the sink node. Saving energy is one of the main apprehension of procedures and applications in WSNs. Combining harvesting units to the sensor nodes are confidently addressing the issues of charging the battery powered sensors. For harvesting sensors (Akbari, 2014), there are many obtainable sources to be harvested, e.g. sun, winds, RF signals.

Study conducted by Ulukus et al (2015) summarises the results in energy harvesting wireless communications and wireless energy transfer from perspectives of communication theory, signal processing, information theory and wireless networking. Energy harvesting brings new dimensions to the wireless communication problem in the form of intermittent and randomness of available energy, as well as the possibility of sharing energy among the nodes in a network via wireless energy transfer, which necessitate a fresh look at wireless communication protocols at the physical, medium access and networking layers, as well as at the fundamental performance limits, i.e. the channel capacity.

Ulukus et al (2015) summarises the advancements of research on an information theoretic view of energy harvesting and associated problems pertaining to wireless systems and WSNs. This article further elaborated on the difference between wireless sensor networks and wireless systems, is that the devices cater to the requirements of data transmission and source acquisition. Precisely individual sensors tracks a source acquisition linking sensing, sampling and compression. These processes frequently involve an energy rate that is similar with radio transmission. Hence it is necessary to have an appropriate distribution of the restricted energy resources to sources acquisition and transmission.

2.3 MODELS OF ENERGY HARVESTING

This section focuses on energy harvesting that is functional within network architectures, node distributions and accurate channel/inference models. Mobile ad hoc network (MANETs) is an evolving category of wire-free networking, in which mobile nodes function on an impromptu or ad hoc basis. MANETs are self-forming and self-healing, permitting peer-level communications between mobile nodes devoid of dependence on centralised resources or secure infrastructure (Ulukus et al, 2015). Nodes in the MANET are minor devices like sensors and wearable computing devices. Assumed their positioning environment, the energy influx processes at dissimilar transmitters are expected to be in unsystematic arrangements called the energy arrival state. The batteries of harvesters are expected to have inestimable volume. The concerns with the MANET model are that bulky density and power can result in robust interference and this can violate the outage constraint (Huang, 2013).

Hung et al (2013) discourses the consequence of the spatial variation of the renewable energy field, e.g. solar or wind power, on the coverage of a cellular network. A docile energy field model is proposed by Huang et al, where the energy amount at a specific site is given by spatial joining of Poisson distributed energy midpoints with secure maximum concentrations known as Boolean random function. Subsequently harvesters cannot transmit high-voltage power, complete energy transmission loss can become substantial as the number of harvesters for energy accumulation increases.

Cognitive radio network model was investigated by Lee et al (2013), where inactive ancillary nodes resourcefully access the band of primary nodes and harvest energy from radiation where probable. Simultaneous networks are modelled as superimposed spatial point processes. The conduction capacity of the ancillary network, assuming the strategy of resourceful energy harvesting is considered and enhanced over the node density and transmission power.

Huang and Lau (2014) presented a model consisting of cellular networks where mobile devices recharged wirelessly using steadfast power stations via microwave power transfer (MPT). This model embraced the stochastic geometric approach for network modelling and investigation. The resources on the MPT network arrangement are studied for different MPT trends.

Heterogeneous cellular network model with energy harvesting was proposed by Dhillon et al (2014), in which multi-tier renewable powered base stations (BS's) are modelled as autonomous Poisson point processes (PPPs). Minor base stations positioned in a built-up area where energy influx procedures for BS's are expected to be free, permits the on/off states of BS's to be exhibited as autonomous Bernoulli random variables and their effect on the network exposure routine can be measured arithmetically using stochastic geometry.

Energy harvesting systems normally function at diminutive distances, the energy expended in transmitter/receiver circuitry can be equivalent, or can lead the energy used in transmissions. The effort in constructing a complete model of total energy minimization resides in gaining models for energy used in circuitry that are sufficient for analysis and precise to produce pertinent approximations of energy utilisation. Youssef-Massaad et al (2008) and Cui et al (2005) explored models comprising of transmitters and receivers utilised as black boxes that ingest a static amount of energy per unit time during the power on stage. Granting the studies are significantly diverse, the results are the same. Systems in the powered by state utilises circuit energy, so both receiver and transmitter must be in the powered off state for a particular duration in order to limit circuit energy.

2.4 TYPES OF ENERGY HARVESTING

Sharma & Balaji (2014) summarises the different types of standard energy harvesting methods and the limitations of each in Table 2.1 below:

Table 2.1: Types of Energy Harvesting

Energy Harvesting Method	**Definition**	**Limitation**
Electromagnetic Energy Harvesting	Uses the principle of electromagnetic induction	Not an effective method – produces 0.1 Volt
Photovoltaic Cells	Converts light energy into electrical energy	Difficulty of positioning the equipment where there is abundant sunlight
Mechanical Vibration Harvesting	Uses mechanical vibration and converts it into electrical energy	Materials are brittle in nature and leads to charge leakage
Capacitive Energy Harvesting	Dependant on the charging capacitance of the vibration-dependent variable capacitors	Requires a supplementary source of voltage for initial charging the specific capacitor
Thermoelectric Generators	Uses thermal energy and converts it to electrical energy	Owing to the minimal capability of attaining energy efficiencies required for energy harvesting

2.4.1 Electromagnetic Energy harvesting

Electromagnetic energy harvesting uses the principle of electromagnetic induction (a method of producing voltage in the conductor by altering the magnetic field surrounding the conductor). The studies according to El-Hami (2001) and Beepy (2006) focusses on the use of permanent magnets along with a coil and resonant cantilever beam. This method is not effective as it can produce a maximum voltage of 0.1 V whereas other schemes (electrostatic / piezoelectric) can generate a voltage in the range of 2-10 V.

2.4.2 Photovoltaic Cells

Photovoltaic cells are a common and cheap method in energy harvesting and converts light energy into electrical energy usually the source is sunlight. The limitation of this method is the installation of equipment in a particular position where abundant sunlight can be found. Challenges experienced with this method, according to Raghunathan et al (2005) are the impact of the equipment installed at high altitudes, rainy days, and features of photovoltaic cells deployed, illumination intensity, and energy supply requirements.

2.4.3 Mechanical Vibration Harvesting

Mechanical vibration harvesting involves the vibration of mechanical components and converts it into electrical energy for the purpose of energy harvesting. It is seen that when electronic equipment is subjected to mechanical vibration, an inertial mass can be thought of being deployed for the purpose of movement generation, which is then converted to electrical energy. These mechanisms are deployed using the following techniques:

2.4.3.1 Piezoelectric

The piezoelectric materials convert all the mechanical vibration (energy captured from force, pressure, or vibration) into electricity (Tang, Yang and Soh, 2013). Sharma and Balaji (2014) states that a need arises for storing the energy produced by piezoelectric materials and this technique can be deployed by circuit design. Such energy can be stored in rechargeable batteries for long durations. Piezoelectric materials are normally brittle in nature and may lead to the leakage of charges. This harvesting method involves generators that use thin membranes or cantilever beams made of piezoelectric crystals as a transducer mechanism. When the crystal is put under strain by the kinetic energy of the vibration a small amount of current is produced due to the piezoelectric effect. These mechanisms are usually very simple with few moving parts, and tend to have a very long service life. This makes piezoelectric the most popular method of harvesting the energy from vibrations (Rang, Hun, et al, 2015) and (Yan, Qunying, et al, 2015).

Vasic and Yao (2013) explored a wideband electrical interface focused on pulse width modulation (PWM) for piezoelectric energy harvesting. Energy harvesting is conducted by piezoelectric components and a full-bridge converter combined with PWM modulation is presented to escalate the power outage for a broad frequency series. The inclusion of a piezoelectric patch is utilised to sense the velocity and to produce the drive signal of the switches of the full bridge. High frequency is used to modulate the piezoelectric voltage and it is correlated to the vibrating velocity. The results of investigation reflect that the method can considerably expand the harvested energy for multi-band frequency vibrations compared with sole frequency.

2.4.3.2 Electromagnetic

Electromagnetic based generators use Faraday's law of induction to convert the kinetic energy of the vibrations into electrical energy. They consist of magnets attached to a flexible membrane or cantilever beam and a coil. The vibrations cause the distance between the magnet and coil to change, causing a change in magnetic flux and resulting in an electromagnetic force being produced. Generally the coil is made using a diamagnetic material as these materials have weaker interactions with the magnet that would dampen the vibration. The main advantage of this type of generator is that it is able to produce more power than the piezoelectric generators (Khan and Izhar, 2015).

One of the major limitations of the magnetic vibration energy harvester developed at the University of Southampton is the size of the generator. At approximately one cubic centimetre, this device would be much too large to be used in modern electronic devices. Future improvements in the size of the device could make it an ideal power source for medically implanted devices such as pacemakers. According to the team that created the device, the vibrations from the heart muscles would be enough to allow the generator to power a pacemaker. This would eliminate the need to replace the batteries surgically (BBC, 2007).

2.4.3.3 Electrostatic forms

This type of harvesting is based on the changing capacitance of vibration-dependent varactors (variable capacitors). Vibrations separate the plates of an initially charged varactor and mechanical energy are converted into electrical energy. Electrostatic generators are mechanical devices that produce electricity by using manual power (Despesse, Jager, Chaillout et al, 2005).

2.4.3.4 Capacitive Energy Harvesting

This technique is dependent on the charging capacitance of the vibration dependent variable capacitors. The plates are segregated for an initial charged variable capacitance and electrical energy is accomplished from mechanical forms. Such techniques make use of electrostatic generators for generating electricity by deploying manual energy. This technique is highly compatible and supportive for micro-electronics as they do not have much external hardware dependency. The limitation of this technique is that it requires a supplementary source of voltage for initially charging the specific capacitor (Yen and Lang, 2005).

2.4.3.5 Thermoelectric generators

This technique uses thermal energy and converts them to electrical energy for specific applications. The devices that produce thermal electricity, essentially are used in space and for specific applications. The usage of such techniques is limited owing to the minimal capability of attaining energy efficiencies required for energy harvesting (Ramadass and Chandrakasan, 2010).

2.5 COMPARISON OF DIFFERENT CHARGING TECHNIQUES

Three major techniques for wireless charging are magnetic inductive coupling, magnetic resonance coupling and microwave radiation.

2.5.1 Magnetic inductive coupling

Inductive coupling uses magnetic fields that are a natural part of current's movement through the wire. Any time electrical current moves through a wire, it creates a circular magnetic field around the wire. Bending the wire into a coil amplifies the magnetic field. The more loops the coil makes, the larger the magnetic field will be. Research conducted by Wilson (2016) explains the functionality of magnetic inductive coupling. By placing a second coil of wire in the already created magnetic field, the field can induce a current in the wire. A transformer works in a similar way. The device that uses this type of charging is an electric toothbrush. This method follows three basic steps; firstly current from the wall outlet flows through a coil inside the charger, creating a magnetic field. In a transformer, this coil is called the primary winding. Secondly, when you place your toothbrush in the charger, the magnetic field induces a current in another coil, or secondary winding which connects to the battery and thirdly, this current recharges the battery (Wilson, 2016).

A higher coupling factor improves the transfer efficiency, and reduces losses and heating. Applications with a larger distance between the transmitting and receiving coils operate as a loosely coupled system. In loosely coupled systems, only a fraction of the transmitted flux is captured in the receiver. That means that loosely coupled systems have higher electromagnetic emissions, making them less suitable for applications with tight Electromagnetic Interference (EMI) or Electromagnetic Frequency (EMF) requirements.

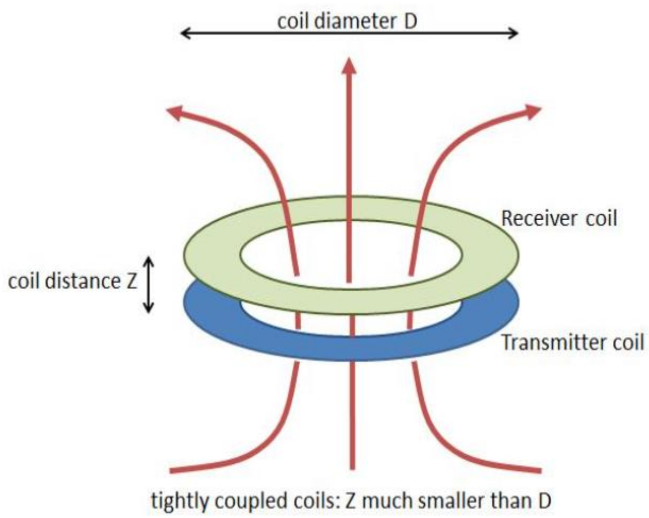

Figure 2.1 Loosely coupled system (wireless power consortium, 2012)

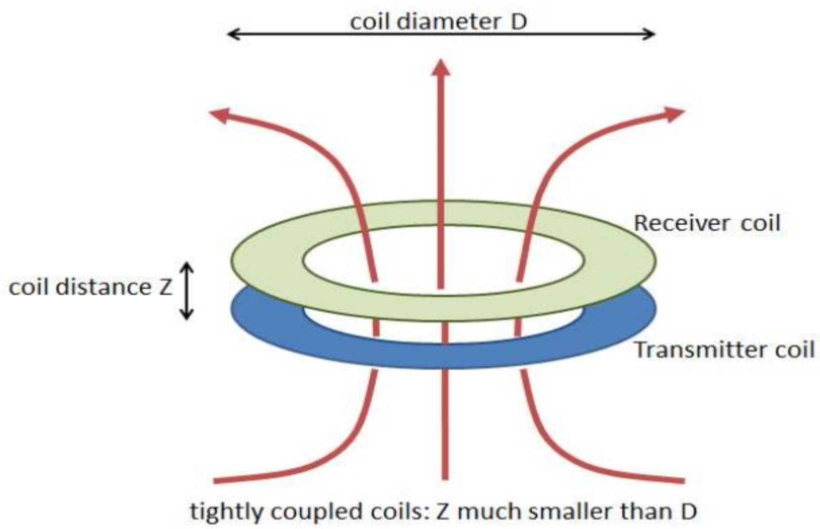

Figure 2.2 Tightly coupled system (wireless power consortium, 2012)

Loosely coupled systems span over larger distances at the cost of lower power transfer efficiency and higher electromagnetic emissions. This may be a suitable choice in applications where tightly aligned coils are impractical, but less suitable for applications with tight EMI or EMF of efficiency requirements.

Tightly coupled systems, because of their higher efficiency, tend to produce less heat which is an advantage in products with tight thermal budgets, such as modern smartphones (wireless power consortium, 2012).

MIT scientists have developed the MagMIMO based on the magnetic inductive coupling technique. The MagMIMO manages to charge a wireless device from up to 30 centimetres away (Jadidian and Katabi, 2014). MagMIMO operates in a similar way to radio communications; innovative WiFI routers are able to sense the starting of a connection from a computer to them and enhances the signal in that route. MagMIMO functions the same way by means of magnetic fields as an alternative to radio waves. An assortment of wire coils produces a magnetic field and once a phone interrupts that field, MagMIMO detects it and concentrates on the phone by generating a considerably altered field with the individual coil. The magnetic fields, strengthen each other in order to get the most out of the strength of the complete field in the direction of the phone. During the testing stages, a small wire was connected to the charging port of the iPhone. The magnetic field produces a current in this coil resulting in charging the phone. MagMIMO uses up considerable power as present systems, however it is able to charge a mobile phone remotely deprived of being detached from the operator’s pocket and unlike WiFi, the magnetic fields created does not result in the heating effect on human tissue. Limitations of this technique is that charging is within a short distance ranging from a few millimetres to a few centimetres and tight alignment is needed between chargers and charging devices.

2.5.2 Magnetic resonant coupling

This technique is based on evanescent-wave coupling which generates and transfers electrical energy between two resonant coils through varying or oscillating magnetic fields. Magnetic coupling occurs when two objects exchange energy through their varying or oscillating magnetic fields. Resonant coupling occurs when the natural frequencies of the two objects are approximately the same.

