DESIGN, SIMULATE AND PERFORMANCE ANALYSIS OF GSM AND WI-FI BANDS OF RF ENERGY HARVESTING CIRCUITS FOR LOW DC POWER APPLICATIONS

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ABSTRACT

The purpose of this research was to design, simulate and optimize a 4-band radio frequency energy harvesting (RFEH) network circuit using the Keysight Technologies Advanced Design System (ADS) design and simulation software used for low power applications. The RF bands used for this study were Global System for Mobile Communication (GSM) (950MHz, 1850MHz, 2150MHz) and Wireless Fidelity (Wi-Fi) (5000MHz). Smith chart was employed to design the impedance matching circuit to match the source impedance (Z_{in}) and the load impedance (Z_{load}) to minimize the signal reflection (return loss) and maximize the power transfer. The impedances were matched at the desired radio frequency (RF) operating frequency. A single, two and three-stage voltage multipliers were simulated to obtain the output impedance at 4-band RF frequencies with the source impedance set to 50 ohms. Simulation results showed that the three-stage voltage multiplier produced the best outcomes, thus, was used for this research. The highest RF to DC power conversion efficiency at 0dBm RF input power were 54.317%, 41.011%, 25.281%, and 23.658%. On the other hand, the optimum DC output voltage found at 30dBm were 5.701V, 5.696V, 5.668V, and 5.674V. In conclusion, this research found that the RFEH system with a three-stage voltage multiplier connected to the impedance matching circuit produced both the optimal DC output voltage and power conversion efficiency. The findings of this research imply that the three-stage voltage multiplier is suitable for harvesting DC electrical energy from 4 different RF band waves for low-power applications, especially for wireless sensor networks (WSNs).

MEREKA BENTUK, MENSIMULASI DAN MENGANALISIS PRESTASI JALUR GSM DAN WI-FI LITAR PENUAIAN TENAGA RF UNTUK APLIKASI DC KUASA RENDAH

ABSTRAK

Tujuan kajian ini adalah untuk mereka bentuk, mensimulasikan dan mengoptimumkan litar rangkaian penuaian tenaga radio frekuensi (RFEH) 4 jalur menggunakan perisian simulasi dan reka bentuk *Advanced Design System (ADS) Keysight Technologies* yang digunakan untuk aplikasi kuasa rendah. Jalur RF yang digunakan untuk kajian ini merangkumi *Global System for Mobile Communication (GSM)* (950MHz, 1850MHz, 2150MHz) dan *Wireless Fidelity (Wi-Fi)* (5000MHz). Carta Smith digunakan untuk mereka bentuk rangkaian pemadanan impedans untuk memadankan impedans sumber (Z_{in}) dan impedans beban (Z_{load}) untuk meminimumkan pantulan isyarat (kehilangan pulangan) dan memaksimumkan pemindahan kuasa. Kedua-dua impedans kemudiannya dipadankan pada frekuensi operasi radio frekuensi (RF) yang dikehendaki. Litar pengganda voltan satu, dua dan tiga peringkat telah disimulasikan untuk mendapatkan impedans keluaran pada frekuensi RF 4 jalur tersebut dengan impedans sumber ditetapkan kepada 50 ohm. Keputusan simulasi menunjukkan bahawa pengganda voltan tiga peringkat menghasilkan hasil yang terbaik, oleh itu, ia digunakan untuk dalam kajian ini. Apabila kuasa input RF bersamaan dengan 0dBm, prestasi kecekapan penukaran tertinggi kuasa RF kepada DC ialah 54.317%, 41.011%, 25.281% dan 23.658% dan apabila kuasa input RF bersamaan dengan 30dBm, kajian mendapati voltan keluaran DC paling optimum sebbanyak 5.701V, 5.696V, 5.668V, dan 5.674V. Kesimpulannya, kajian ini mendapati sistem RFEH dengan pengganda voltan tiga peringkat yang disambungkan kepada litar pemadanan impedans menghasilkan voltan output DC yang optimum dengan kecekapan penukaran kuasa terbaik. Dapatan kajian ini menunjukkan bahawa pengganda voltan tiga peringkat adalah sesuai untuk menuai tenaga elektrik DC yang terhasil daripada 4 jalur gelombang RF yang berbeza untuk aplikasi kuasa rendah terutamanya untuk rangkaian sensor tanpa wayar (WSN).

