OPTIMIZATION AND ANALYSIS OF WLAN RF ENERGY HARVESTING SYSTEM ARCHITECTURE FOR LOW POWER WIRELESS APPLICATIONS

A Thesis

by

Syeda Wajiha Munir

Submitted to the
Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Electrical and Electronics Engineering

Özyeğin University
January 2017

OPTIMIZATION AND ANALYSIS OF WLAN RF ENERGY HARVESTING SYSTEM ARCHITECTURE FOR LOW POWER WIRELESS APPLICATIONS

Approved by:

Asst. Prof. Ali Özer Ercan, Advisor
Department of Electrical and Electronics Engineering
Özyeğin University

Assoc. Prof. Onur Kaya
Department of Electrical and Electronics Engineering
Işık University

Asst. Prof. Ahmet Tekin
Department of Electrical and Electronics Engineering
Özyeğin University

Date Approved: 05 January 2017

To my beloved parents and supporting siblings......

ABSTRACT

The presented work proposes a radio frequency (RF) energy harvesting circuit design, which scavenges energy from WLAN dual frequency band. In comparison to other available sources for energy scavenging, e.g. solar, wind and thermal, RF energy harvesting has received much attention in recent research work. Despite of the low power density, RF energy harvesting can be a promising solution to power the energy constrained wireless networks with careful design of energy harvester antenna and processing circuitry. However, it is a critical challenge to obtain usable DC output voltage from RF signals as signals received by harvester is of low amplitude, whereas required voltage to operate any wireless device is proportionally high. Moreover, most of the past work in RF energy harvesting is only effective for single frequency and have less efficiency response.

Therefore, this research focuses to design an improved and optimized WLAN dual band energy harvesting circuit with the inclusion of real time channel losses, as well as fabrication dissipation loss; which is a novel aspect of the presented work. The contribution of this dissertation goes beyond simulated design only, it also reports the non-ideal simulation analysis and PCB implementation of designed circuit. Ideal and non-ideal circuit design has been compared, with accompanying simulations on both ideal and non-ideal conditions to investigate the upper bound on achievable harvested energy. Simulation results report approximately 67% efficiency and total output of 13 μJ of energy, when the transmitter power is 1 Watt and distance from transmitter is kept as 1 meter; with the ideal channel characteristics considered.

ÖZETÇE

Bu tezde WLAN ikili frekans bandında, radyo frekansında (RF) enerji harmanlayan devre tasarımı önerilmektedir. Güneş, rüzgar ve ısı gibi diğer enerji kaynaklarına kıyasla, RF enerji harmanlaması son çalışmalarda çok ilgi çekmiştir. Düşük güç yoğunluğu olmasına karşın RF harmanlama, dikkatli anten ve işleme devresi tasarımı ile enerji yönünden kısıtlı telsiz ağların güç kaynağı olmak için ümit veren bir çözüm olabilir. Telsiz cihazların işlediği DC voltajın kıyasla yüksek olduğu durumda düşük genlikli RF sinyallerinden kullanılabilir DC çıkış voltajının elde edilmesi kritik seviyede önemli bir zorluktur. Ayrıca önceki çalışmalarda çoğunlukla tek frekans bandında RF harmanlama üzerinde durulmuştur ve verimlilikleri daha düşüktür.

Bu çalışma, geliştirilmiş ve eniyilenmiş iki bantlı WLAN enerji harmanlama devresi tasarımı üzerine yoğunlaşmaktadır. Gerçek zamanlı kanal kayıpları ve üretimden kaynaklı kayıplar tasarımda göz önünde bulundurulmuştur ve bu, tezin yenilikçi yönlerinden birisidir. Tasarlanan devrenin ideal olmayan benzetim analizi ve PCB gerçeklenmesi de raporlanmıştır. İdeal ve ideal olmayan devre tasarımı her iki durumun da modellendiği benzetimlerde kıyaslanmış ve harmanlanabilecek enerjinin üst limitleri incelenmiştir. Benzetim sonuçları verici gücü 1 Watt ve verici-alıcı mesafesi 1 metre olduğunda, ideal kanal karakteristikleri altında yaklaşık 67% verimlilik ve toplam 13 μJ enerji çıkışı göstermektedir.