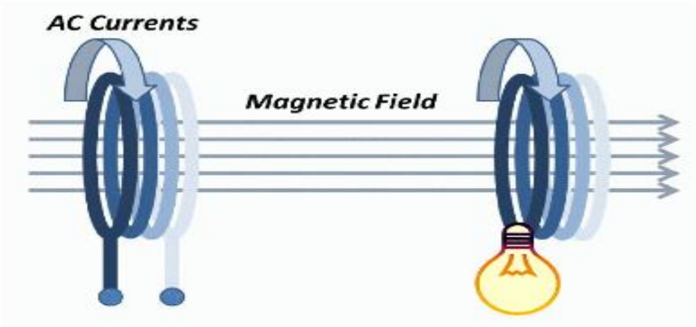

Figure 2.3 Magnetic resonance (Dansie, 2013)

MIT scientists have proposed WiTricity which is based on coupled magnetic resonance. This technology can charge multiple devices concurrently and offers non-line-of-sight charging (Kurs, Karalis, et al, 2007).

WiTricity power sources and capture devices are magnetic resonators that efficiently transfer power over large distances via the magnetic near-field. These proprietary source and device designs and the electronic systems that control them support efficient energy transfer over distances that are many times the size of the sources/devices themselves (Kurs, Karalis, et al, 2007). Resonant coupling transpires when the ordinary frequencies of the two arrangements, a source and a receiver, are roughly similar. WiTricity power sources and receiver systems are particularly developed magnetic resonators that resourcefully transmit power over huge distances using magnetic-near field. The limitations of this charging technique as argued by Singh (2016) are that the resonance condition should be satisfied and in the event of an error occurring results in no power transfer. The other limitation is based on the presence of very strong ferromagnetic material which results in a lower power transfer due to radiation.

2.5.3 Microwave radiation

This technique utilises microwave as a medium to carry radiant energy. The typical frequency of microwave ranges from 300MHz to 300GHz. The energy transfer can use other electromagnetic waves, such as infrared and X-rays; however, due to safety issues, these are not widely used. The microwave energy can be radiated isotropically or towards some direction through beamforming. The former is more suitable for broadcast applications. For point-to-point transmission, beamforming transmit electromagnetic waves, referred to as power beamforming (Zang and Ho, 2013).

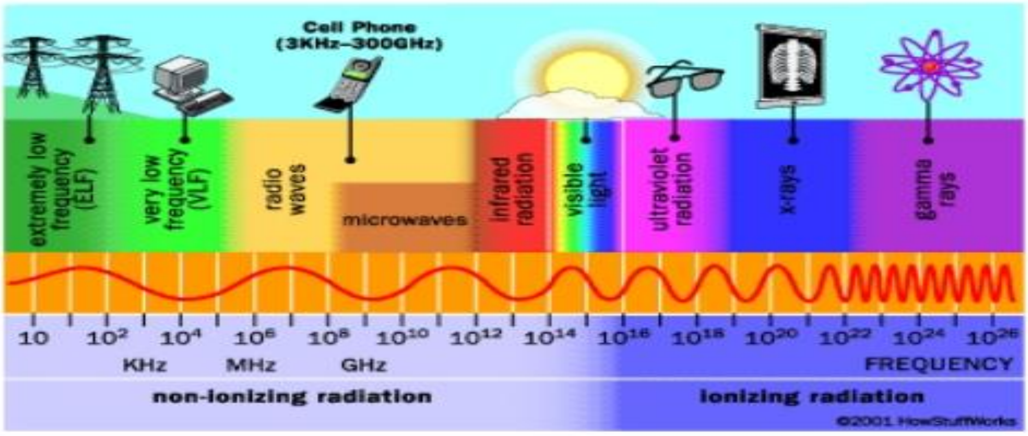

Figure 2.4 Microwave radiation (Wilson, 2016)

Devices using the microwave technique are the Powercaster transmitter and Powerharvester receiver and this technique allows 1W or 3W isotropic wireless power transfer (Powercast Corporation, 2003).

Microwave radiation is effective for long distance charging with the limitation of being not safe when RF density exposure is high and has a low charging efficiency which is line-of-sight. Distance ranges from within several tens of meters up to several kilometres.

In a study by Rewaskar & Datar (2014), microwave signals were studied to charge mobile devices wirelessly. The microwave signal transmitted from the transmitter using a special kind of antenna called slotted wave, guide antennas at a frequency of 2.45GHZ. A sensor rectenna circuit was added to the mobile phone in order to charge successfully. However the limitations of this were the transmitter and receiver should be very powerful devices as the distance increases, the charging is very slow, wireless transmission of the energy causes some drastic effects to the human body because of its radiation, it is more costly and the practical possibilities are not yet applicable in this field.

Sakthi & Vidhya (2014) have proposed the concept of charging mobile phones automatically while talking on the mobile phone. This system includes a magnetron, which is a high power microwave oscillator that can be found in microwave ovens and radar transmitters. Included in the design is a rectenna and a combination of Schottky diodes. Limitations of this design are based on the magnetron ability to only work on a fixed frequency. And since this is microwave radiation, constant exposure will also cause harm to the human body.

2.6 RADIO FREQUENCY HARVESTING

Radio frequency (RF) energy is another name for radio waves. It is one form of electromagnetic energy which consists of waves of electric and magnetic energy moving together (radiating) through space. The area where these waves are found is called an electromagnetic field.

For mobile and miniature electronic devices, a promising solution is available in capturing and storing the energy from external ambient sources, a technology known as energy harvesting. Other names for this type of technology are power harvesting, energy scavenging and free energy, which are derived from renewable energy (Sivaramakrishnan and Jegadishkumar, 2011).

A study by Zeng et al (2017) focused on antenna design for RF harvesting. A compact fractal loop rectenna for RF harvesting was presented at GSM1800 bands. The rectenna design comprised of a fractal loop with novel in-loop ground plane (ILGP) impedance matching. This design included a high-efficiency rectifier based on the full wave Greinacher circuit. The results reflect that the rectenna was capable to pass charge to LCD watch that did not comprise of a battery at a distance of 10 meters from the cell tower and the rectenna is stated to be beneficial in numerous energy harvesting applications.

Aminov and Agrawal (2014) demonstrated a system capable of harvesting RF energy. The system comprised of the following components; an antenna, matching circuit, 5 stages of voltage doubling and a storage capacitor. Established on accompanied studies and analysis it is determined that far field RF energy harvesting is conceivable when the midpoint frequency of the circuit is concentrated on the medium wave frequency band operating at 531-1,611 kHz. Restrictions based on the quantity of energy harvested from the RF energy harvesting system are due to the power of the RF field, applied antenna and the multiplier circuit. The system can be utilised to acquire the RF energy from a local AM radio station by pointing the loop antenna in the direction of the site of the station. The system was capable in harvesting sufficient energy to charge a super capacitor to 2.8 V and endure the voltage in the process of no load linked to the circuit. This charge is adequate in powering a 1kΩ load for approximately one hour.

Xu et al (2017) investigated the design of simultaneous wireless information and power transfer (SWIPT) systems. Wireless power transfer using RF signals has been established as a substitute for charging wireless sensor networks. RF signals are presently utilised for wireless information transfer, that is transmitting information wirelessly. The integration of wireless power transfer and wireless information transfer results in simultaneous wireless information and power transfer (SWIPT) (Varshney, 2008; Grover and Sahai, 2010; Zhang and Ho, 2013). SWIPT systems comprise of using RF signals simultaneously to transmit information to information receivers and power to energy receivers. SWIPT system structures have been explored under several situations. Zhang and Ho (2013) investigated broadcast channels, Nasir et al (2013) demonstrated relay channels, Park and Clerckx (2014) and Ozcelikkale and Duman (2015) proposed interference channels, and orthogonal frequency division multiple access (OFDMA) systems was studied by Huang and Larsson (2013). The issue with a non-linear energy harvesting model was stated by Xu et al (2017), the measurement data are usually accessible for a definite range of input power values.

Sangare and Han (2017) describe the fifth generation (5G) of mobile technology as anticipated to permit a completely mobile and connected society to satisfy the increasing demand of advanced frequency and mobility variety, better throughput, lesser latency and much developed connectivity compactness than the existing 4G. This article further elaborated on smart services such as metering, light management in the city or building, monitoring the environment and controlling vehicle traffic becoming prevalent in built-up areas. The accumulation of these services in high density devices coupled with diverse characteristics anticipated to be joined in a shared communication and internet framework. This ultimately results in requiring very low cost devices with extended battery life. In WSNs the challenge is assessing substituting batteries in sensors dispersed over great areas. Xiao et al (2015) has suggested wireless energy harvesting to be an alternate to batteries, basically through the use of capacitive coupling, inductive coupling, magnetic coupling or RF energy.

The sources of radio signals used to operate the WSN are either dedicated (energy is provided using a specific bandwidth for functioning precise sensors (Sangare et al, 2015) or ambient (providing freely available energy through the atmosphere from sources originally not proposed for energy transfer). Sangare and Han (2017) mention the two categories of sources as being static RF sources and dynamic RF sources. Static RF sources consist of transmitters discharging a moderately steady power over a certain period, such as TV and radio towers. The challenges with static sources are the long and short term instabilities resulting from service schedule and waning. Dynamic RF sources involve transmitters working sporadically or using a time changing transfer power, such as Wi-Fi access points and licensed users within cognitive radio environment. The challenge experienced with these sources is based on these sources being difficult to instrument, subsequently the harvester has to be adaptive and smart to pursue for energy harvesting prospects in a defined frequency range (Sangare and Han, 2017).

2.7 BENEFITS OF RF HARVESTING

The advantages of RF harvesting, such as control of the source and the ability to operate in any environment, not only make RF harvesting very practical, but may also drive RF harvesting to the mainstream. According to Ostaffe & Tollefson (2011), the advantages of RF harvesting are summarised as; RF energy is available on demand; RF harvesting works well in dark and hazardous locations; provides mobility and tracking capabilities; makes possible the charging of a secondary battery; and can be embedded between walls.

2.8 DRAWBACKS OF RF HARVESTING

While proven as a viable power source for low applications, some people still remain sceptical of its wider potential. An article by European Editors (2013) has stated the disadvantages of RF harvesting to be; levels of RF energy available drop considerably with distance; despite the proliferation of RF transmitters across a variety of frequency ranges, the amount of ambient RF energy available is not huge and is unlikely to grow; many governments have issued guidelines designed to limit RF power output from a single transmitter; objects can reflect and absorb RF energy.

2.9 WIRELESS CHARGING TECHNOLOGY

Wireless charging technology enables wireless power transfer from a power source emitted from a charger to a load on a mobile device (Lu, Niyato, et al, 2014).

Wireless power transfer (WPT) or wireless energy transmission is the transmission of electrical energy from a power source to an electrical load, such as an electrical power grid or a consuming device, without the use of discrete man-made conductors. Wireless power is a generic term that refers to a number of different power transmission technologies that use time-varying electric, magnetic, or electromagnetic fields. In WPT, a wireless transmitter connected to a power source conveys the field energy across an intervening space to one or more receivers, where it is converted back to an electrical current and then utilised. Wireless transmission is useful to power electrical devices in cases where interconnecting wires are inconvenient, hazardous, or are not possible (Davis, 2014; Marks, 2014).

Wireless power techniques fall into two categories, non-radioactive and radioactive. In a non-radioactive technique, power is typically transferred by magnetic fields using inductive coupling between coils of wire. Applications of this type include electric toothbrush chargers, RFID tags, smart cards, and chargers for implantable medical devices like artificial cardiac pacemakers, and inductive powering or charging of electric vehicles like trains or buses. A current focus is to develop wireless systems to charge mobile and handheld computing devices such as cell phones, digital music players and portable computers without being tethered to a wall plug. Power may also be transferred by electric fields using capacitive coupling between metal electrodes. In radioactive far-field techniques, also called power beaming, power is transferred by beams of electromagnetic radiation, like microwaves or laser beams. These techniques can transport, energy over longer distances, but must be aimed at the receiver. Proposed applications for this type are solar power satellites, and wireless powered drone aircrafts (Davis, 2014).

A study conducted by Sharma and Balaji (2014) states the challenge of storing and processing trapped energy stored in ambient resources for some of the low powered devices like sensors require a high degree of hardware and experience limitations with processing and storing energy.

2.10 BLUETOOTH AND WIFI

Rouvala, a researcher based at the Nokia Research Centre in UK (Graham-Rowe, 2009), stated that ambient electromagnetic radiation- emitted from WiFi transmitters, cell phone antennas, TV masts and other sources could be converted into enough electrical current to keep a battery charged.

The next successful attempt at wireless charging is a device called Cota developed by a company called Oasis. Devices that are Cota-enabled can receive power within a 10 foot radius. The device employs the same frequencies used by Wifi and Bluetooth to send magnetic charges to designated devices or hot spots. The limitation with this attempt is that the mobile devices have to be Cota-enabled and the distance to charge is limited to 10 feet only (Chu, 2013).

Rizzone, CEO of Energous, (Patrizio, 2015) proposed a wireless charging technology called WattUp that sends power in a 15-ft. Radius using radio frequency transmissions. The WattUp transmitter works much like a wireless router, sending radio frequency signals that can be received by enabled mobile devices, such as wearables and mobile phones. A small RF antenna in the form of PCB board, an ASIC and software makes up the wireless power receivers.

Because the amount of wattage WattUp can send is limited, Energous is focused on powering small mobile devices rather than laptops or batteries that require higher capacities (Patrizio, 2015).

2.11 WBANs AND ENERGY HARVESTING

Wireless body area networks (WBANs) are branches of wireless sensor networks (WSNs) and are multidisciplinary and intersectional technology for mobile healthcare industry. A linking of several smart miniaturised devices are either worn or implanted within the patient in WBANs for continuous ambulatory monitoring of vital physiological signs. The wearable and implanted physiological devices with integrated wireless communication capability in the innovative system can measure the physical properties of human body and convert a physical signal into an electrical signal and then the devices collect data to a base station or transmit the data to a hospital or clinic, to provide the ability of remote patients vital signs monitoring and diagnosis, thereby improving the quality of smart healthcare information monitoring (Chen, Liu and Hao, 2009).

The sensor nodes of WBANs rely mainly on battery power. However, batteries are troublesome due to the fact that they have a limited lifetime. They only allow very low energy consumption on tiny devices which have weaker processing capacity and less memory capacity for a while. Therefore, a small-sized rechargeable battery (a super capacitor or a thin-film rechargeable battery) is the alternative solution to achieve the network energy autonomy throughout the entire network lifetime (Schaijk, 2011).

Energy harvesting from the ambient environment has been proposed as an attractive solution. It is designed as an alternative to battery as it can provide an almost green supply of energy. It has many benefits such as lower system costs and environmental impact.

2.12 DIFFERENCE BETWEEN ENERGY HARVESTING AND INDUCTION CHARGING

RF energy harvesters are different from typical induction charging systems, such as the popular power mats and electric toothbrushes that require a nearby power source. The close proximity of the power source is needed to ensure an efficient transfer of power usually within millimetres.

In contrast, RF energy harvesters work over a much larger distance from about 10 to 15 meters and at much higher frequencies, typically these are in the GSM mobile radio band. The key to successful RF power transfer lies in the design of the antenna system (Blyler, 2012).

2.13 CHARGING STANDARDS

From the reviewed literature, there are three major wireless charging standards, Alliance for Wireless Power (A4WP), Power Matters Alliance (PMA) and Wireless Power Consortium (Qi).

2.13.1 A4WP

The A4WP uses a transfer technology called Rezence, based on magnetic resonance, which is basically the opposite of magnetic induction charging. (Maxwell, 2014). A4WP uses a large area of the magnetic field and this enables the device positioning requirements to be less critical and it allows a single power transmitter to charge multiple devices at any one time.

A4WP states that it uses magnetic resonance charging. Essentially, it uses the same magnetic inductive techniques that allow devices placed within the inductor ring to be charged without having to line up perfectly with the coil.