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LIST OF ABBREVIATIONS

ADS	Advanced Design System
CMOS	Complementary Metal Oxide-Semiconductor
CPU	Computer Processor Unit
EH	Energy Harvesting
EM	Electromagnetic
EMF	Electromagnetic Field
E-Plane	Electric Plane
GPS	Global Positioning System
GSM	Global System for Mobile
H-Plane	Magnetic Plane
IC	Integrated Circuit
ICT	Information and Communication Technology
IoTs	Internet of Things
IR4.0	Industrial Revolution 4.0
NF	Noise Figure
LAN	Local Area Network
MHz	Mega Hertz
Non-RE	Non-Renewable Energy
PCs	Personal Computers
RE	Renewable Energy

RF	Radio Frequency
RFEH	Radio Frequency Energy Harvesting
RFID	Radio Frequency Identification
RMS	Root Mean Square
SBD	Schottky Barrier Detector
Wi- Fi	Wireless Fidelity
WPT	Wireless Power Transfer
WSNs	Wireless Sensor Networks

LIST OF SYMBOLS

C	Capacitor
c	Speed of Light $3x10^8$ m/s
dB	Decibel
DC	Direct Current
f	Frequency in Hertz (Hz)
Hz	Hertz
J_c	Junction Capacitor
L	Inductor
Z_{load}	Load Impedance
Z_{in}	Input Impedance
R_s	Series Resistance
S_{11}, S_{21}	Reflection Coefficient
V_b	Breakdown Voltage
V_t	Threshold Voltage
V	Voltage
Z_{in}	Input Impedance
Zo’	Output Impedance
λ	Wavelength In Meters
η	System Efficiency
Ω	Ohm (Resistance Value)

CHAPTER 1

INTRODUCTION

1.1 Research Background

The incessant upsurge of the global population brings about tremendous implications towards the cost of energy. Since World War I, energy security has been a matter of national strategy. The idea of energy security has, in some ways, evolved since the 1973 oil price shock since there is now less emphasis on relying on erratic oil supply, which has socioeconomic and environmental implications as well. Additionally, a strong reliance on imported energy would lead to high foreign exchange costs, expensive energy, a high cost of production, decreased competitiveness, high carbon dioxide (CO_2) emissions, psychological costs, and many other negative effects. Reducing reliance on imported fuels and diversifying the energy sources used to produce power are significant policy initiatives to improve energy security, which also reduces emissions and fosters economic growth (Naeem Nawaz & Alvi, 2018). Electrical energy has an undoubtedly significant role in our daily modern lives since it can be converted into different forms of energy for use at home, in transportation, manufacturing, and other applications. However, some energy is lost during the energy transformation process which resulted in higher energy consumption and waste. According to the law of conservation of energy, energy cannot be generated or destroyed, but it can be transformed from one form to another.

Energy harvesting is the process of converting, storing, accumulating, and converting waste energy into useful electrical energy. In recent years, energy harvesting technologies have attracted a lot of attention from the research community as a way to deliver continuous wireless power to sensor nodes (Hamza et al., 2021). Sustainable development can be defined as living, producing, and consuming in a manner that meets the needs of the present without compromising the ability of the future generations to fulfill their own needs. It has become a key guiding principle in the 21st century world. One of the most essential concerns in today's low-power electronics for smart environments is green self-sustaining functioning (internet of things, smart cities, etc.) (Baroudi, 2019a). This entails the stakeholders to practice well-organized strategies for economical and productive green energy harvesting.

Conventional energy sources have their disadvantages as they are non-renewable, risking the environment for pollution and have a finite lifespan. Hence, scientists are looking for renewable energy (RE) sources that are readily available, non-polluting, and low-cost (Trikolikar & Lahudkar, 2021). Various energy sources, such as solar, vibration, thermal, and radio frequency (RF), are available for harvest in our immediate surroundings. An important characteristic of renewable energy sources that can be used as off-grid solutions is their ability to be implemented at small and medium scales. In light of this perspective, the world has shifted its attention from high-cost imported energy sources to lower-cost renewable sources, bringing about socioeconomic and environmental sustainability in the nation (Naeem Nawaz & Alvi, 2018).