ACKNOWLEDGEMENTS

First of all, I would like to express gratitude to Almighty ALLAH, Who has bestowed limitless blessings on me and made me capable of completing my thesis successfully. I would like to express my grateful feelings for my adviser, Prof. Ali Özer Ercan. Without any doubt, his extensive knowledge in multiple areas always inspired me and has an influential role in my research career. He always illumine me towards my research goals, with his careful assessment and full encouragement. Moreover, I also had an honour of taking his courses, which later on played a significant role in my dissertation. Without any reservation, I can say that my Prof. will be a role model for me in my possible future research career.

I really want to thank the respected Asst. Prof. Ahmet Tekin for his motivation. He helped me to look at my research problems from different points of view and always making insightful suggestions at our discussions. Here, i also want to mention the name of Mr. Mert at Electronics Lab of OzU, who has been very helping in the PCB fabrication and in other hardware experimental tasks.

I would also like to thank my colleague and a very good friend Osama Amjad. He has always been very encouraging and cooperative throughout my Master research. I am really obliged of his support and patience with me. I am highly thankful to all of my great friends during MS studies. Without their support, help and friendship, this work would not be possible.

I wish to thank TÜBİTAK for supporting this thesis work under Grant No. 114E739. I also wish to thank to all the great people at Department of Electrical and Electronics Engineering Ozyegin University. Without any doubt, I have learnt a lot from them during my entire degree at OzU.

Last but not least, I would like to express my greatest gratitude to my parents and my siblings. Their blessings and sincere wishes have always been a constant source of encouragement and strength for me. Without their support, this work would not have been possible and I feel very blessed to have them. This dissertation is dedicated to my great mother and father.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In recent years, there has been a rapid growth in many wireless communication applications such as wireless sensor networks and IoT etc [1]. Since these applications constitute of large number of low power sensors, so ubiquitous supply of energy is essential for their operation [2]. This led to the need of self sustained energizing technique for powering wireless sensor networks (WSNs), with no need of battery replacement. In this regard, energy harvesting from ambient environmental sources and converting them to usable DC voltage is the key solution [3]. Energy can be harvested from different sources like solar, wind, vibrational, thermal and electromagnetic Radio Frequency (RF) sources [4].

Solar energy can be a good option for harvesting energy, as it provides highest energy density and it can easily operate the low power IoT applications. Despite of the greater amount of harvested energy obtained, it is only able to function when sunlight is present. Similarly, wind energy and other sources have the same constraint of not been available all the time. Whereas, RF signals are omnipresent and thus feasibility of RF harvesting for IoT applications is kept as the main focus of this thesis. Although energy harvested from RF source may be enough only to supply very low power applications today but still among all the sources, RF signal source is preferred because of its adverse advantages [4]. With improvement and advancements in the technology, RF energy harvesting may become more efficient, which can ultimately solve the problem of replacing the batteries [5]. Secondly, RF energy is available throughout the day and being transmitted from many radio transmitters present in the specific vicinity. They include mobile cellular phones, mobile base stations, hand-held radios and television broadcast stations within a frequency range of 3 kHz to 300 GHz [2]. Therefore, it provides diverse spectrum opportunity for energy harvesting and energizing the low power devices without the regular need of replacing batteries [6]. In addition to this, there is an active research potential in the investigation of the multiple ways to scavenge energy from environment and convert them into electrical energy to energize low power devices [7]. These low power wireless applications can store this harvested energy for later use as well. Moreover, this particular area of RF/ microwave research also provides an enabling solution to the companies against finite electrical battery life. Consequently, it makes easy to drive wireless mobile devices for an increased duration of time. Therefore, there is a concrete motivation to equip the WSNs with energy harvesting ability that would not only lessen the operational cost of the system but also make it self sustained system (shown in Figure 1) [8]. As