A further advantage of A4WP is that it enables the possibility of Z axis caring placement. This means that chargers can be built deeper into other objects, like a desk for example, while still allowing the electromagnetic fields to permeate the material (Maxwell, 2014).

2.13.1.1 Features of A4WP

The features of A4WP make it different from other wireless charging techniques and table 2.2 summarises the categories of A4WP:

- Wireless power transfer – this uses a relatively high frequency of 6.78MHz. This is a frequency that is internationally available for this type of application, and using one as high means that it avoids inductive heating issues seen with tightly-coupled inductive systems using much lower frequency.
- Control / management protocol – the frequency used for control and management is within the 2.4 GHz ISM (Industrial Scientific and Media) band. It is internationally available and is ideal for use with smartphones and other electronic items.
- Power transmitter unit (PTU) – this is the unit that transmits the power to the unit requiring charging.
- Power receiving unit (PRU) – this unit takes the power from the transmitter and uses it often for charging a battery. There are several classes of PRU dependent upon the application envisaged.

Table 2.2 A4WP Categories (Poole, 2004)

A4WP PRU CATEGORIES		
PRU CATEGORY	**POWER OUTPUT**	**ANTICIPATED APPLICATIONS**
Category 1	On roadmap	Headset
Category 2	3.5 W	Featured phone
Category 3	6.5 W	Smart phone
Category 4	On roadmap	Tablet
Category 5	On roadmap	Laptop

2.13.2 Qi

Qi is a wireless charging standard developed by Wireless Power Consortium (WPC). Qi allows the charging procedure to be controlled by the charging device. This standard uses the magnetic inductive coupling technique within the range of 40 millimetres. Two power requirement categories standard exist;

- Low power category – power is transferred within 5W on 110 to 205 kHz frequency range
- Medium power category – up to 120 W of power transmission on 80 – 300 kHz frequency range.

Qi standard is based on aligning the mobile device with the charger. Three approaches exist for this alignment:

- Guided position – one-to-one fixed positioning charging
- Free-positioning with movable primary coil - one-to-one charging where the charging device can be located
- Free-positioning with coil array – multiple devices can be charged without alignment to the charging device. (Lu, Niyato, et al, 2014).

2.13.3 Powermat

Powermat works through the process of inductive charging where an alternating magnetic field is generated for a particular charging location. Powermat is a new type of device that allows for wireless charging, a new alternative to wired or cabled charging for smart phones, mobile devices and other types of equipment. Using an accessory called a ring, the user plugs the ring into the device before placing it on a pad for charging (Technopedia, 2008).

2.14 USING WIFI ROUTERS TO CHARGE BATTERIES

Wi-Fi routers are popular in homes and offices and transmit energy signals similar to operating voltages required by many consumer electronics. The study conducted by Talla et al, (2015) describes how constant low amounts of energy through Wi-Fi signals was used to charge sensors 20 feet away, a camera 17 feet away and rechargeable batteries that were 28 feet away (Gilbert, 2015).

A limitation with this research was due to the restriction of one-watt power output by the Federal Communications Commission (FCC).

2.15 5G NETWORK AND ENERGY HARVESTING

5G networks are already being tested and will be the trend in the near future. This network has the features of higher data rates, enhanced end-user quality of service (QoE), reduced end-to-end latency and lower energy consumption (Hossain and Hasan, 2015).

The introduction of the 5G network focusses on energy harvesting to prolong battery life. The benefit associated with this is wire free and energy-aware (green) energy efficiency, applicable to small cell networks. Research challenges of energy harvesting in 5G networks are multi-user scheduling, advanced channel acquisition beamforming, harvest or transmit time adaptation, interference management, simultaneous wireless information and power transfer (SWIPT) enabled resource allocation (Hossain and Hasan, 2015).

2.16 PREVIOUS WORK WITH THE RECTENNA

Combining the words rectifying circuit and antenna results in the term rectenna, originally created by W.C. Brown (1984). Rectenna is an inactive component linked with a diode capable of receiving and rectifying microwave power to DC, resulting in it functioning devoid of any power source. Numerous literature exists based on the rectenna concept.

There are various kinds of antennas that can be operate in a rectenna circuit, these being, a dipole antenna comprising of a straight electrical conductor gauging half wavelength from end to end and linked at the hub to a radio frequency source (Brown, 1984; Degenford, 1964), Yagi-Uda antenna resembling a directional antenna frequently utilised in communications when the frequency is beyond 10 MHz (Gutmann and Gworek, 1979) (Shinohara et al, 1998), mircrostrip antenna also stated as a printed antenna, is made-up by means of microstrip methods on a printed circuit board (PCB) (Ito et al, 1993) (Fujita et al, 1996), monopole consists of a straight rod-shaped conductor frequently attached vertically above some type of conductive surface, termed a ground (Shibata, 1997), loop antenna is a radio antenna comprising of a loop or spiral of wire tubing or additional electrical conductor with its ends linked to a stable broadcast line, minor loops have low radiation resistance and resulting in meagre efficiency and are mostly used as receiving antennas at low frequencies (Gutmann and Gworek, 1979; Strassner and Chang, 2002), coplanar patch entails a patch enclosed by narrowly spaced ground conductor and a CPW feed line which has a comparable geometric shape as the loop slot antenna (Chin et al, 2005), spiral antenna (Hagerty et al, 2000) and the parabolic antenna utilises a parabolic reflector, a rounded exterior with the cross-sectional outline of a parabola to direct the radio waves, the supreme arrangement is shaped like a dish and is widely referred to as a dish antenna or parabolic dish (Fujino and Ogimura, 2004). These previous studies based on the aforementioned antennas were conducted during the 20th century entering the 21st century. Currently advancements towards antenna designs have been made considering the number of new components and devices that have been developed.

2.17 PROPOSED CIRCUIT DESIGNS

Related research studies have proposed numerous circuit designs relevant to the field of RF energy harvesting, from 2011 to 2017. The majority of these had been tested using simulation software. Below are summaries of the various circuit designs proposed and their relevance to the current research study. Similar designs will be discussed based on RF energy harvesting functionality. The very first design was proposed by Nikola Tesla (figure 2.5). This design was patented in 1901 as Apparatus for Utilization of Radiant Energy.

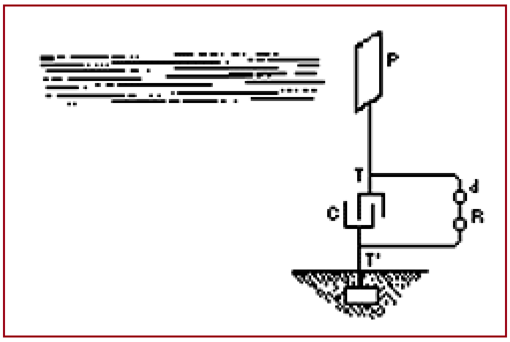

Figure 2.5 Tesla's radiant energy receiver (Perreault, 2016)

Tesla's design was a storage for static electricity attained from the air and transforms it to a functioning form. Starting with the prospective electricity that exists between the raised plate (positive) and the ground (negative), energy forms in the capacitor and after an appropriate time interval the accumulated energy will be evident manifest in a powerful release that can do work. The capacitor according to Tesla should be of substantial electrostatic volume and its dielectric made up of the paramount quality mica for it has to endure capacities that could break a feeble dielectric.

2.17.1 Voltage Doubler Circuit

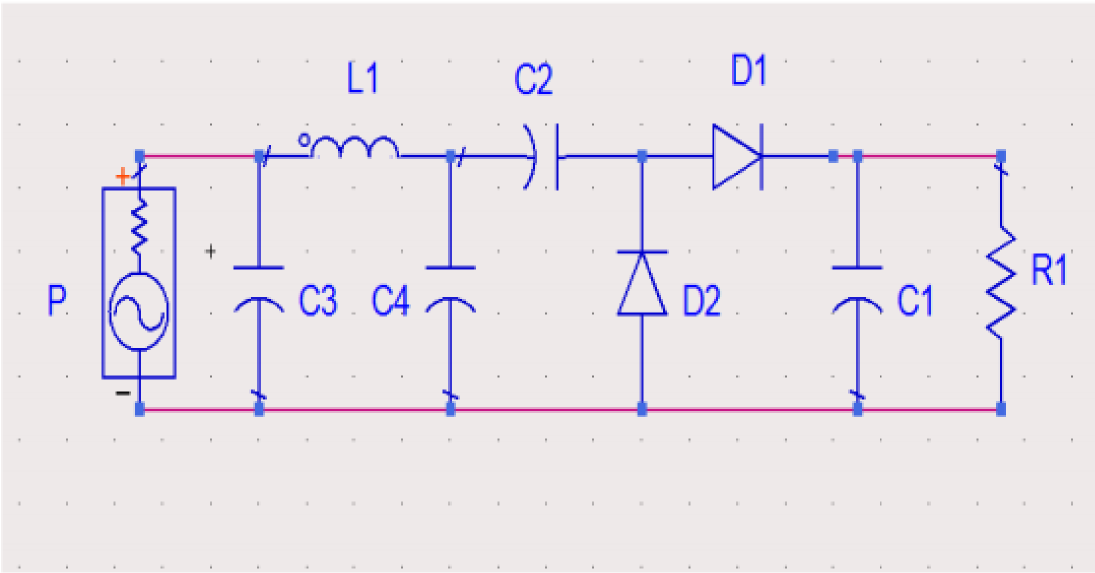

Figure 2.6 Voltage doubler circuit (Sivaramakrishnan and Jegadishkumar, 2011)

This circuit design proposed by Sivaramakrishnan and Jegadishkumar (2011) consists of a 50 Ω power source to deliver power ranging from 15dBm to 40dBm operating at the same power range compared to mobile phones (figure 2.6). A resonant circuit is encompassed operating at a frequency of 0.9GHz to 1.8GHz and is the legal communication frequency allowed. An inductor is included in the resonant circuit. Resistance is added to the inductor to achieve a wide band of frequencies to boost the output power for a range of frequencies. The frequency range can be altered by tuning the impedance matching circuit which also behaves as a resonant circuit. A voltage doubler circuit is also added to the design. Through the positive half cycle, diode D1 becomes forward biased and charges the capacitor C1. Through the negative half cycle, diode D2 gets forward biased and charges the capacitor C2. The output conveyed across the load resistance RL.

The ADS simulation tool was used to design, implement and simulate the circuit. The results of this study indicate the use of Bluetooth rectifies the output voltage when paired with a mobile device battery and should operate at a frequency of 2.4GHz. The limitations seen with this proposition infer the applicability to a Bluetooth environment and requires pairing. The pairing process itself consumes energy. Mobile phone communication is operational at a frequency range of 0.9GHz to 1.9GHz and Bluetooth operates at a desired frequency of 2.4GHz. This is contrasted to the Bluetooth environment being used to charge a mobile device battery.

2.17.2 Conventional Circuit

A research study by Monti and Congedo (2012) had proposed a rectenna (figure 2.7) designed to concurrently harvest the EM energy related to both the UHF (Ultra High Frequency), Radio Frequency Identification (RFID) systems and the Global System for Mobile Communications (GSM) is suggested. The rectenna design is suggested to be useful in industrial situations using UHF RFID systems and requiring low-power sensors such as temperature or humidity sensors.

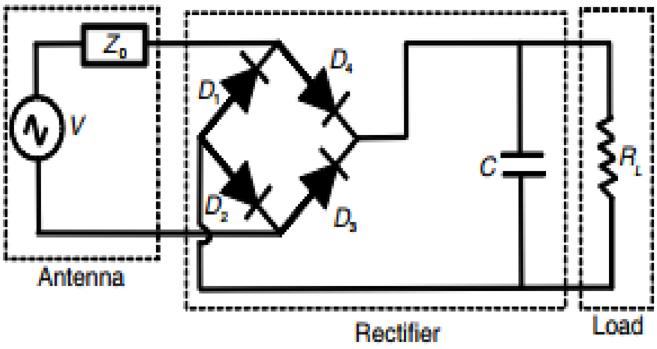

Figure 2.7 Conventional RF to DC Converter circuit (Monti and Congedo, 2012)

The projected device uses an improved bowtie antenna to accumulate the electromagnetic energy approaching from UHF RFID systems, and the RF Schottky diodes converts the electromagnetic energy into DC power. This design is limited to RFID applications based on RFID sensors consume very low power.

2.17.3 LC Tank Circuit

The study conducted by Gabrillo et al (2011) had proposed a conventional rectenna circuit with the addition of an LC tank circuit (figure 2.8). The design included a loop antenna tuned at 165MHz. The LC tank circuit comprised a tuner that receives radio frequency transmissions similar to radio broadcasts and converts the particular carrier frequency into a fixed frequency of 165MHz.

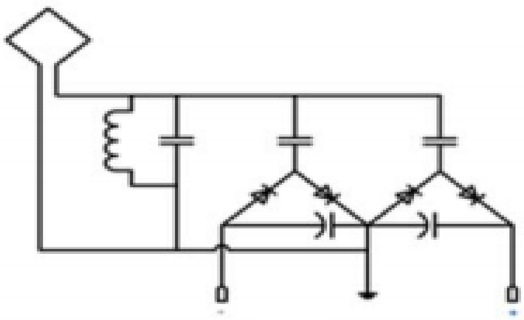

Figure 2.8 LC Tank Circuit (Gabrillo et al, 2011)

The researchers considered both silicon and germanium diodes in the design due to the comparison of the forward voltages on both passive components. The Germanium diodes are well suited for RF signal harvesting due to their low threshold voltage. The design comprised a voltage multiplier to increase the created voltage. The two cascaded half-wave doubler circuit demonstrated the highest power harvested from RF energy. This system proved to be very useful and limited to indoor applications like wireless sensors.

2.17.4 Dickson diode based multiplier

An approach to RF energy harvesting circuit design (figure 2.9) proposed in work by Nintanavongsa, et al (2012) is based on the voltage rectifier circuit. The impact of this research exceeds the conceptual design, and exhibits the functionality on a commercial Mica2 sensor mote, with supplementary replications on both ideal and non-ideal conditions for recognising the higher bound on attainable proficiency. The results were conducted in the power range of −20 to −7dBm for the Mica2 mote.

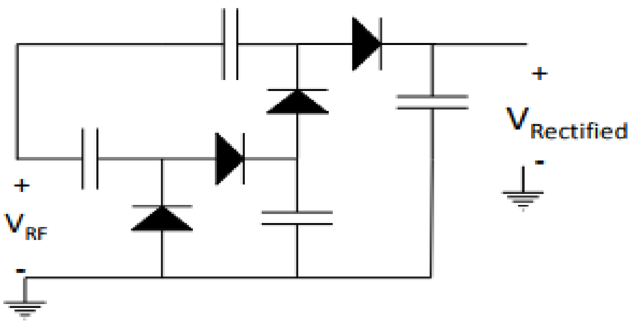

Figure 2.9 Dickson diode based multiplier (Nintanavongsa, et al, 2012)

This circuit design entails the Dickson layout (figure 2.9), which comprises of a parallel arrangement of capacitors in each stage. The parallel arrangement of the capacitors reduces the circuit impedance. Therefore, this simplifies the task of matching the antenna side to the load side. A Schottky diode was included in the design based on the energy harvesting circuit functioning in high frequencies and diodes with precise fast switching time was required. Schottky diodes utilise a metal-semiconductor junction as a substitute to a semiconductor-semiconductor junction. This permits the junction to function much faster, and provides a low forward voltage drop. This contribution to RF energy harvesting was only applied to sensor nodes.

2.17.5 Modified Greinacher Rectifier

Pavone et al (2012) proposed the modified Greinacher rectifier circuit based on a wireless sensory environment (figure 2.10). The structural design entails the rectifying output connection to be in the series. More than one rectifier circuit is linked together in this arrangement. The Ultra-Wide Band (UWB) or multiband antenna is included in the design.