The society we are living in today is not demonstratively aware of the existence of various types of green energy in their surroundings. It is accessible and all these energies can be categorized into two classifications which are renewable energy (RE) and non-renewable energy (non-RE). RE is a type of inexhaustible energy that originates from natural sources which will not diminish and replenish able within the lifetime of the human populace. This energy is on the rise due to technical advances that are cutting costs and delivering on the promise of a future clean energy (Shinn, 2018). Generally known examples of RE include solar, hydropower, and wind. In contrast, non-RE is a source of energy that is irreplaceable once it is consumed. Non-renewable energy sources are also more common in certain parts of the world, making them more abundant in some countries than others. The types of energy are illustrated in Figure 1.1 below.

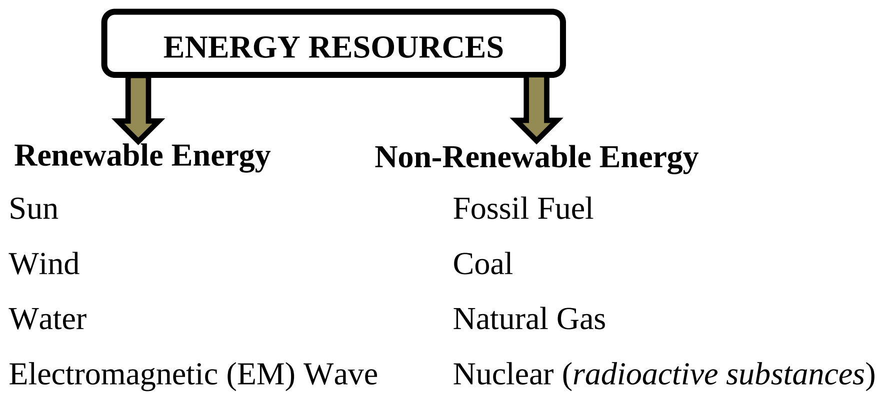

Figure 1.1. Types of Energy Resources. Adapted from Khan et al. (2021).

Industrial Revolution 4.0 (IR4.0) is sweeping the globe, necessitating digitalizationand the creation of intelligent industrial applications (Haque & Baroudi, 2021). Renewableenergy technology enables humans to take maximum advantage of its sources. Some commonly seen instances of the technology are solar photovoltaics which directly poweredby the sun, wind turbines from the wind, hydropower from flowing water resources as wellas biomass from plant or waste resources. All of the aforementioned technologies enable humans to create electrical energy from ambient sources for daily usage without emitting harmful gases, unlike conventional power plant (coal and diesel power plant) which may cause pollution. Furthermore, renewable energy could serve as the most excellent alternatives for conventional energy resources as it lines up some advantages such as:

i. The durability of renewable energy allows it to operate and power the technologies for an extensive length of time.

ii. Reducing environmental pollution by lowering the risk of fuel spills which couldaffect the sea ecosystems and greenhouse gas emissions which could cause serious health problems.

iii. Being low-cost on a large scale globally, for instance, by decreasing the demand for imported fuels.

iv. Being naturally accessible from natural processes that are constantly restored.

v. Helping in conserving the natural resources, for example, the utilization of renewable energy preserves the supplies of fossil fuels underground.

Despite this current era of science and technology, some parts of our society are still uninformed of the existence of energy which is constantly obtainable in our lives. Weare unremittingly bombarded with electromagnetic (EM) waves, the energy carriers that travel through space. This radiation interacts with entangled electric and magnetic fields, both of which must be present at the same time. EM waves travel at the speed of light in vacuum, which is 3 x 10^8 m/s, but they cover a wide frequency range known as the EM spectrum (Amineh, 2020). It is a new scheme of renewable energy resources which shouldbe exploited and is rather worth exploring at the present.