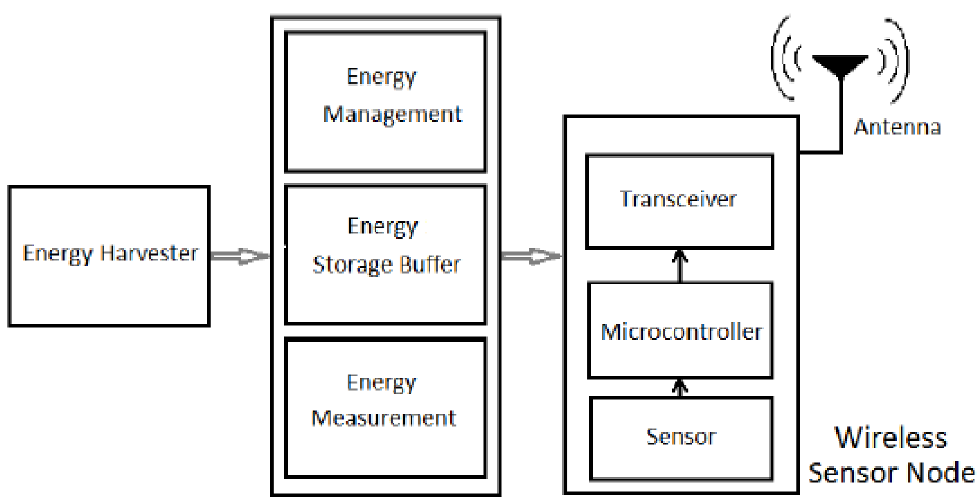

Figure 1: Block Diagram of Energy harvesting Wireless Sensor Node [8]

a result of this motivation, the presented work explains the design and optimization of WLAN energy harvesting system architecture. The analysis shows that designed system is efficient enough to provide power to the wireless sensor node.

1.1 Brief Overview of Energy Harvesting Architecture

The basic architecture of RF energy harvesting has been shown in Figure 2. It includes the receiving antenna, matching network and voltage rectifier, that finally provides DC output voltage for load circuitry. There are certain constraints associated with processing circuitry of RF energy harvesting system, which are also dealt in this work. By optimizing and improving such constraints, overall system output and efficiency can be increased thus, making RF energy harvesting a promising solution for low power applications [9].

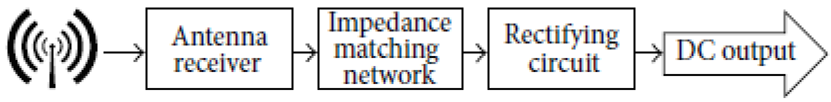

Figure 2: Overall General Architecture

Different RF sources can be used to harvest energy e.g. FM/AM, WLAN, LTE/GSM cellular base stations and DTV sources. The design of processing circuitry is dependent up on the type of RF source used as mentioned in the next chapters.

1.2 Contribution

This dissertation considers energy harvesting from WLAN dual RF frequencies i.e. 2.4 GHz and 5.8 GHz and includes the optimized circuit design for energy harvesting on Advance Design System (ADS) Agilent software. Moreover, it also presents RF signals transmission from WLAN source to receiver at a distance ranging from 1 m to 10 m via wireless channel, while considering realistic channel models provided by ADS. In simulation environment, dual-band microstrip patch antenna has been designed and used at receiving side to scavenge energy from Wi-Fi routers, which was published in [5]. Two separate impedance matching networks are designed for dual operating frequencies of WLAN which are composed of different combination of inductive and capacitive elements using smith chart utility [8]. It exhibits the efficient matching and maximum power transfer from antenna to the rest of circuit. 4-stage voltage rectifier has been designed to provide enough voltage to energize the low power devices and storage circuit has also been optimized. To compare this ideal design with practical realistic design, we have considered non-idealities in this design, by including PCB losses and component losses. In the end, we not only analyze this non-ideal system efficiency but also compares it with ideal design.

- In the previous work, only receiving part of RF energy harvesting was considered, which did not include the transmitter parameters and wireless channel attributes. It is the matter of fact that energy harvested is dependent on many factors out of which channel conditions, distance between source and harvesting circuit is an important consideration. In this work, characteristics of wireless channel and transmitter attributes have also been analyzed under different conditions.

- The past work majorly refers to the single RF band energy harvesting, while this work explains the design and analysis of dual band RF energy harvesting system. It is observed that harvested energy can be increased if multiple frequency bands are used. In this regard, two separate LC matching networks have been designed.