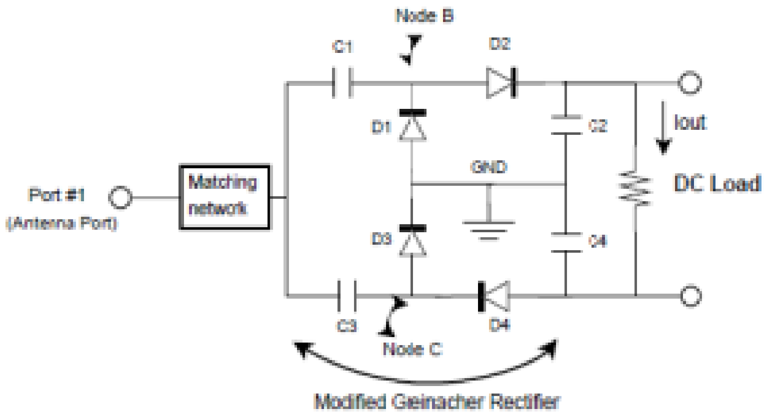

Figure 2.10 Modified Greinacher Rectifier (Pavone et al, 2012)

The outputs of the *N* rectifier circuits are coupled in series and the DC capacity is joined between the ground and the first rectifying circuit. This design caters for more rectifying circuits, operating at altered frequencies and this enables more harvested energy than a single rectifying circuit. The limitation of this design is that it is applicable to wireless networks only and focus was on reducing the use of batteries in a wireless network.

2.17.6 Seven Stage Voltage Doubler Circuit

Din, N.M. et al. (2012) proposed the 7-stage voltage doubler circuit with an E-shaped patch antenna (figure 2.11).

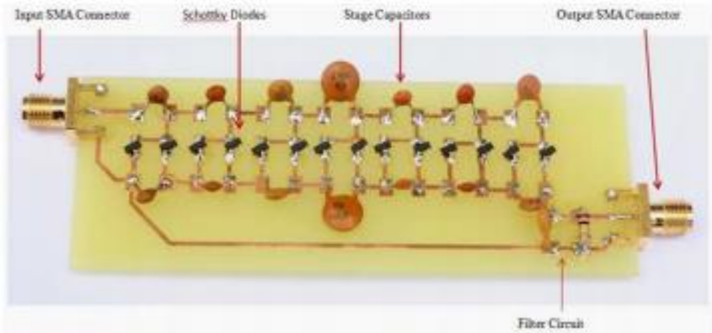

Figure 2.11 7-stage voltage doubler (Din et al, 2012)

The innovation of this design rests in the partial ground plane in the antenna structure which resulted in increasing the energy captured and producing a greater DC output voltage that can power low power devices. The energy transformation module that encompasses of 7-stages voltage doubler circuit with zero bias Schottky diodes was designed, implemented, tested and found to be resourceful in converting the RF signals captured by the antenna to the required DC output voltage for powering the temperature sensor. This design unfortunately was only applicable to a sensor network and the accumulated power was limited to pass charge to a mobile device battery.

2.17.7 Rectenna and Filter

Sakthi and Vidhya (2014) have demonstrated wireless charging of mobile phones using microwaves. The proposed circuit composed of a rectenna, a filter, sensors and a slotted wave guide antenna operating at a frequency of 2.45GHz (figure 2.12).

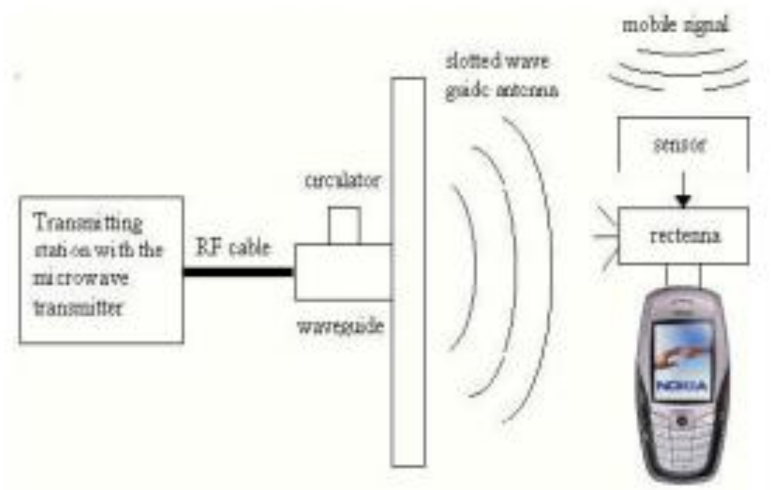

Figure 2.12 Rectenna with sensors (Sakthi and Vidhya, 2014)

This method requires the rectenna circuit and sensors to be embedded in the phone circuitry. The structure includes Schottky diodes that rectify the current entering into the antenna by the microwaves. The antenna accumulates the microwave signals and directs these signals to the sensors in the mobile phone. The rectenna converts these microwave signals into power to charge the battery. The limitation of this development is that the mobile phone needs to be switched on all the time for the sensors to function. And the sensors will consume power as well.

Similar design was proposed by Rewaskar and Datar (2014) and also included a slotted wave guide antenna operating at a frequency of 2.4GHz, a rectenna and sensors (figure 2.13).

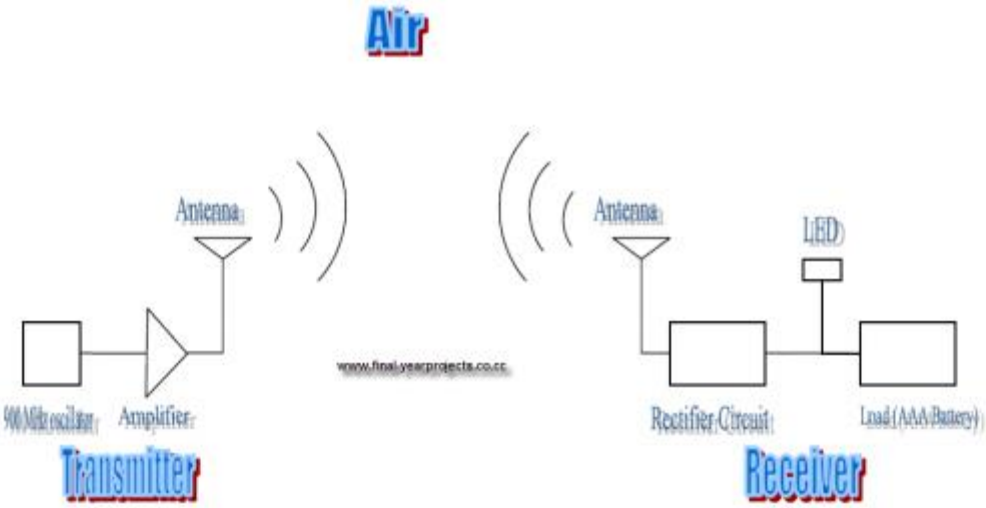

Figure 2.13 Transmitter and receiver structure (Rewaskar and Datar, 2014)

2.17.8 LC Tuning Circuit and Supercapacitor

Aminov and Agrawal (2014) had proposed the LC tuning circuit comprising of 5-stage Villard voltage multiplier circuit and using the supercapacitor to store the energy (figure 2.14).

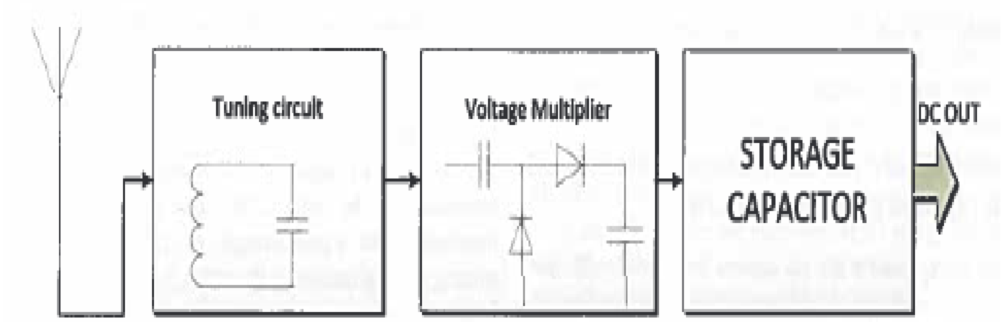

Figure 2.14 LC Tuning Circuit, voltage multiplier and supercapacitor (Aminov and Agrawal, 2014)

The design included a loop antenna tuned to 1230 AM and the parallel to the capacitor. The voltage multiplier circuit raised the voltage from the RF signal. The difference of this design compared to the previous circuit designs mentioned was the addition of the supercapacitor to store the converted power and the limitations seen with this proposal was the RF energy was acquired from the AM frequency band and this limited the portability of the antenna. This structure was also applicable and limited to the sensor network.

2.17.9 Oscillator by L-C Circuit

The research study by Sayem and Afrin (2015) was based on WPT and the model proposed was based on the magnetic resonance (figure 2.15). This design includes two self-resonant coils in which the source coil is fixed inductively to an oscillating circuit and the device coil is fixed inductively to a resistive load.

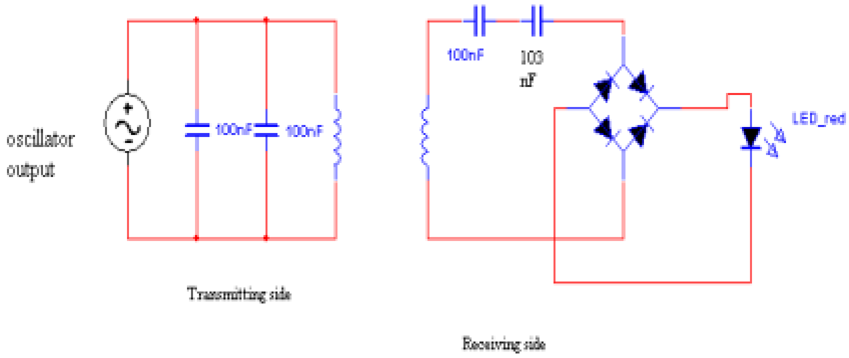

Figure 2.15 Oscillator using resonance (Sayem and Afrin, 2015)

The proposed design saw the limitation of low range and low efficiency. Major factor to consider is the decay constant of the coils. This model is applicable to wireless sensor network. This model was not developed in its entirety due to the limitation of the available equipment.

2.17.10 Spike based RFID System

The proposed design created by Machnoor, Gaggatur and Sanjeev (2015) also included an oscillator but was limited to RFID communication (figure 2.16). This design was compared to chipless RFID systems and was seen to not require a wideband pulse reader to simplify the RFID reader structure.

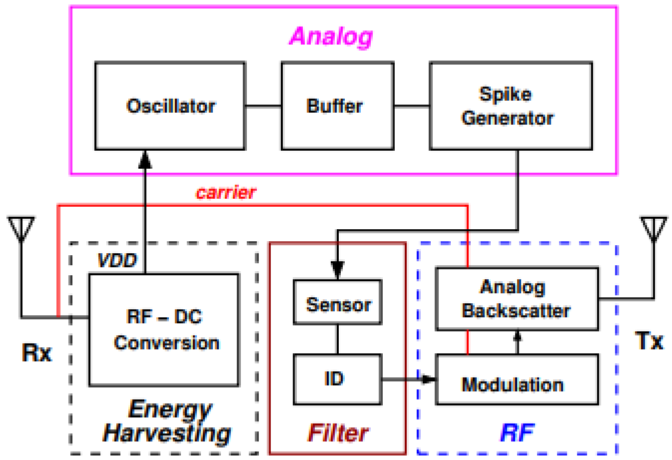

Figure 2.16 Spike Based RFID system (Machnoor, Gaggatur and Sanjeev, 2015)

The limitation compared with the current research study was the design is only applicable to RFID communication systems comprising of sensors and ID information. It does however include an energy harvesting circuit to keep the system operational.

2.17.11 GSM 3 Band Antenna for RF Energy Harvesting

Batchelor and Taylor (2012) have contributed to the further development of RF energy harvesting with the model depicted in figure 2.17. Their proposed design included a supercapacitor of storing the harvested energy and a three band antenna operating at the following frequencies, 1.8GHZ, 920MHZ and 2GHz. The antenna could capture signals operating on those frequencies. This model practically focused on developments in antenna design efficiency in energy harvesting. Limitations seen with this was the lack of focus on the detection and DC rectification of the circuit.

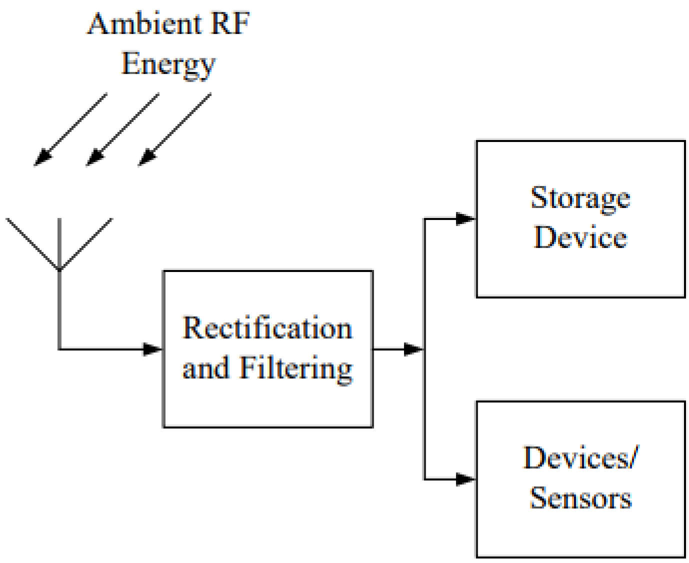

Figure 2.17 RF Rectification and Energy storage (Batchelor and Taylor, 2012)

2.17.12 Three-Stage Schottky diode based Villard Voltage-Doubler Circuit

Figure 2.18 was proposed by Gobinath, Kumar and Lenin (2014). This contribution to energy harvesting was focused on combining Bluetooth with a charging circuit. The three-stage Villard voltage circuit was designed to comprise of two Schottky diodes, capacitors and film-type antenna.

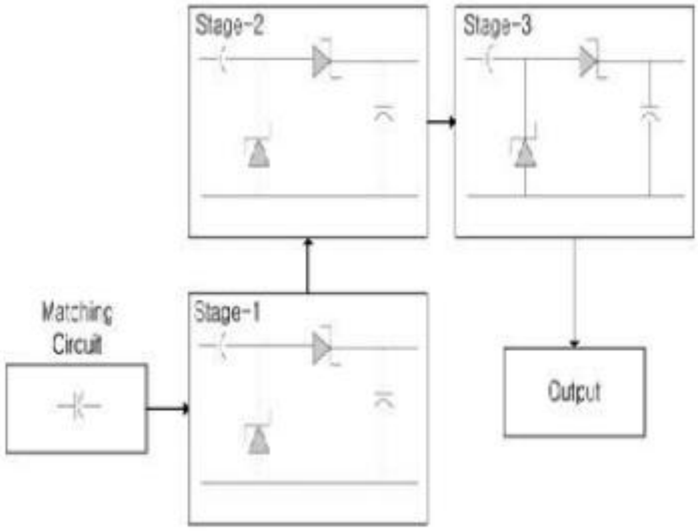

Figure 2.18 3-stage Villard circuit using a Schottky diode (Gobinath, Kumar and Lenin, 2014)

This study proved that ambient energy is not enough to acquire the charging energy, hence Bluetooth was the source of the harvested energy and this is applicable to a short range wireless charging technique. Pairing is essential for this process to work and the paring task also places a strain on the battery.

2.18 SUMMARY OF LITERATURE FINDINGS

Table 2.3 below summarises research conducted in the energy harvesting field. This entails research pertaining to WSNs, antenna designs, energy harvesting, RF energy harvesting and novel models proposed by the authors. The methods adopted in each research study and the remarks pertaining to the research are summarised.

From 2014 to 2015 extensive research was conducted on the different methods for Energy harvesting. The design of the most feasible antenna was also proposed. An interesting point mentioned in the bulk of the previous studies was based on the supercapacitor as an alternative to the battery for the storing of the accumulated energy from the energy harvester. The concept of self-sustaining WSNs is touched on elaborately and should be noted for future work.