Specifically, the resources of EM energy are the broadcast transmitter, radio masts and towers, cell phones, walkie-talkie, Wi-Fi as well as wireless devices that operate on electromagnetic waves. The following waves are found in the electromagnetic spectrum, from lowest to highest frequency (longest to shortest wavelength): RF, microwaves, millimeter waves, terahertz, infrared, visible light, ultraviolet, X-rays, and gamma rays (Amineh, 2020). This EM wave can be categorized into three types of spectrums as illustrated in Figure 1.2 which are:

i. The low-frequency spectrum
ii. Radio frequency (RF) spectrum
iii. Microwave spectrum

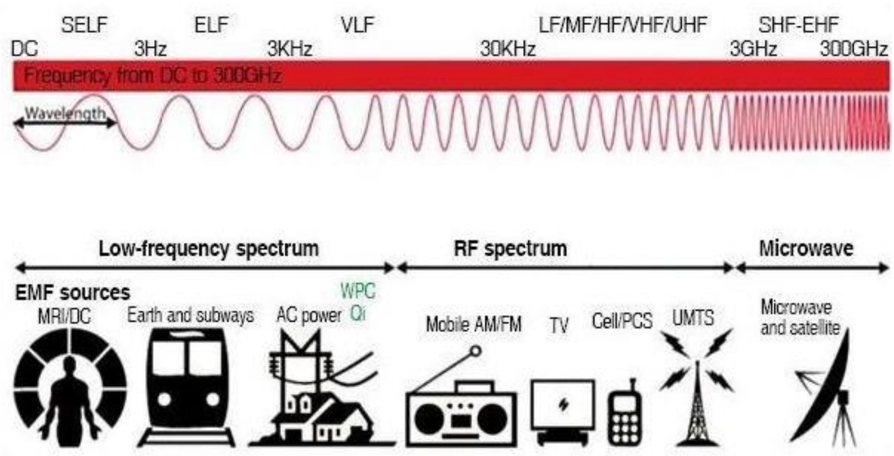

Figure 1.2. Types of Spectrums for Electromagnetic Waves. Adapted from Electronicsforu (2017).

The RF spectrum is used by most modern gadgets, such as mobile phones, global positioning systems (GPS), radio and television broadcasts, and Wi-Fi, to operate and convey information from sources to the end user. However, users of the aforementioned technology gadgets are probably unaware of the fact that RF waves are sources of ambientenergy that can be transformed into usable electrical energy. RF waves have two fields: a magnetic field and an electric field, both of which can be collected and turned into continuous electrical energy using a novel technology called RF energy harvester (RFEH) system. This energy can be fully utilized, and a continuous harvest of energy resources can be seen. Additionally, the intense development of Wireless Sensor Networks (WSNs) acts as the key factor in harvesting new energy from the RF energy resources. Due to its accessibility, RF energy harvesting (RFEH) has become increasingly popular as wireless communication and broadcasting have advanced. A potential method to supply modest amounts of power to the electronic gadgets is RF energy harvesting (RFEH). A node can scavenge power from a few microwatts to a few milliwatts, depending on the sent power and the distance between the sending source and the receiving source (Sansoy et al., 2020; L. G. Tran et al., 2017).

Recently, with the rapid development of devices with low power requirements, thistechnology has become commercially available. Examples of successful use of this methodare Radio Frequency Identification (RFID) and all applications (Figure 1.3) which requirea specific source of EM energy to transmit the data.