- In most of the work only design and simulations for ideal circuit has been shown as in [3], whereas presented work models the actual non-ideal behaviour of RF energy harvesting system. It explains the inclusion of PCB losses and parasitic losses and shows their effects on the overall efficiency of an ideal system. The ADS simulations have been performed under different source power values, at different distance range from transmitter and finally the overall efficiency and total harvested energy has been calculated for both WLAN frequencies.

1.3 *Outline of Thesis*

This dissertation is organized in five chapters, as follows:

The first chapter is an introduction section that outlines the work as well as instigates the research covered in this work. The second chapter covers theoretical background research work and also some of the existing research potential in RF energy harvesting that was used as beginning step point for the circuit design outlined in this thesis. The third chapter explains the circuit design to harvest energy from WLAN dual band RF and analysis in the light of system efficiency and total energy harvested. Moreover, it also includes the effect of transmission frequency, channel conditions, distance between source and receiver and source power. The fourth chapter includes the simulations used to model the actual non-idealities, that occur in real circuits, such as the PCB and parasitic losses, and compares the harvesting results with the ideal case. The final chapter concludes the thesis by providing the conclusions drawn from this work as well suggests some improvements in energy harvesting circuit that would lead to a more efficient design and overall total harvested energy can be increased.

CHAPTER II

RELATED WORK

Recently, there has been an upsurge of research interest in providing energy harvesting ability to wireless devices . It enables the wireless system or node to sustain its energy consumption demand, which in turn is a promising solution against limited battery lifetime and its replacement [8]. Moreover, energy harvesting has a key enabling role in virtually perpetual operation of wireless sensor networks (WSNs). Energy scavenging can be classified, according to the source, from where energy is harvested as shown in the Figure 3 [2].

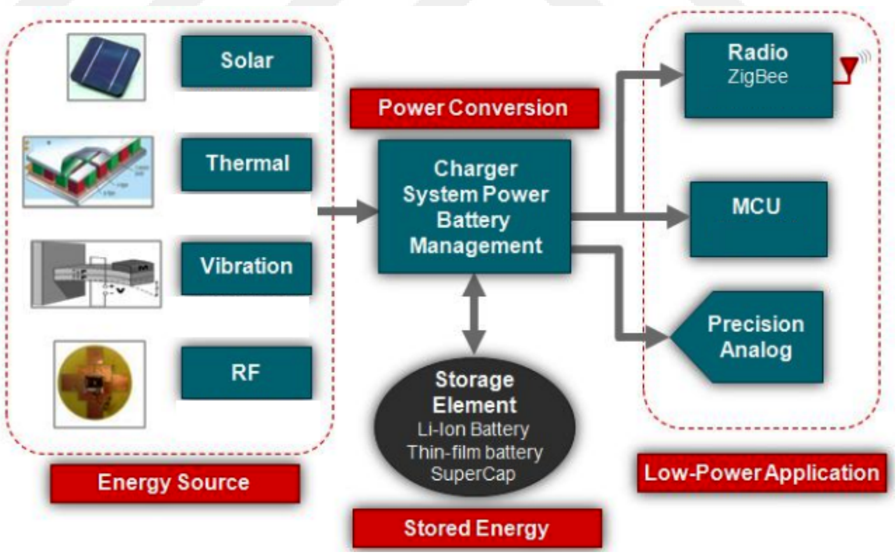

Figure 3: Energy Harvesting from different sources [2].

Above flow diagram shows the fact that after energy has been collected from environment, the signals are directed to the power conversion unit, which is designed according to the type of source [8]. However, overall hierarchy remain the same i.e. conversion of collected signal to DC voltage. It is important to note the total amount of energy harvested from different sources are not same, as Table. 1 shows the estimated power per unit area, that can be harvested from different available sources. In [4] it has been explained, that energy can be scavenged from solar and vibrational sources but RF sources are widely used, despite of the fact that less amount of energy can be harvested from RF as compared to solar, wind and other sources.