Table 2.3 – Researcher's contributions to RF harvesting

No	Author(s)	Title	Method/design/	Remarks
1	Omar Andre Campana Escala (2010)	Study of the efficiency of rectifying antenna systems for electromagnetic energy harvesting	Rectification circuit with polarised aperture coupled patch antenna	Indoor measurements for testing the workable range of the system was lacking – useful for wireless sensors
2	Sivaramakrishnan and Jegadishkumar (2011)	A highly efficient Power Management System for Charging Mobile Phones using RF Energy Harvesting	Voltage doubler circuit	Generates minimum rectified output voltage. Needs to be increased by reducing the capacitance values and

				increasing the voltage multiplier stages.
3	Gabrillo, Galesand and Hora (2011)	Enhanced RF to DC converter with LC resonant circuit	An LC tank circuit using loop antennas	Useful for wireless sensors only
4	Jambek, See and Hashim (2012)	Analysis of Energy Harvesters for Powering a Wireless Sensor Node Device	Multi-energy harvester	The wireless sensor node needs to be adjusted to match the available energy
5	Nintanavongsa, P., Muncuk, U., Lewis, D.R. and Chowdhury, K.R. (2012)	Design Optimization and Implementation for RF Energy Harvesting Circuits	Double stage energy harvesting circuit based on seven stages and ten stage design	Applied to the commercial Mica2 sensor mote only
6	Pavone, D., Buonanno, A., Urso, M. and Corte, F.D. (2012)	Design Considerations for Radio Frequency Energy Harvesting Devices	2 stage voltage rectifier	Applied to a wireless sensor network
7	Din, N.M. et al (2012)	Design of RF Energy Harvesting System for Energising Low Power Devices	Single wideband 377 Ω E-shaped patch antenna, a pi matching network and a 7-stage voltage doubler circuit	It addresses only low powered sensors
8	Zungeru, A.M., Ang, L., Prabaharan, S.R.S. and Seng, K.P. (2012)	Radio Frequency Energy Harvesting and Management for Wireless Sensor Networks	Improved Energy Efficient Ant Based Routing Algorithm (IEEABR)	Based on WSNs
9	Shrestha, S., Noh, S. and Choi, D. (2013)	Comparative Study of Antenna Designs for RF Energy Harvesting	Circuit based on the patch antenna	Discusses the improvement of rectenna design to obtain better RF energy

				harvesting – not suited for mobile phone charging
10	Modupe, Olugbara, Ojo and Modupe (2013)	Experimental Comparison of Genetic Algorithm and Ant Colony Optimization to Minimize Energy in Ad-hoc Wireless Networks	Geographic Adaptive Fidelity (GAF) topology management scheme	Based on wireless ad-hoc networks only
11	Modupe, Olugbara, Ojo and Modupe (2013)	Minimizing Energy Consumption in Wireless Ad-hoc Networks with Meta heuristics	Genetic Algorithm (GA) and Simulated Annealing (SA) metaheuristics	Based on wireless ad-hoc networks only
12	Vasic and Yao (2013)	PWM Interface for Piezoelectric Energy Harvesting	Wideband electric interface based on pulse width modulation (PWM) for piezoelectric energy harvesting	Research is focused on transferring energy to a storage buffer – the application is not mentioned
13	Parks, A.N., Sample, A.P., Zhao, Y. and Smith, J.R. (2013)	A Wireless Sensing Platform Utilizing Ambient RF Energy	RF energy harvesting sensor node using a TV transmitter antenna set at 6dBi	Based on RFID and sensor nodes – not applicable for mobile charging
14	Sakthi and Lakshmi V.S. (2014)	Wireless Charging of Mobile Phones using Microwaves	Microwave signals and slotted wave antenna at frequency 2.45GHz	Involves a phone sensor and can be utilised when the phone is active or in operation – is not tested to charge mobile phones
15	Rewaskar, P.A. and Datar, D. (2014)	Wireless Charging of Mobile Phone	Microwave signals and slotted wave 16antenna at	Practical possibilities are not yet

		Using Microwave	frequency 2.45GHz	applicable in this field
16	Kumar, A. and Kumar, S. (2014)	Energy Saving Model and Application for Smart Phones	Optimization of battery life	The method suggested limited to Android users
17	Lu, X., Niyato, D., Wang, P., Kim, D. and Han, Z. (2014)	Wireless Charger Networking for Mobile Devices: Fundamentals, Standards and Applications	Review of charging standards Qi and A4WP	Is not applicable for charging mobile devices
18	Xu, X., Shu, L., Guizani, M., Liu, M and Lu, J. (2014)	A Survey on Energy Harvesting and Integrated Data Sharing in Wireless Body Area Networks	WBANs	Only focused on wireless body area networks
19	Sharma and Balaji (2014)	Investigating Techniques and Research Trends in RF Energy Harvesting	Review of the trends in RF energy harvesting	Concludes the limited work from 2011 to 2014.
20	Aminov, P and Agrawal, J.P. (2014)	RF Energy Harvesting	LC tuning circuit, 5-stage of Villard voltage multiplier and super capacitor for storage purpose	The strength of the RF field affects the energy accumulated – practical applications are not evident for mobile charging
21	Lenin, A. and Abarna, P. (2014)	Design and Simulation of Energy Harvesting System Using GSM Signal	A Seven stage Villard Voltage multiplier circuit was designed - electromagnetically-coupled E- Shaped microstrip antenna	Not benchmarked
22	Gobinath, J., Kumar, M.V. and Lenin, M. (2014)	Short Range Wireless Charging System for Smart Phone through New Energy	Schottky diode with film type antenna.	Focused on using Bluetooth and not ambient RF energy

		Harvesting Circuit		
23	Prasad, K. S. S. (2014)	An Efficient AC-DC Step-Up Converter for Low-Voltage Piezoelectric Micro Power Generator Energy Harvesting	Sepic converter and a cuk converter	Applicable to micro generator
24	Sayem, A.S. and Afrin, H. (2015)	Wireless Power Transfer via Strongly Coupled Magnetic Resonance	Magnetic resonant coupling	Applicable to wireless sensor networks only
25	Hamid, S., Nyakoe, N.G. and James, K.N. (2015)	Energy Harvesting and Optimisation from Ambient RF Sources: A Review	Review of RF sources	FM source is limited
26	Machnoor, M., Gaggatur, J.S. and Sanjeev, K. (2015)	Design of a spike-based architecture for Energy Harvested RFID-system	Rectifier circuit and receiving antenna – TV broadcast transmitters	Limited to RFID
27	Lu, X., Flint, I., Niyato, D., Privault, N. and Wang, P. (2015)	Performance Analysis of Simultaneous Wireless Information and Power Transfer with ambient RF Energy Harvesting	SWIPT system	Not applicable to charging mobile devices
28	Ansari, T.R., Khan, A. and Ansari, I. (2015)	Wireless Charging of Mobile Battery via Optimisation of RF Energy Harvesting System	Greinacher voltage doubler circuit – ADS simulation	Prospective alternative to charging mobile device batteries
29	Batchelor, J. and Taylor, P.S.	Radio Frequency Harvesting Project	Design of a 3 GSM band antenna for RFEH	Focused on antenna design – Focused on alternative storage

				compared to a battery
30	Hossain, E. and Hasan, M. (2015)	5G Cellular: Key Enabling Technologies and Research Challenges	5G network technologies	Difficult to integrate RF energy harvesting into 5G technology
31	Ulukus, S., Yener, A., Erkip, E., Simeone, O., Zorzi, M., Grover, P. and Huang, K. (2015)	Energy Harvesting Wireless Communications: A Review of Recent Advances	Self-sustaining energy harvesting	Focused mainly on wireless networks
32	Kamalinejad, P., Mahapatra, C., Sheng, Z., Mirabbasi, S., Leung, V.C.M. and Guan, L.Y. (2015)	Wireless Energy Harvesting for the Internet of Things	Power Management Unit (PMU)	Focused on WEH-enabled IoT devices to reduce energy consumption
33	Mishra, D., De, S., Jana, S., Basagni, S., Chowdhury, K. and Heinzelman, W. (2015)	Smart RF Energy Harvesting Communications: Challenges and Opportunities	RFH hardware advances - MIMO	Challenge with time, phase and frequency synchronisation
34	Zeng, M., Andrenko, A.S. , Tan, H., Lu, C. and Liu, X. (2016)	Fractal Loop Antenna with Novel Impedance Matching for RF Energy Harvesting	Koch fractal loop antenna at GSM1800 band	Only focused on design of antenna – design with the rectifier circuit is noted as future work
35	Ku, M., Li, W., Chen, Y. and Liu, K. J.R. (2016)	Advances in Energy Harvesting Communications: Past, Present, and Future Challenges	Review of cooperative, cognitive radio, multi-user and cellular networks	Challenges in each structure highlighted and research gaps stated
36	Liu, X., Hu, F., Shao, M. Sui, D. and He, G. (2017)	Power Allocation for Energy Harvesting in Wireless Body Area Networks	Lagrange multiplier method	Limited to WBANs to optimise sensors
37	Zhai, C., Zheng, L., Lan, P., Chen,	Decode-and Forward Two-	Cooperative relaying network	Focused on energy

	H. and Xu, H. (2017)	Path Successive Relaying with Wireless Energy Harvesting	using two half-duplex relays	harvesting sensors in wireless networked control systems
38	Al-Qamaji, A. and Atakan, B. (2017)	On Exploiting Spatial Correlation for Energy Harvesting Wireless Sensor Networks	Event Distortion-Based Node Selection (EDNS)	Limited to sensor nodes
39	Xu, X., Ozcelikkale, A., McKelvey, T. and Viberg, M. (2017)	Simultaneous Information and Power Transfer under a Non-Linear RF Energy Harvesting Model	SWIPT system	Applicable to WSNs
40	Sangare, F. and Han, Z. (2017)	Joint Optimization of Cognitive RF Energy Harvesting and Channel Access using Markovian Multi-Armed Bandit Problem	5G multi-channel cognitive radio system	Applicable to WSNs
41	Celik, A., Alsharoa, A. and Kamal, A.E. (2017)	Hybrid Energy Harvesting-Based Cooperative Spectrum Sensing and Access in Heterogeneous Cognitive Radio Networks	Hybrid energy harvesting secondary users (EH-SU) model - can harvest energy from both renewable sources, e.g., solar, and ambient radio frequency signals	Applicable to Cognitive radio networks (CRNs)
42	Zeng, M., Andrenko, A.S., Liu, X. and Tan, H. (2017)	A Compact Fractal Loop Rectenna for RF Energy Harvesting	Fractal loop antenna proposed with rectenna design	Applicable to battery-less LCD watch

Table 2.4 summarises the contributions made by industry towards RF energy harvesting. These studies seem more focused on RF harvesting for mobile devices however these are limited to the devices or embedded circuits for the proposed devices, however these contributions shows a promising advancement in the research within RF energy harvesting for mobile devices.

Table 2.4 – Industry contributions to RF harvesting

No.	**Author(s)**	**Title**	**Method/design/approach**	**Remarks**
1	Duncan Graham-Rowe (2009)	Wireless Power Harvesting for Cell phones	RF harvesting on the Nokia device using 2 passive circuits	This is limited to the Nokia mobile phones only - embedded
2	Andy Patrizio (2015)	Energous shows wireless charging via Bluetooth	Proposed WattUp	The use of Bluetooth – securing devices is an issue on WiFi network
3	Shah, A. (2015)	Researchers claim to boost cell phone battery life with radio signals	Energy harvesting circuitry using a rectifier	Embedded in the iPhone6 only by Nokia labs
4	Gilbert, D. (2015)	WiFi routers can wirelessly charge batteries, cameras and sensors	Power-over-Wi-Fi/ PoWi-Fi	Limited to 1W power output – applicable to sensors.
5	Titcomb, J. (2016)	The search for a better battery: Is a solution near?	Lithium-superoxide battery	Commercial applications not stated

2.19 CONCLUSION

In the study conducted by Harrist (2004), the foundation for charging a cellular phone battery while in a phone using wireless RF energy harvesting had been laid. However a charging stand was implemented in the charging of the mobile phones so some contact with the mobile phone had to be established. And this was implemented over 10 years ago, technology and the mobile devices have changed drastically from that time till date.

The concept of RF energy harvesting utilising the antennas conducted previously by Sivaramakrishnan & Jegdishkumar (2011) is looked at for this research.

Researchers at Ohio State University have developed circuitry that converts radio signals from a handset into energy, which is then fed back to the device's battery. The researchers declare the technology can increase the battery life of mobile devices by up to 30 percent. This is limited to only the iPhone6 (Shah, 2015).

From the research papers reviewed it is evident that RF harvesting is an energy-efficient method to charge mobile devices since this consists of collecting free energy and converting it into DC signals to be used to charge the mobile devices battery. Present technologies, such as solar photovoltaics and wind turbines can create energy in a sustainable and ecologically friendly manner yet their sporadic nature still prevents them from becoming a primary energy carrier. Energy storage technologies have the potential to counterbalance the intermittency issue of renewable energy sources then making it available upon demand.

Compared to the limitations of the charging in the research previously conducted, using the RF harvesting system to implement this wireless wire-free or contact free charging over a larger distance is seen as innovative and much needed.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter presents an important aspect of the RF energy harvesting through mathematical modelling method. The study focuses on a mathematical model of the components that are based on the energy harvesting circuit. The research method is explained and the components of the initial RF energy harvesting model are explained. The chapter further describes the simulation software used during this research.

Research refers to a search for knowledge. One can also define research as a scientific and systematic search for pertinent information on a specific topic. Research can be summarised as an art of scientific investigation (Department of Defense, 2009).

Modelling and simulation (M&S) refers to using models physical, mathematical, or otherwise, as a logical representation of a system, entity, phenomenon, or process. This forms a basis for simulation methods for implementing a model (either statically or) over time, to develop data as a basis for managerial or technical decision making. M&S assists in acquiring information about how something will behave without actually testing it in real life (Department of Defense, 2009).

The use of M&S within engineering is well recognized. Simulation technology belongs to the tool set of engineers of all application domains and has been included in the body of knowledge of engineering management. M&S helps to reduce costs, increase the quality of products and systems, and document and archive lessons shared (Department of Defense, 2007).

The reasons for adopting the mathematical modelling method is based on this research being of an engineering type. Mathematics has the potential to prove general results, these results depend critically on the form of an equation used. Mathematical models can accommodate for small changes to be made to the equation and not enormous changes to the entire system (Marion and Lawson, 2008).

3.1 Mathematical Modelling and Simulation

Research method adopted for this study was based on quantitative research in mathematical modelling and simulation. The experimental test results were quantified to provide a solution. Variables considered were distance, device and amount of energy harvested based on the feasibility of the circuit model.

Simulation models were chosen since it can be used to compress the time frame to acquire the necessary components for the circuit. The RF harvesting concept was difficult to investigate being a complex system and was based on engineering a prototype, simulation of the design made it easier to cater for changes in the circuit design without physically building a circuit each time.

Mathematical modelling allows finding out the most essential characteristics of the object studied and abstracting away from non-essential ones. Modelling provides the basis for formulating hypotheses and to gain new knowledge about the object which were unavailable before. This research method provides a low cost approach which are required for direct study.

A construction of a model and formalisation of relations often removes gaps in knowledge about the object and move forward novel quality problems, which could not be formulated beforehand. Authors of the model can build the desired result implicitly or explicitly into its structure, which would guarantee the confirmation of the proposed hypothesis (Marion and Lawson, 2008).

3.1.1 Advantages of using models:

A model serves as a blueprint for new systems or processes, or may be used to evaluate existing systems or processes. Olivier (2009) summarises the following reasons for using a model approach: a simple model makes it possible to comprehend the essence of the modelled concept; comprehensiveness in models systematically addresses most of the research problem, because the model prevents one from getting lost in the detail of the actual problem; the model has the capacity to address variations of the problem; if the model fits the perceived problem closely it is more likely to be accepted; the purpose of all components or facets of the model, the operation or use of each facet, and the interaction or flow between components should be evident.