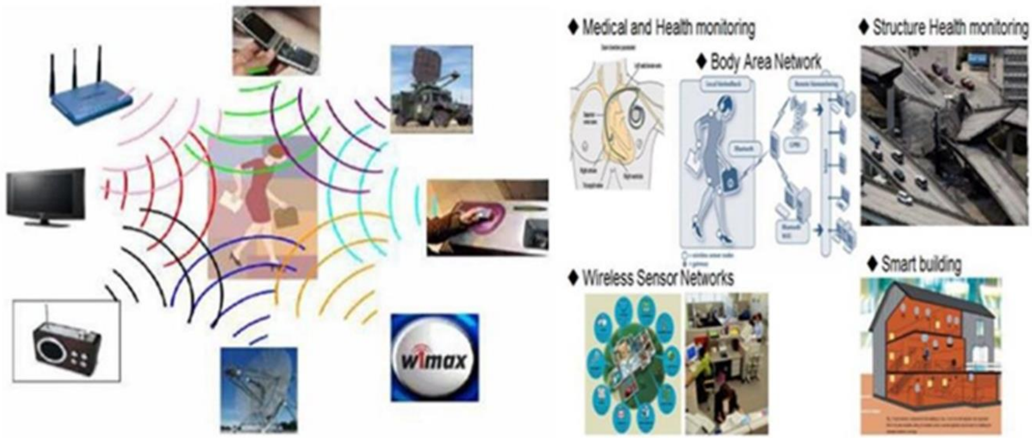

Figure 1.3. RF Energy Harvesting (RFEH) Applications. Adapted from Elsheakh (2017).

However, with the advancement of modern communications technologies, a varietyof ambient RF transmissions are available in the urban environment. RF energy harvester can generate small amount of electrical power which is suitable to be used or stored (Kaur et al., 2018). Moreover, the decreased power requirements of the sensor nodes used in theautonomous systems nowadays, are creating opportunities for new fields of application forharvesting ambient RF energy. RFEH system may be considered as an urgent technology in application areas such as:

i. Health Monitoring: power supply for cardiac pacemakers, prostheses sensors, etc. where high uptime is required, and too risky to install batteries or any otherconventional power source.

ii. Smart Sensors for Environmental Monitoring: in remote locations, e.g., forest fire detection where it is difficult to have access to a powered device for maintenance and no wired power source is available.

iii. Embedded in Structures: inside the asphalt of the bridges and other structures where it is impossible to install batteries or other conventional power sources and require high uptime.

If RFEH system is given the chance and a serious research focus, it has various benefits that have been promised for the future. The following are a few of the benefits that can be highlighted:

i. Near Universal Supply: Electromagnetic waves are present everywhere in theenvironment due to the widespread use of computing devices, mobile and internet networks; as a result, RF energy is essentially free energy that may beused whenever it is needed.

ii. Cheaper: When compared to battery-based systems, RF energy harvesting (RFEH) is orders of magnitude more cost effective over the long term becausebatteries need to be maintained periodically. Even the longest-lasting batterieseventually need to be recharged or replaced; RFEH eliminates all these costs inone fell swoop.

iii. Useful for Extending Battery Life: With RF based technology, batteries can besupported and recharged in situations where power requirements are high or ofa kind that necessitates the usage of batteries. By offering an alternative to labor-intensive methods of maintenance and recharging, the RFEH system cangreatly increase the battery's lifespan.

iv. Eco Friendly: In the growing environmental problem, batteries play a significant role. It can be quite difficult to appropriately dispose of lithium-ionbatteries because they are regarded as hazardous waste and can have terrifyinghealth effects on the local population. All of these environmental drawbacks that batteries have are addressed by RFEH, which is a practical substitute.

Even though the RF waves exhibit a very low-density energy as compared to the energies which are powered directly by the sun, the waves are constantly projecting radiation. Hence, the harvesting of energy waves from the RF is hypothetically the most fitting solution which guarantees and provides the sustainability of energy resources for the future.

1.2 Problem Statement

Due to the fairly high consumption of power supply in electronic devices, a recharging process is required. A lot of electrical equipment’s have been downsized and are now batterypowered. However, these gadgets must be recharged regularly, and they will eventually wear out and need to be replaced. The batteries will subsequently become garbage and contaminate the environment. The best solution to this problem is to harvest the energy from the environment and utilize it to charge the batteries or to power the electronic circuitdirectly. The ambient EM waves would come from the transmitting stations such as TVs, Wi-Fi routers, radios, and cell phone base stations. However, the signal is weak, ranging between -40dbm and -60dBm, and it is crucial for researchers to take this into consideration.