The most promising source for harvesting energy is sun. It is because of the fact, that it provides the highest energy density and solar cells are easily available in variety of sizes and capacity. Moreover, in [10] a solar energy harvesting method is used as a power source for wireless sensor networks, that consists of sensor motes. The integrated solar energy harvester presented in [11], scavenges energy by using array of photo-diodes, fabricated with storage capacitors on a chip. In spite of above mentioned benefits of solar harvesting, it also has a drawback of being able to operate only when direct sunlight is present.

Vibrational energy source can also be one of the candidate to energize the low power applications [8]. In [12] vibrational energy harvesting technique is presented, which uses the piezoelectric crystal. It elaborates the conversion of force applied on shoes during walk, to usable DC output voltage. Moreover, [13] has indicated that vibrational energy from environment can be used to operate autonomous wireless monitoring sensor system.

Despite of the fact that low energy can be harvested from RF signals, yet many recent research work is focused on RF energy harvesting because of ubiquitous availability of RF signals [14]. A wireless battery charging system using RF energy harvesting has been studied in [6]. Different RF sources have been used by the researchers to estimate the total amount of energy harvested, details are mentioned in Table. I. The maximum theoretical power available for RF energy harvesting is 7.0 μW and 1.0 μW for 2.4 GHz and 900 MHz frequency respectively; for free space distance of 40 meters, which is according to the FCC regulations limits defined [15]. Moreover, [4] presents an RF energy harvesting system that can scavenge energy from the ambient surroundings at the down-link RF frequecny of GSM-900. Similarly, an experimental RF energy harvesting system for cell towers is presented in [16]. The recent research also shows that a mobile phone can be energized with the charging rate of 4mV/second at a frequency of 915MHz [2].

Table 1: Total Harvested Power from Different RF Sources

RF Sources	Transmitting Power	Frequency Band	Distance	Harvested Power
TV tower [17]	960 kW	674680 MHz	4.1 km	60 mW
Downlink-GSM [18]	3 W	915 MHz	5 m	189 mW
LTE band [8]		906 MHz	15 m	0.3 μW
Mobile Phone [19]	0.5 W 0.5 W 0.5 W	915 MHz 915 MHz 915 MHz	1 m 5 m 10 m	40 mW/m^2 1.6 mW/m^2 0.4 mW/m^2
Cellular Tower [14]		800 MHz	30 cm	21.9 mW
Uplink-GSM [14]		1.9 GHz	30 cm	4.1 μW
WiFi Router [20]		2.4 GHz	1 m	0.001mW

WLAN 2.4 GHz RF energy harvesting system has been designed and analysed in [20] to achieve optimum amount of efficiency. The research in [6] provides different techniques for RF energy harvesting, that includes the generation of a small amount of the DC electrical power to drive circuits in wireless communication electronics devices. In [17], it has been mentioned that total of 60 μW energy is harvest-able

from Tokyo TV towers, which is 4.1 km away from energy harvesting system.

2.1 Recent Research on Energy Harvesting Antennas

Antenna at the receiving end of energy harvesting circuit has always been an important consideration for research teams [21], [22]. Receiving antenna and rectifying circuit combined called as rectenna, has significant impact on the efficiency of RF energy harvesting system [1], [23] and [24]. Recently, improved designs of rectenna have been implemented to increase the efficiency in terms of energy scavenging [6]. It has been reported in [5], [25], that an efficient energy harvesting system requires a rectenna with high RF-DC conversion. The primary design focus of past research on RF energy harvesting is scavenging energy from a single RF band [22], [20]. However, in the recent reported research, the design of dual band [24] and triple band [26] antennas for RF harvesting applications, have gained much attention. Moreover, in [27], [28], authors have highlighted the advantages of compact multiple band microstrip patch antennas for wireless applications.