Mathematical models are simplified representations of some real world entity, can be in equations and are intended to mimic essential features while leaving out inessentials. Mathematical models are characterised by assumptions about: variables (the things which change); parameters (elements of a system that is useful, or critical, when evaluating its performance, status, condition, etc.); functional forms (the relationship between the two).

The following variables were considered in proving the theory on the possibility of RF energy harvesting; the type of mobile device; the transceiver being used, the circuitry of the mobile device and the signal strength of the receiving antenna and the size of the battery.

The mobile device, the transceiver and the antennas being used are the parameters; frequency selection, the signal strength, distance and size of the battery are the variables; and the functional forms are between signal strength and the receiving antennas also the relationship between the distances of the mobile device battery to the energy source to receive the charge.

According to Taylor (2012) super capacitors store energy by physical-charge storage, not chemically as in batteries, so super capacitors have effectively infinite cycle life.

3.2 RESEARCH METHOD

Figure 3.1 represents research method adopted for this study and it is based on theblock diagram for the energy harvesting system. The received RF signals are converted to electrical power via the RF energy harvester circuit. The power management module sends this converted electrical power to be stored or used by the application or computing device via the low-power microcontroller as needed. The power is transferred to the application using the RF transceiver antenna.

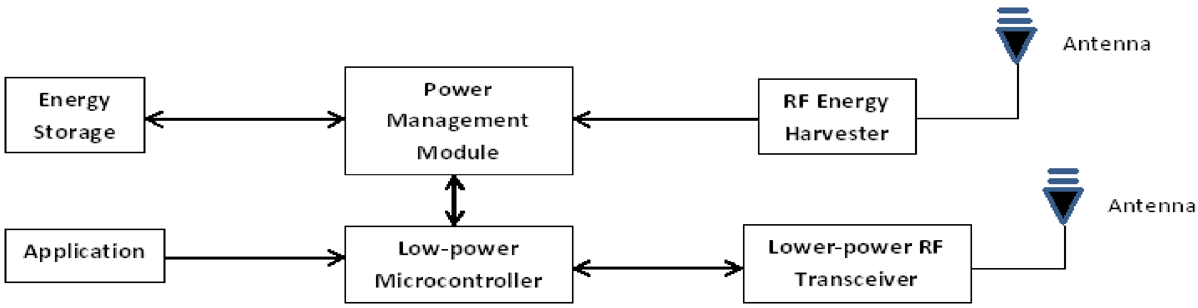

Figure 3.1 Block diagram of the Energy Harvester (Sivaramakrishnan and Jegadishkumar, 2011)

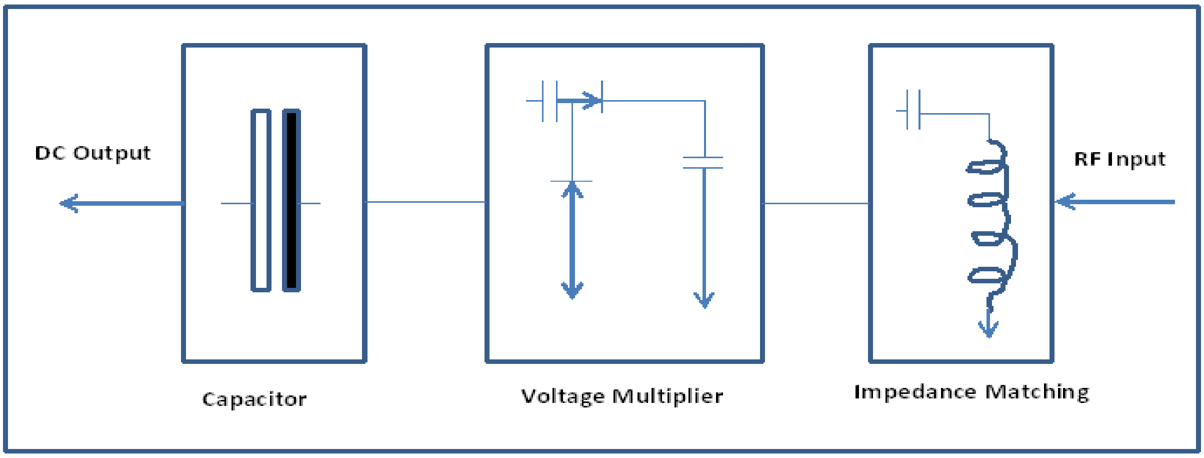

Figure 3.2 Block diagram of the Energy harvesting circuit (Sivaramakrishnan and Jegadishkumar, 2011)

Figure 3.2 represents the block diagram for the actual energy harvesting circuit in the harvesting system. The received RF power of an antenna is streamed through the rectifier circuit and then through a power converter circuit which increases the rectified voltage. Finally the converted output DC power can be used for charging the mobile device battery. The significance of the Impedance matching circuit is to match the impedance of antenna with that of the rectifier circuit. This achieves higher efficiency in attaining the output power. According to the study conducted by Sivaramakrishnan and Jegadishkumar (2011), by using the impedance transformation circuit, operation of the circuit is restricted to a specific frequency range of 0.9GHz – 1.8GHz which is an operating band for mobile communication.

3.3 COMPONENTS FOR THE MODEL

3.3.1 Antenna Design

An antenna is essentially a conductor visible in space. If the dimension of the conductor is a particular ratio or multiple of the wavelength of the signal, it becomes an antenna. This state is called resonance, as the electrical energy delivered to the antenna is discharged into free space.

The purpose of an antenna is dependent on its surrounings. Whether it is placed on a desk, on a manufacturer's development board, or visible for a product, all three scenarios result in different routine. Unlike most components in a design structure that can be released with a predictable result in the circuit, an antenna is affected by all around it. The radiated electromagnetic fields from an antenna interrelate with proximate materials, and can change its frequency of operation. The antenna must be placed in its closing environment and impedance matched so that it functions in the chosen frequency band. A poorly matched antenna can degrade by 10-30 dB and harshly reduce range. All antennas, whether purchased or designed in a lab may need matching.

Lienau (2012) provided clarity on why an antenna is affected by objects near it, the operation of an antenna must be reviewed. As stated in the article, firstly focus should not be on what is happening to the antenna or what is nearby, the focus should be on the input impedance of the antenna. When a potential is applied to the antenna inputs there is opposite charge build-up on the ends. Essentially the dipole ends can be viewed as open circuits, with a high voltage and no current. Due to the charge build-up at either end of the dipole, current begins to flow. As one moves from the end of the dipole inwards towards the feed point, the voltage falls and the current rises. At the feed point the current reaches its peak along with some now reduced voltage. The ratio between the voltage and current at the feed point is the input impedance of the antenna. This is the impedance that drives the antenna performance. Additionally, since there is current flow on the antenna, electromagnetic fields are radiating.

3.3.2 Impedance matching

Impedance Matching was initially established for electrical power, and is also applicable to any other field in which a form of energy (other than electricity) is conveyed between a source and a load. The foremost impedance matching idea in RF field was linked to antenna matching. Construction of an antenna is seen as matching the open space to a transmitter or a receiver.

The focal purpose of impedance matching is to match two dissimilar ends, the source and the load (Rsource and RLoad) via a definite pass-band, lacking the control over stop-band frequencies (Pues and Capelle, 1989).

In electronics, impedance matching is concerned with the exercise of creating the input impedance of an electrical load or the output impedance of its matching signal source to capitalize on the power transfer or lessen signal replication from the load.

The conception of impedance matching originated in electrical engineering applications, but is pertinent in additional applications in which a form of energy that need not be electrical, is conveyed amid a source and a load. Impedance bridging is seen as a substitute to impedance matching, in which the load impedance is selected to be much greater than the source impedance and increasing voltage transmission, rather than power, is the objective (Pues and Capelle, 1989).

3.3.3 RF Antenna Tuning

Antennas can be tuned using the following methods; either by regulating the measurements or with a matching network characteristically containing isolated components. Normally altering physical dimensions is not a choice, so a distinct network is positioned just former to the antenna response. The trial with tuning an antenna is that its impedance is affected by neighbouring materials. If the antenna is tuned to 2.4 GHz on the counter and thereafter it is placed in an enclosure, the tuned frequency will change. Figure 3.3 below proves this outcome. The red line denotes unmatched antenna in free space. The green line signifies the identical antenna now matched in free space. And the blue line is the concluding antenna reaction with it placed in the enclosure. Since the antenna was not tuned in the enclosure the impedance is not matched to the 50 Ohm PCB trace line over the frequency of interest. The antenna essentially should be tuned in the enclosure to allow for the changes in impedance to be accounted for (Firrao, Annema and Nauta, 2008; Lienau, 2012).

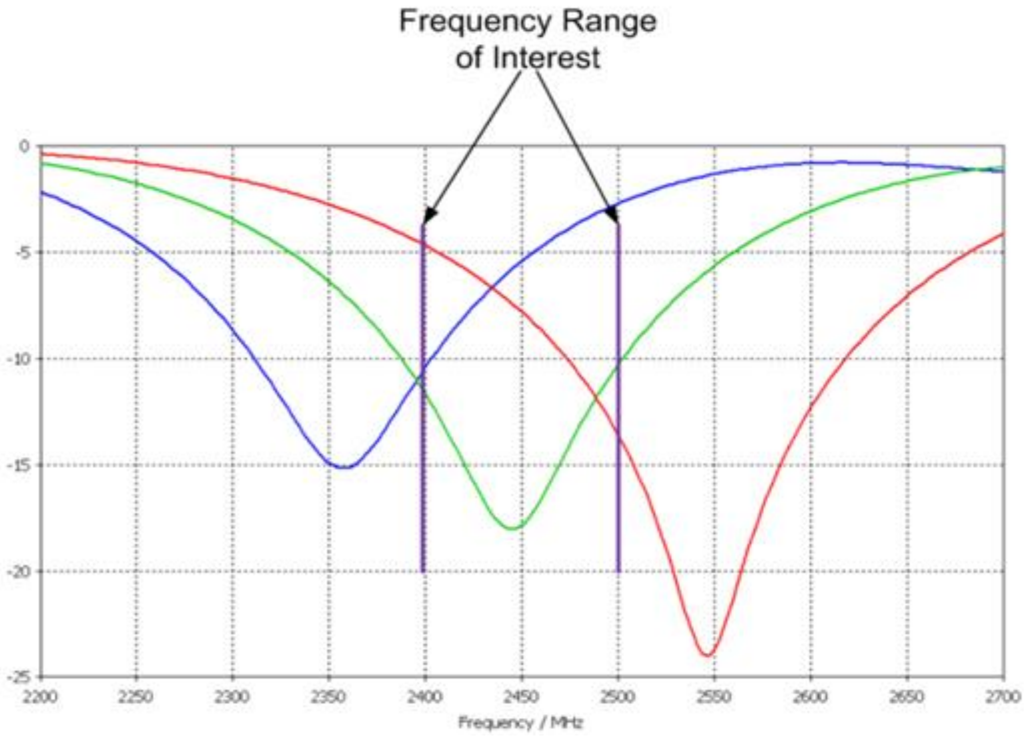

Figure 3.3: Frequency Shift of Antenna due to Mismatch (Lienau, 2012)

All materials affect the antenna differently. For instance, a shared mistake is to use a prototype enclosure that is alike in size and shape but not complete of the same production quality material. Even by altering the PCB material a trace antenna is reproduced on, can cause the impedance match to change. The tuning of the antenna must always be rechecked if anything in the enclosure has changed, even objects several centimetres away can have an impact.

When deciding on a position for the antenna in the model, the following points were considered: the enclosure; objects near the antenna; the evidence of metal nearby and the device usability. The purpose of the antenna must be taken into consideration before tuning it since this will impact on the tuning. Additionally, the final use of the model must should be considered.

The most effective method to anticipate antenna tuning and radiation problems is to use simulation software to evaluate and predict the effects of an enclosure. An antenna designer must identify the materials in the product, define their electrical properties, and understand how the antenna will interact with them. A well designed and simulated antenna will usually require no matching network; however, it will only be tuned correctly for the exact product it was designed for (Lienau, 2012).

3.3.4 Antenna Selection and Placement

Lienau (2012) further explains the antenna selection and placement can be a difficult task, and the challenges of implementing the antenna are not over once it’s placed on the board. As previously stated earlier in this chapter, the enclosure affects the antenna match. The process of matching an antenna can be a very complicated process. Not only is an in-depth knowledge of RF principles and components needed, but proper technique and understanding of the antenna properties is required. Any error introduced into the measurement while matching the antenna will ultimately reduce the effectiveness of the antenna and its performance. For this reason, as much care should be taken in the setup of your measurements as the actual matching process itself.

The key to successfully matching an antenna is maintaining accuracy in the measurement. Good grounding of the coaxial shield, proper solder location of the feed line, and knowledge of your component are all very important. Small inaccuracies can easily result in an engineer designing the wrong matching network for an antenna.

Figure 3.4 represents the Global System for Mobile (GSM) communication antenna coverage throughout the world. GSM forms the most popular standard for mobile phones in the world. GSM 900 / GSM 1800 MHz is used in most parts of the world: Europe, Asia, Australia, Middle East and Africa. GSM 850 / GSM 1900 MHz is used in the United States, Canada, Mexico and most countries of South America.

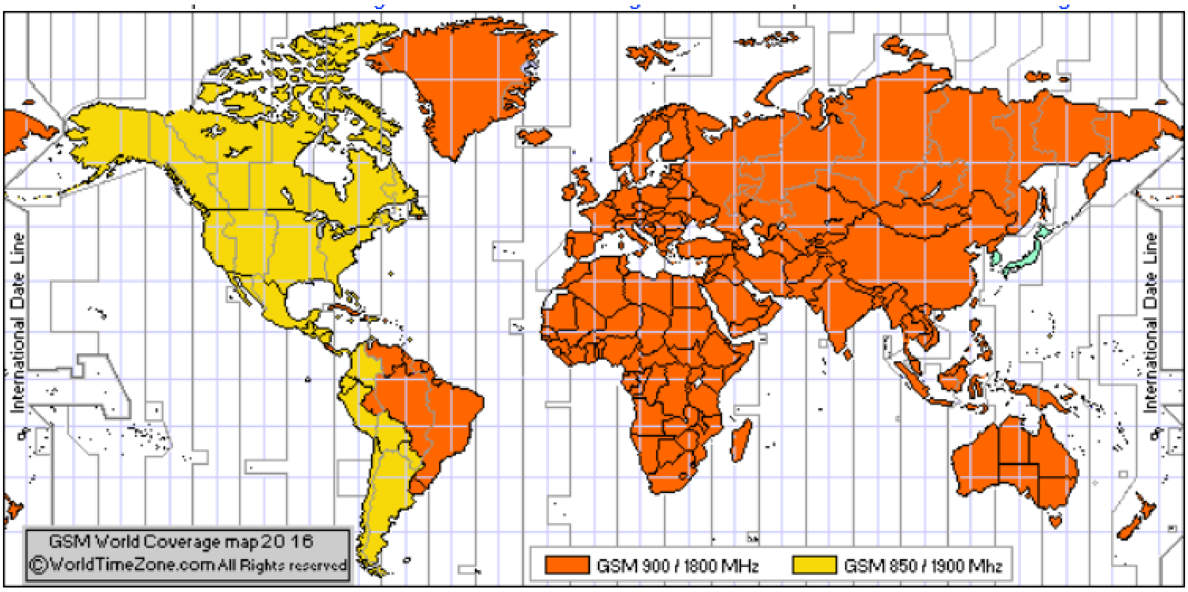

Figure 3.4 GSM World coverage map (GSM Coverage, 2016)

Table 3.1 is based on the frequency bands available in South Africa as well as the types of networks the frequency bands operate in. This research focused on gaining energy utilising the GSM antenna from the frequency available in the table below. Frequencies are set by law to operate within a particular range.