The RFEH system is found to be one of the candidates to solve this problem by providing a continuous DC power supply with the existence of a high attainability global system for mobile (GSM) and Wi-Fi signal. To operate the conditioning circuit, the optimalimpedance matching should be designed to amplify the signal from the RF wave harvester(receiving antenna) to exceed 0.5V (rectifying diode circuit). For several years, the numberof consumer oriented electronic devices such as cellular phones, tablet personal computers (PCs), and global positioning system (GPS) units have been increasing at an exponential rate. With the increment of reliance on these gadgets for everyday navigation, scheduling, and information collecting, users have come to demand longer battery life and fewer charging cycles with each new generation of product.

Consumers want to be able to use all of their device's features without worrying ofcharging them or replacing their batteries the night before they use it the next day. Besidesthat, wireless communication has advanced rapidly and widely spread along with the development of WSNs. WSNs is mostly used in factories, industrial complex, and urban areas. The functions of WSNs are to monitor the surrounding situation, infrastructure management, energy management, safety management, transportation, user applications, and other networking. This condition raises several crucial problems for both researchers and device designers which is the way to enhance battery life and provide consumers with more time of usage with fewer charging interruptions. A creative step in design evolutionwould be to reduce dependency on large and wasteful power sources, such as high-capacity batteries. The energy needed to solve this problem must originate from a tangible and generally available ambient source. Solar energy, wind energy, kinetic energy, and ambientelectromagnetic or RF energy are only a few examples of ambient energy sources that canbe used by the aforementioned consumer devices.

The rapidly increasing number of commercial and personal wireless installations are to be the focus of the ambient gathering of RF energy from cellular base stations, Wi-Fi access points, and hundreds of other sources. In other words, the number of RF potentialpower sources will increase as the industry grows. Thus, it is a logical sense to target an energy source that most probably will continue to grow over time. Mostly, the WSNs system operates from the generation of batteries as the main source of energy. Energy harvesting from the resource of RF has immense potential in supplying power for low applications via wireless method without being completely dependent on the consumptionof batteries. The aptitude of an energy harvesting system from RF waves may have a solution for battery substitution in secluded locations with difficult accessibility. These settings are usually sited at bridge areas, hills peak as well as locations that are highly exposed to radioactive substances, particularly near chemical implants. Furthermore,battery consumption demonstrates several drawbacks. For instance, it has a limited life expectancy and the exorbitant cost of periodic replacement. The issue that is more severe for us is the need for battery disposal, which is a perilous act leading to environmental pollution. Likewise, the related incurred cost for this exceeds the cost of endorsing the development of WSNs devices greatly. The finest alternatives for the previously stated concerns are to conserve the RF waves and convert them into electrical energy. This optionis intended to substitute the batteries in order to establish the application system of the device.

1.3 Research Scope

The research focuses on the design of an RFEH system for low-power devices, particularly WSN applications, that operates in the GSM (900MHz, 1800MHz, 2100MHz) and Wi-Fi (5000MHz) bands. The need to develop an impedance matching and voltage multiplier rectifier for WSNs sensors power up will be emphasized. The chosen approaches are studied to occupy the compact rectifier circuit coupled with impedance matching structures. The proposed impedance matching, and rectifier circuit are simulated and optimized using the Agilent Keysight Advanced Design System (ADS) based on the required performances. The optimum design is measured in terms of the DC output voltage (V) and system efficiency (%).

1.4 Research Objectives

This research aimed to design a realistic electronic circuit network for harvesting RF waves to generate a source of renewable energy for low-power applications. For this purpose, this research covers supporting objectives that could be elaborated as follows:

i. To design an impedance matching and voltage multiplier circuit network for RFEH system operating at GSM band (900MHz, 1800MHz, 2100MHz) and Wi-Fi band (5000MHz).

ii. To simulate the proposed design network circuit by using Advanced Design System (ADS) simulation software for RFEH performance.

iii. To optimize the DC output voltage (V) and efficiency (%) for the three-stage voltage multiplier for RFEH system.

1.5 Research Questions

To satisfy the aim and objectives of this research, a few research questions ascended:

i. What frequency band is the most convenient for harvesting of RF waves radiation?