Table 3.1 Frequency bands in South Africa (GSM Coverage, 2016)

South Africa	900	1800			3G 2100 Cell C; 3G 900/2100 MTN-SA; 3G 2100 Telkom; 3G 2100 VodaCom;	4G LTE VodaCom 1800Mhz; 4G LTE MTN-SA 1800Mhz; 4G LTE Neotel 1800Mhz; 4G LTE Telkom-8ta 2300Mhz; 4G LTE Cell C;

3.3.5 The Friis Transmission Equation.

Figure 3.5 represents the derivation of the Friis equation for the operation of the antennas for receiving and transmitting RF signals ((Ismail, 2008). The antennas Tx (transmitting) and Rx (receiving) are in free space with no obstructions nearby are separated by a distance *R*:

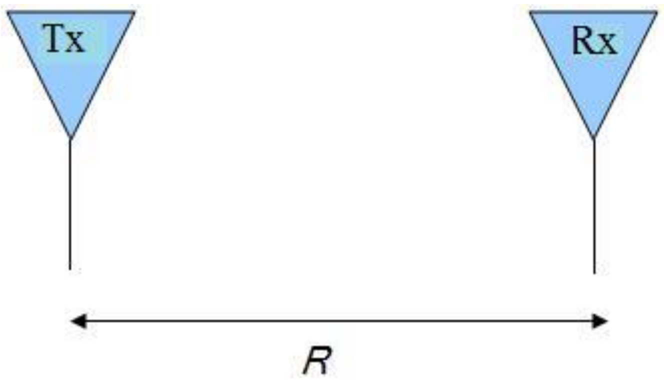

Figure 3.5 Transmit (Tx) and Receive (Rx) Antennas separated by *R* (Ismail, 2008)

The Friis Transmission Equation (equation 3.1) is used to calculate the power received from one antenna with gain Gr, when transmitted from another antenna with gain Gt, separated by a distance *r*, and operating at frequency for wavelength lambda λ. This is given by the following equation 3.1:

$$\frac{\mathrm{Pr}}{Pt} = GrGt\left(\frac{\lambda}{4\pi r}\right) \tag{3.1}$$

"where Gt and Gr are the antenna gains with respect to an isotropic radiator of the transmitting and receiving antennas respectively, λ is the wavelength of the antenna and *r* is the distance between the antennas". Pt is the transmitted power and Pr is the received power of the antennas. The opposite of the third factor results in the loss of the signal strength within line of sight of the antennas. The antennas used in the energy harvesting circuit for this research must be tuned to 0.9 – 1.8 GHz for mobile charging.

The antennas are in unobstructed free space, with no multipath. The antennas are correctly aligned and have the same polarization. The bandwidth is narrow enough that a single value for the wavelength can be assumed (Shaw, 2013).

A study conducted by Shaw (2013) further states that the ideal conditions are difficult to achieve in ordinary terrestrial communications, due to obstructions, reflections from buildings, and most importantly reflections from the ground. One situation where the equation is reasonably accurate is in satellite communications when there is negligible atmospheric absorption; another situation is in anechoic chambers specifically designed to minimize reflections.

3.3.6 Equation for voltage loss

The determination of voltage loss was necessary in this study because the circuit layout with the least voltage ripple is the most feasible for the design of the final rectifier circuit. Equation 3.2 (Copello, 2014) is used to calculate the voltage loss (ripple) of the half-wave rectifier circuit compared to the full-wave rectifier circuit:

$$V_r = \frac{I_v}{f \times c} \tag{3.2}$$

where V_r is the voltage ripple, I_v is the input voltage, f is the antenna frequency and c is the capacitance value of the capacitor in the circuit. To compare the half wave rectifier circuit to a full wave rectifier circuit, the voltage ripple (loss) can be computed for the two circuits by equation 3.2. Accordingly, for a half wave circuit with I_v of 1V, frequency of the antenna at 908 kHz and a capacitance of 100 farads the resulted voltage ripple is 0.110mV. In comparison to the voltage ripple of a full wave rectifier circuit with input voltage set at 1V and twice frequency and capacitance, the computed result is a lower voltage ripple of 0.055mV. A half wave rectifier circuit shows more voltage ripple than a full wave.

3.3.7 Capacitor

Capacitors are used in the circuit to smooth the rectified current and to store charge. The following capacitors were used in the initial RF harvesting circuit and the simulation; ceramic capacitors and supercapacitors (studyelectrical.com). Capacitance is the ability of a circuit to store charge. The capacitance is calculated using equation 3.3 below:

$$Cp = \frac{Cc}{Va} \tag{3.3}$$

where Cp is the capacitance and is expressed in Farads, Cc is the charge on the conductor and Va is the potential applied across the conductor. Equation 3.4 below is used when capacitors are connected in series:

$$\frac{1}{Cps} = \frac{1}{Cp1} + \frac{1}{Cp2} + ... + \frac{1}{Cpn} \quad (3.4)$$

Equation 3.5 below is used for capacitors connected in parallel:

$$Cpa = Cp1 + Cp2 + ... + Cpn \quad (3.5)$$

The above stated equations were used to determine the most effective layout of the components in order to gain maximum charge. Capacitors can be used as a storage of energy compared to the mobile device battery.

According to an article by Miret (2013) it is stated that energy storage is the main aspect of generating ecological energy systems. The storage system of a supercapacitor was compared to a normal mobile device battery. Presently leading energy storage is the battery, predominantly the lithium-ion. Lithium-ion battery power practically every portable electronic device as well as almost every electric car, including the Tesla Model S and the Chevy Volt. Batteries store energy electronically, where chemical reactions discharge electrical carriers that can be removed into a circuit. The charge and discharge method in batteries is a slow process and can degrade the chemical components inside the battery over time. The end result is, batteries have a low power density and lose lifespan due to the material damage.

The supercapacitor uses a diverse storage mechanism. In the supercapacitor energy is stored electrostatically on the surface of the material and does not involve chemical reactions. Assumed their essential mechanism, supercapacitors can be charged swiftly, leading to a precisely high power density and do not lose their storage abilities over time. Supercapacitors are be able to last for millions of charge / discharge cycles devoid of losing energy storage capability.

The disadvantages associated with supercapacitors are the cost, the supercapacitor materials exceed the cost of battery materials due to the increased difficulty in creating new supercapacitor materials. Improving on material production methods will bridge the energy density gap for some commercial applications. The other shortcoming is the low energy density, the amount of energy supercapacitors can store per unit weight is very small, particularly when compared to batteries (Miret, 2013).

3.3.8 Diodes

Rectifier diodes are electronic devices that are used to control the current flow direction in an electrical circuit. Two commonly used materials for diodes are germanium and silicon. While both germanium diodes and silicon diodes perform similar functions, there are certain differences between the two that must be taken into consideration before installing one or the other into an electronic circuit (Millman and Grabel, 1987).

3.3.8.1 Silicon Diodes

The construction of a silicon diode starts with purified silicon. Each side of the diode is implanted with impurities (boron on the anode side, arsenic or phosphorus on the cathode side), and the joint where the impurities meet is called the p-n junction.

Silicon diodes have a forward-bias voltage of 0.7 Volts. Once the voltage differential between the anode and the cathode reaches 0.7 Volts, the diode will begin to conduct electrical current across its p-n junction. When the voltage differential drops to less than 0.7 Volts, the p-n junction will stop conducting electrical current, and the diode will cease to function as an electrical pathway.

Because silicon is relatively easy and inexpensive to obtain and process, silicon diodes are more prevalent than germanium diodes (Millman and Grabel, 1987).

3.3.8.2 Germanium Diodes

Germanium diodes are manufactured in a manner similar to silicon diodes. Germanium diodes also utilize a p-n junction and are implanted with the same impurities that silicon diodes are implanted with. Germanium diodes, however, have a forward-bias voltage of 0.3 Volts.

Germanium is a rare material that is typically found with copper, lead or silver deposits. Because of its rarity, germanium is more expensive to work with, thus making germanium diodes more difficult to find (and sometimes more expensive) than silicon diodes (Millman and Grabel, 1987).

3.3.8.3 Diodes to use

Germanium diodes are “best used in low-power electrical circuits”. “The lower forward-bias voltage results in smaller power losses and allows the circuit to be more efficient electrically”. “Germanium diodes are also appropriate for precision circuits, where voltage fluctuations must be kept to a minimum”. “However, germanium diodes are damaged more easily than silicon diodes.”

Silicon diodes are excellent general-purpose diodes and can be used in nearly all electrical circuits where a diode is required. Silicon diodes are more durable than germanium diodes and are much easier to obtain. While germanium diodes are appropriate for precision circuits, unless there is a specific requirement for a germanium diode, it is typically preferable to use silicon diodes when fabricating a circuit (Millman and Grabel, 1987).

3.3.8.4 Schottky Diode

A diode is an electronic component with asymmetric transfer characteristic, with low resistance to current flow in one direction, and high resistance in the other. A semiconductor diode is a crystalline piece of semiconductor material.

Schottky diodes: A Schottky diode is constructed from a metal to semiconductor contact. Their forward voltage drop at forward currents of about 1 mA is between

0.15 V and 0.45 V, therefore making them useful in voltage clamping applications and in the prevention of transistor saturation.

Schottky diodes are often used in high frequency applications, and specifically for the gain control stages in the RF part of a cell phone. They can also be found in power rectifiers and Solar cell applications (Future Electronics, 1968).

For the RF energy harvesting circuit model, germanium diodes and Schottky diodes was compared for efficiency using the simulation software LTSpice (Brocard, 2013).

CHAPTER 4

MODEL IMPLEMENTATION

This chapter presents the implementation of the RF energy harvesting prototype circuit of this research. The implementation uses the prototype circuit to test the possibility of harvesting RF energy, the simulation software was used to test the feasibility of the components and the appropriate layout of the circuit to gain maximum charge. The simulation software helps perform the evaluation of circuit components and most effective layout of the components and allowed the use of third party SPICE models enabling the prediction of RF harvesting circuits.

4.1 PROTOTYPE

Figure 4.1 shows the prototype of the rectifier circuit (Tesla air circuit) developed in this study since the methodology adopted is mathematical modelling. Components used in the rectifier circuit prototype were 2 x 100Mf capacitor, 2 x ceramic diodes and 4 x germanium diodes. The antenna used here was the copper wire antenna.

The prototype was developed to test for the feasibility of capturing RF signals and the amount of energy that can be obtained from the RF signals. The components of the prototype rectifier circuit are two ceramic capacitors, four germanium diodes and a copper straight wire antenna that converts alternating current (AC) into direct current (DC). The two ceramic capacitors store DC and the four germanium diodes allow AC to pass through to the ceramic capacitors as used in.

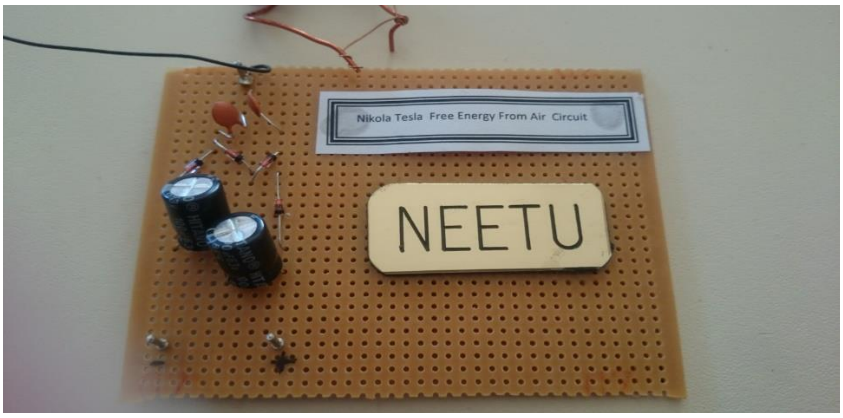

Figure 4.1: Photograph showing the prototype of the energy harvesting circuit

Due to the antenna used, the combination of diodes and capacitors, the output energy, according to the multi-meter read at 0.13mV was not enough to pass charge to a mobile device. This is because 0.5mV is required for current to pass through the selected diodes and minimum voltage required to charge the battery of a mobile device is approximately 5mV.

4.1.1 Limitations of the Prototype

The limitations of the circuit were due to the impedance transformation of the antenna being limited to a particular frequency range *viz*. 0.9GHz – 1.8GHz. This is an operating band for mobile communication. The prototype used was based on the Tesla Air circuit and the antenna used in the Tesla Air circuit was the straight wire antenna. The results of the prototype reflected that the antenna was not tuned to 0.9 – 1.8 GHz, which resulted in the low voltage obtained. Another limitation with rectifiers as seen from the prototype was that AC power has peaks and lows, which may not produce a constant DC voltage. Usually, a smoothing circuit or filter needs to be coupled with the power rectifier to receive a smooth DC current.

4.2 SIMULATION SOFTWARE

The LTspice simulation software was used for the simulation and analysis of the test results. Tools do not need to be changed by the engineer in order to completely optimise and characterise a RF plan. This is because all the steps of the design process, including electromagnetic field simulation, schematic capture, frequency-domain, layout, time-domain circuit simulations and design rule checking, are supported by LTspice (Brocard, 2013).

The benefit of using LTSpice software in circuit analysis is firstly, LTSpice is a freeware software for circuit design and analysis. It can serve as an alternate for the professional licensed software like Cadence, ADS, Altium, for study of circuit behaviour. The key analysis in circuit design like DC analysis, frequency response, n-port analysis is much simpler to simulate in LTSpice than analysing all responses theoretically which is time consuming (Brocard, 2013).

To complete the aim of this research, a theoretical analysis of the components was made and eventually built as a prototype. Thereafter, LTSpice was used to simulate the effectiveness of components to cater for the limitations found in the prototype circuit.

4.2.1 Comparison of the Diodes

A simulation experiment was conducted using the LTspice software to test the most appropriate diodes that would improve the limitations of the prototype circuit. The Schottky diodes 1N5819 and 1N5817 where experimentally compared to the Silicon diode 1N4148 for this purpose. The reason for this comparison is that the silicon diodes have a forward-bias voltage of 0.7 Volts. Once the voltage differential between the anode and the cathode reaches 0.7 Volts, the diode will begin to conduct electrical current across its p-n junction. When the voltage differential drops to less than 0.7 Volts, the p-n junction will stop conducting electrical current, and the diode will cease to function as an electrical pathway. The forward voltage drop of Schottky diodes at forward currents of about 1 mA is between 0.15 V and 0.45 V, therefore making them useful in voltage clamping applications and in the prevention of transistor saturation. The simulation software was used to prove this theory. Figure 4.2 shows the schematic diagram of the different diodes with a common resistance of 1mA. A direct current (DC) sweep test was conducted on the LTspice simulation software where the DC operating point of the circuit is computed on the individual components.

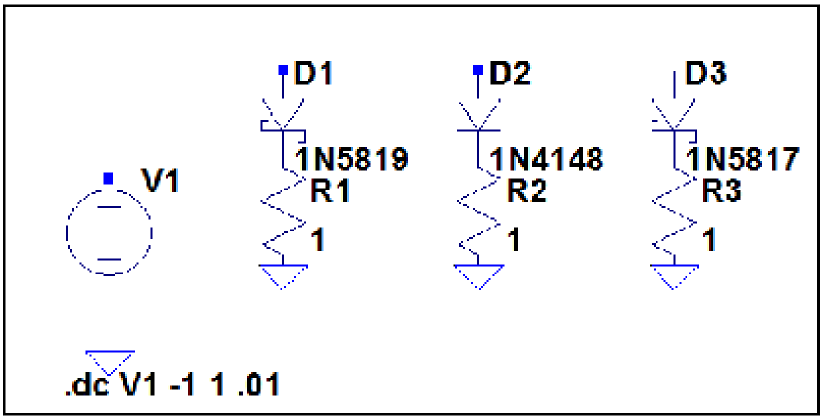

Figure 4.2: LTspice schematic comparison of diodes

Figure 4.3 shows the LTspice simulation waveform for the diode component that closely approaches 1V behavior for the improved circuit development. The Schottky diodes D1 (1N5819) and D3 (1N5817) components have the lowest resistance and they show the same 1V behavior compared to the Silicon diode D2 (1N4148) component. This result shows that the Schottky diode is the feasible passive component to be used in the improved rectifier circuit.