In the EM spectrum, the RF radiation oscillated between 3kHz to 3GHz, and in this research, the targeted frequency band as the main source to harvest the new energy is cellular sources including GSM band (900MHz, 1800MHz, 2100MHz), and the source from Wi-Fi band (5000MHz).

ii. What type of circuit should be employed to convert the energy source of RF waves into the DC signal?

The RF waves we encounter in our environment are sinusoidal (sine waves), but the DC signal is used to generate fresh electrical energy. To convert an RF wave signal into a DC signal, a multiplier rectifier circuit will be used. A diode and a capacitor are used in the rectifier circuit. The diode utilized is from the Skyworks SMS-7630 solution family, which has a special specification to improve the RFEH system's efficiency.

iii. What is the most suitable technique which could ensure that the harvested RF waves are capable of transmitting the maximum amount of power to the load without triggering any reflected signal?

The most efficient way for maximizing the passage of power from the lower input signal to the load through the voltage multiplier circuit is the impedance matching circuit. The impedance matching circuit utilized in this study is a short circuit stubs configuration that consists of shortened or opened line segments linked in parallel or series with the line at a suitable distance from the load. Any complex load is commonly matched to a transmission line using stub matches.

1.6 Significant of Research

Advances in wireless sensor technologies, as well as mobile handheld devices including microprocessors and miniaturized radio transceivers, have accelerated the development of smart structures and machinery in the urban city particularly. Wireless sensors can warn users or systems of impending hazards besides eliminating wasteful scheduled maintenance. However, for sensor networks to be totally autonomous, batteries must be replaced with alternatives that are able to continuously harvest and store energy, allowing the entire network system to self-sustain. There would be no service interruption due to the lack of a requirement for battery replacement, resulting in cheap maintenance costs. Energy harvesting technology guarantees the procedures of replacing or extending the life of rechargeable batteries in low-power electronic devices particularly for WSNs.

Consequently, the research's significance is to design an RFEH energy harvester system from RF wave signals source. The RF wave signal can be found in the GSM spectrum between 900MHz to 2100MHz, as well as the Wi-Fi band at 5000MHz. These spectrums were chosen because they are broad spectrum bands that are utilized by a variety of devices for data transmission and communication, particularly for mobile phone frequencies that are licensed by the Malaysian Communications and Multimedia Commission (MCMC) (MCMC, 2023; Spectrum Monitoring, 2021). The RFEH energy harvesting system can be developed in a variety of ways, but there is still room for improvement. The entire RFEH energy harvesting system is comprised of the antenna, impedance matching circuit, voltage multiplier, power management, and load.

This research takes use of the chance to show progress in the design of two mediums: impedance matching circuit and voltage multiplier circuit. impedance matching circuit s (IMNs) are often divided into two categories: lumped component based, and distributed component based. Although IMNs with lumped components (capacitor and inductor) are generally compact, they are not recommended in circuits that operate at higher frequencies (above 1GHz) due to the inherent loss associated with lumped components. For RFEH voltage multipliers, IMN insertion loss is crucial since it reduces the overall efficiency of the RF energy harvesting RFEH circuit system. A distributed component based IMN was employed to eliminate the intrinsic losses of lumped components. Besides that, the IMN designed using distributed component shows the advantage in part of cost of components compared to the IMN lumped based because the number of the inductor and capacitor should be considered to design the IMN.

The design IMN with this method is to narrow the band frequencies to protect the RFEH system from being disrupted by a lot of noise in the RF spectrum, as opposed to the wideband, which contained more noise and harmonics that could affect the entire RFEH system due to passive components like inductor and capacitor. Therefore, IMN distributed based is a new technique to configure the IMN for the high frequencies. The forms of impedance matching circuit s, notably for distributed component IMN, will be explained in detail in Chapter 2. Moreover, the voltage multiplier is one of the mediums in part of RFEH circuit system. Voltage multiplier is to convert the input signal to DC signal load and to increase the output signal. The configuration of voltage multiplier is built by diode and capacitor based on the particular topologies. Diode is the main rectifying element in RFEH, and its behavior influences the overall performance of the circuit. Selection of the diode is one of the most critical steps in the design of a rectifier because the efficiency of the rectification depends on it.