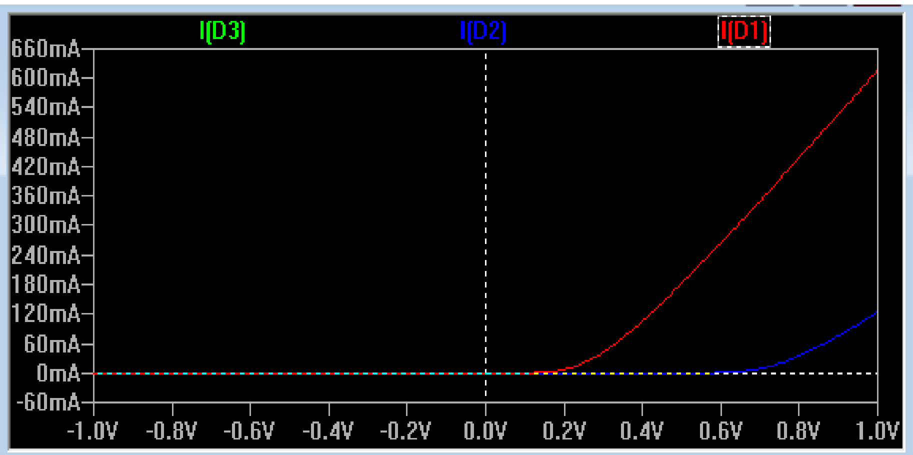

Figure 4.3: LTspice schematic of the waveforms for the diodes

Calculation of the ideal diode behaviour is given as equation 4.1:

$$Dc = Sc(\frac{Vd}{nTv} - 1) \qquad (4.1)$$

where *Dc* is the diode current, *Sc* represents the reverse bias saturation current, *Vd* is the voltage across the diode, *Tv* is the thermal voltage and *n* is the ideality factor. The ideal diode behaviour (figure 4.3) shows that no current passes through the diode until the voltage reaches 0 V and then it switches to infinite current. In other words, the ideal diode would act as a switch on at all positive voltages. For this project finding a diode that approaches the ideal in behaviour would be best for low voltage RF signal rectification.

4.2.2 Rectifier Circuit Simulation

A rectifier is an electrical device that converts AC to DC. AC occasionally reverses direction and DC flows in one direction only (Lemmon, 2009). Rectifiers are normally used in circuits that require a steady voltage.

Rectification produces DC that encompasses active voltages and currents, which are then adjusted into a type of constant voltage DC, this varies depending on the current's end-use. The current is allowed to flow uninterrupted in one direction, and no current is allowed to flow in the opposite direction.

Rectifiers can contain more than one diode in a certain arrangement. A rectifier can take on different waveforms, such as the half wave rectifier were the positive or negative wave is passed through and the other wave is blocked. This is not efficient because only half of the input waveform reaches the output. The full wave reverses the negative part of the AC waveform and combines it with the positive. Single-phase AC in which two diodes can form a full-wave rectifier if the transformer is centre-tapped and four diodes arranged in a bridge are needed if there is no centre-tap. Three-phase AC generally uses three pairs of diodes (Lemmon, 2009).

Figure 4.4 shows the schematic diagram of the circuit layout of the half-wave rectifier circuit, which is a single diode that allows current to flow in one direction only. The purpose of the diagram is to test the most feasible layout of the components by comparing the 1N5819 Schottky diode with and without capacitance for converting RF to DC. For the simulation circuit, the tantalum capacitor was chosen due to a variety of reasons *viz* higher operating temperature than other electrolytic capacitors, high capacitance per volume and weight, lower leakage and lower equivalent series resistance (ESR).

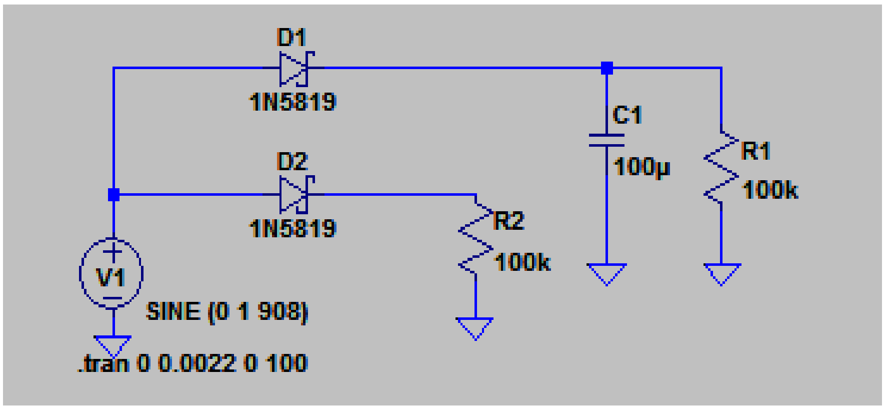

Figure 4.4: LTspice schematic of the rectifier circuit simulation

4.2.3 Capacitance

Figure 4.5 demonstrates the central need for the diode and the capacitor in combination for the rectification of RF to DC. The blue sinusoidal wave represents a 908 kHz carrier wave. The diode only allows for the positive voltage portion of the waveform to pass through it, and thus converts the alternating current to just positive current, i.e. direct current. Notice the loss of voltage in the green wave due to forward bias of the Schottky diode, another efficiency loss critical in converting weak RF to DC. In addition, this is a half wave rectifier, and thus another 50% is lost if only this circuit was used. The red line shows the effect of a capacitor in line with the diode that store the voltage and thus converts the AC to almost pure DC.

Figure 4.5 displays the wave patterns for the circuit diagram that connects the diode with a capacitor. There are two conductors or plates of a capacitor and an insulator between them called the dielectric. The two plates inside the capacitor are wired to two electrical connections on the outside called terminals, when this is connected to a circuit the insulator actually prevents dissipation of energy. The result shows that the DC voltage has less rippled effects on the diode. The loss of voltage is seen as the green waveform that corresponds to 1V. The red waveform represents the output voltage is constant at 1V and above -0.2V, which means that a capacitor connected to the circuit results in less voltage loss. The capacitor must be included in the circuit to act as a filter to reduce the ripple voltage. As the capacitor can be seen in figure 4.5, converts the rippled output of the rectifier into a more smooth DC output voltage.

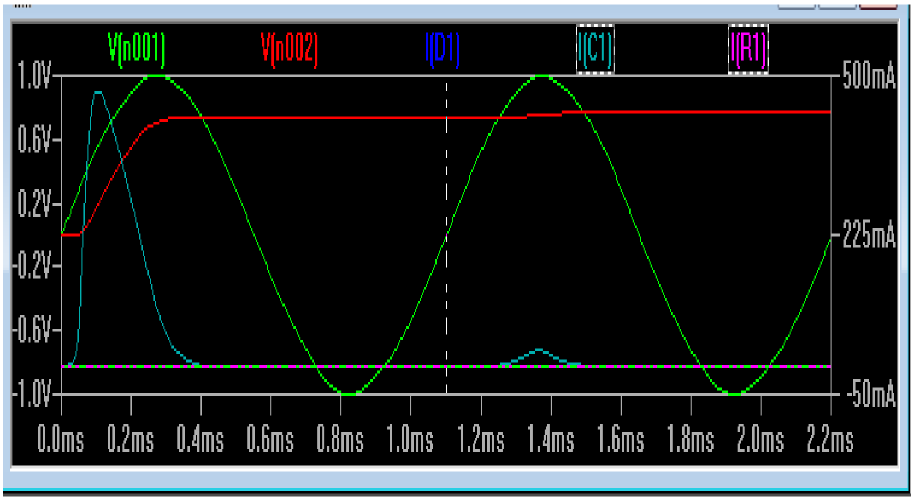

Figure 4.5: LTspice schematic of 1N5819 diode with Capacitance

Figure 4.6 displays the wave pattern of the diode not connected to a capacitor. The result shows the loss of voltage of 1V and the wave pattern falls below -0.2V. The waveform of the voltage is not regulated. The uutput of the rectifier needs to be regulated over a specific voltage range, in figure 4.6 the voltage range is set at 1V, for regulator circuit to get DC output further.

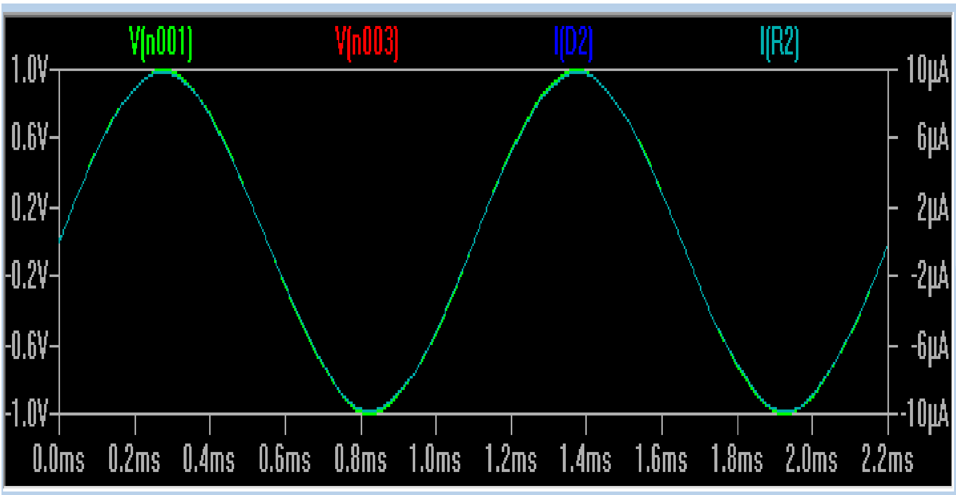

Figure 4.6: LTspice schematic of 1N5819 diode without Capacitance

Based on the results shown in Figures 4.5 and 4.6, the input voltage for the diodes D1 and D2 was set at 1V, and the inclusion of a capacitor to the rectifier circuit is much needed to reduce the voltage ripple and create a smooth DC output. As can be seen in figure 4.5 Positive charge collects on one plate and the negative charge collects on the other plate.

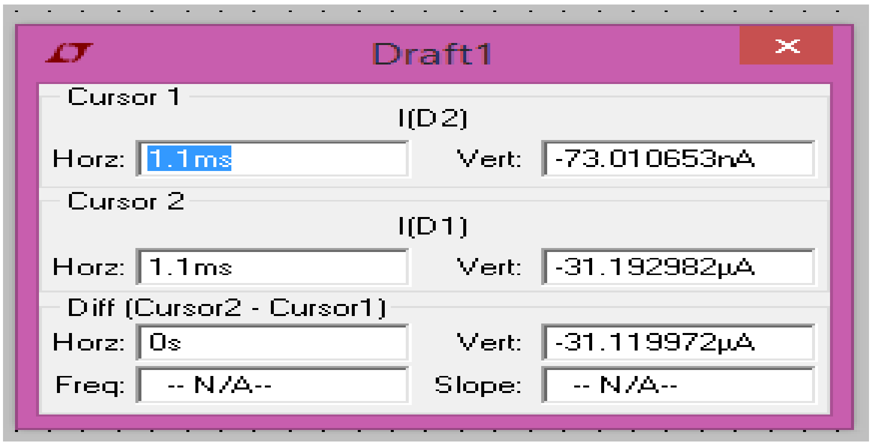

Figure 4.7: LTspice simulated result between D1 and D2

Figure 4.7 displays the LTspice simulated difference between the current passing through D1 and D2 as 31.11 μA. The result of the simulation shows that a capacitor is used to lessen the lost current or to prevent a ripple effect on the output voltage. The raw DC supplied by the rectifier alone consists of a series of half sine waves with the voltage (not including any diode and other losses). Without capacitance, a supply of this nature would not be useful for powering circuits because any analogue circuits would have the huge level of voltage ripple superimposed on the output, and any digital circuits would not function because the power would be removed every half cycle.

As there would always be some ripple on the output of a rectifier using a capacitor, it is necessary to be able to estimate the approximate value as can be seen in the figure 4.7.

CHAPTER 5

CONCLUSION AND FUTURE WORK

This chapter presents a summary of the research study documented in this thesis. The synopsis of the research task and the final result is presented first. Then, insights into possible future work and improvement are stated.

5.1 CONCLUSION

RF harvesting was seen as a promising innovation to charging mobile phones. This concept was explained as a green energy source and making the mobile devices self-sustaining. Several methods and techniques were presented on how well this concept could be addressed. RF harvesting was the most convenient type of scavenging energy compared to the other methods and techniques explained in this thesis.

A considerable number of research pertaining to RF energy harvesting was explained in related studies, each bearing limitations and using different methods or techniques, however, RF energy harvesting directly aimed at charging mobile devices was limited and lacking.

The components of this research project were analysed theoretically and implemented in a prototype model. Conclusions of the prototype model are summarised as, and the theory of RF energy harvesting is proven. RF energy can be scavenged from the environment, however the design of the circuit must be improved on and the most appropriate components should be implemented in this circuit.

The analysis of the capacitor proved it to be an alternate source of energy storage compared to the mobile device battery. The mobile device battery is chemical based and wears out after a certain amount of uses. The capacitor is not chemically based and can last for a lifetime.

The antenna must be tuned to the frequency of the GSM band considering the wireless network operates using this band and devices operating on a wireless medium exude RF energy. The capacitance was lacking in the prototype model to smooth the current and gain maximum voltage. The components were simulated using the LTSpice software and the full wave rectifier circuit layout was the most effective compared to the half wave rectifier circuit. The full wave rectifier simulation converted both the positive and negative halves of the input waveform to a single polarity (positive or negative) is its output. By using both halves of the AC waveform, full wave rectification is more efficient than half wave which is only 50 percent efficient.

A comparison of the diodes was simulated and the results showed that a Schottky diode was more feasible to be used in the upgraded circuit based on it having a very fast switching speed. When the Schottky diode is conducting there is less power dissipated at the Schottky junction than in an equivalent PN diode, so less heat is generated at the junction.

The prototype model and simulation of the components has proved to be a RF energy harvester that could be very useful in both the domestic and commercial environments.

5.2 FUTURE WORK

This research showed that the concept of charging mobile devices using the RF energy harvesting technique is possible. Although the amount of charging energy is not enough to use ambient charging technology now, the propose analysis of the different combinations of components, layout of the circuit and type of antenna will increase the charging energy for a mobile device.

Future work to be done following this project is to demonstrate the charging of a mobile device using the full rectifier circuit, Schottky diodes as an alternative to the battery and a multi-band antenna to gain the maximum RF signals. There are confines of the amount of energy that could be harvested by the RF energy harvesting system which could be produced by the strength of the RF field, implemented antenna and full wave circuit. The improved design of the circuit can be applied in an assortment of RF energy harvesting and wireless communication applications.

The circuit can be improved by implementing it with a SWIFT system, making it using the following scenarios; broadcast channels, relay channels, interference channels and orthogonal frequency division multiple access systems.

Based on this research study it is worth mentioning that wireless RF energy harvesting networks concurrently present novel hypothetical issues based on physical occurrences and applied concerns. The area of wireless RF energy offers a rich set of potentials for gaining design perceptions from mathematical formulations which take practical deliberations into account. These deliberations comprise such physical assets as storage imperfections, consummation models, processing costs, inclusive of accurate modelling such as casual energy harvesting outlines. Furthermore the area of energy and information transfer delivered stimulating potentials to further adjust the network operation and advance its performance. The conceivable development is closely related to the proficiency of energy transfer and to the device and circuit technologies, linking the theory to the actual world.

The frequencies focused on during this research study was the 0.9 – 1.8 GHZ operating band. It is important to consider for future projects the frequencies above 1800 MHz such as 2100 MHz and 2600 MHz, since 3G and 4G (LTE) mobile networks operate at these frequencies.

Toward this completion, the research study concludes by affirming that the impending challenges for RF energy harvesting wireless networks exist not only in progressions in several layers of network design, initially signal processing and communications physical layer ending in the networking layer, but also in accepting the accurately interdisciplinary environment of the RF energy harvesting wireless networks combined with the advances from circuits and devices that harvest and transfer energy.

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