Normally, Schottky diodes are used for RF to DC conversion due to their low threshold voltage. In order to make the best choice, diodes Skyworks SMS-7630 were investigated and used in this research compared to other Schottky diodes based on their parameters, which has an important part in the selection such as series resistance (R_s), junction capacitance (J_c), threshold voltage (V_t) and breakdown voltage (V_b). As a result, this study is significant since it introduces the design of impedance matching and voltage multipliers, both of which will be simulated and optimized using ADS software, the best software for modelling RF circuit design. The research explores the energy harvesting methods and presents the network architecture circuit including impedance matching, voltage multiplier and load modules for an improved RFEH circuit system. This research explores the various methods of RFEH and introduces elements of a better collection circuit that can be implemented into any low-power electronic device, such as a WSNs. The use of numerous RF bands allows for higher energy collection rates and, as a result, faster charge accumulation. The key contributions of the research are summarized as follows:

i. **The development of the stubs impedance matching circuit configuration to maximize the low input signal.**

The multiple input signal RF sources add an opportunity for higher energy collection rates and thus, more power output produced. The main contribution of this thesis emphasizes the design of an impedance matching circuit network using the efficient short circuit stubs network configuration topology.

ii. **The development of a two-stage voltage multiplier (rectifying circuit) to enhance the DC signal values for WSNs operating power system application.**

The voltage multiplier circuit is coupled with an impedance matching circuit to increase the low input power from the receiving antenna. The targeted DC voltage is appropriate for powering the WSN sensors range between 3.0V to 3.3V (Bhattacharya, n.d.; Grady, 2011).

iii. **The development of the RF harvesting system for quad-band frequency encloses the GSM cellular and Wi-Fi band.**

The frequency bands targeted for energy harvesting in this research will be those that are the most readily available to the urban city environment with quad-band frequency for GSM band range from 950MHz, 1850MHz and 2150MHz, and Wi-Fi 5000MHz band.

The main contribution of this research is the design of a three-stage voltage multiplier coupled with the short stub impedance matching. The goal is to improve on comparable recent concepts in terms of power conversion efficiency and get closer to a viable solution that can be employed in low-power devices.

1.7 Thesis Organization

This research discusses the design of an efficient and competent energy harvesting circuit for RF waves. The outcome of the new energy harvest will be utilized in generating low power applications, especially for WSNs sensors. The contents of this thesis discussion are organized as follows from introduction, literature review until discussion of the research. Chapter 1 of this thesis is an introduction to the writing process; it summarizes and clarifies the research that has been conducted. The first section of this chapter is an introduction to the planned study's origins and causes. This chapter also includes a problem statement and a research objective. The research objective will define the purpose and direction of the research, which will be based on the problem statement's cause. Chapter 2 delves deeper into the research, including information on the methodologies and components used in the development of the RFEH energy harvester, as well as past facts and studies. This chapter also looks into impedance matching circuit s and voltage multiplier topologies for four-band operation, as well as their characterization. The design aims and contribution are also taken into account. The design, simulation results, and optimization of the RFEH energy harvester's four-band circuit design are described in Chapter 3.

The development will focus on project methodology and system design, with an emphasis on the process for finishing the project and presenting it in a flowchart. The components for the RFEH energy harvesting system's design and software solution are explained in this chapter. The simulation model Keysight Advances Design System (ADS) was utilized to test and optimize the system. Chapter 4 presents the anticipated outcome of the simulation and analysis. The predicted outcome for the entire project system will be discussed in detail in this chapter. The simulation results are also examined in terms of possible uncertainties. The final chapter, Chapter 5, presents the research's general conclusion. It also contains some suggestions and areas for further research. These suggestions are based on this thesis project, although they are not confined to the system solution that was chosen. The conclusion is relevant to the study. It is crucial in order to ensure that the research objectives are achieved.

1.8 Summary

This chapter introduces the background study and investigation for the development of the RFEH. This RFEH system will be built using comprehensive research on the topologies of multiband voltage multipliers as well as the construction of an impedance matching circuit technique. The study exposed the problem of limited battery energy supply for WSN working lifetime, and it prompted to suggest and disclose a new technique in electrical generation employing RF waves.