Antennas can be designed in different structures, for instance dipole, unipolar and patch antennas. Whereas out of all forms of antenna, microstrip patch antenna has attained the great interest and attention because of its diverse advantages [6]. In this regard, several studies have been reported where microstrip patch antenna has proven the improved efficiency. The literature in [21], explains the comparison of different antennas and their impact on overall energy harvesting system. Microstrip patch antennas designed in [5], [24] consists of a square-shaped patch and it is fed via 50 Ω microstrip line. Such antennas are potentially well suited for RF energy harvesting system, due to the bandwidth criteria and return loss at designed frequencies [1]. Furthermore, miniaturized microstrip antennas have reduced overall size, so they are more likely to use in wireless devices [6]. In addition, they have wide range applications in telecommunication systems as they are economically low profile, light weight and compact, which consequently allow multi-band operation [26]. Different methodologies have been proposed by researchers, to fulfil the dual-band operation requirements; for example by simple variation in slot length and width of patch antenna has received much attention [27], [28]. In the presented work, dual band microstrip patch antenna has been utilized for designed RF energy harvesting system (explained in next chapter), which has also been published in [5].

2.2 Literature Review on the Processing Circuitry of RF Energy Harvesting

It is known that input impedance of harvesting circuit should be matched to the characteristics impedance of receiving antenna, to maximize the energy transfer [9]. In literature, different impedance matching techniques are discussed, matching can be accomplished by means of a LC matching, stub-matching network or pi-matching network [23], as shown in Figure 4.

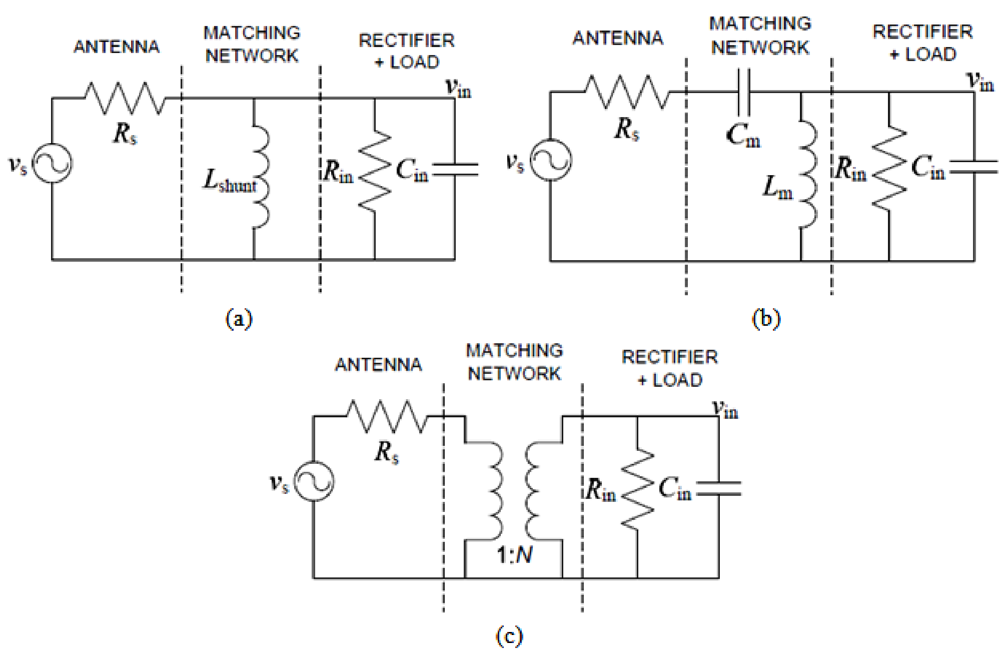

Figure 4: (a) Stub Matching (b) T- Matching (c) Pi-Matching [7].

In [4], the design of pi-matching network using inductor and capacitor has been presented, that matches the antenna impedance to the input impedance of rectifier. In [8], ADS smith chart utility has been used to find the optimum matching network for RF energy harvesting system. Similarly, [17] shows the design and implementation of matching network for harvesting energy from DTV source,which utilizes the design of T-matching network using the ADS smith chart tool. The output of matching circuit is fed to rectifier circuit, that converts the matched AC signal to usable DC voltage. Different topologies of rectifier circuit has been discussed in the literature for RF energy harvesting such as Greinacher rectifier [29], Villard voltage rectifier and Dickson rectifier [30]. Figure 5 shows the Villard and Dickson rectifiers, while Greinacher rectifier is used in [31]. The most important component of rectifier is diode, which plays significant role in harvesting maximum energy and consequently, enhances the overall efficiency of system. [2], [7].

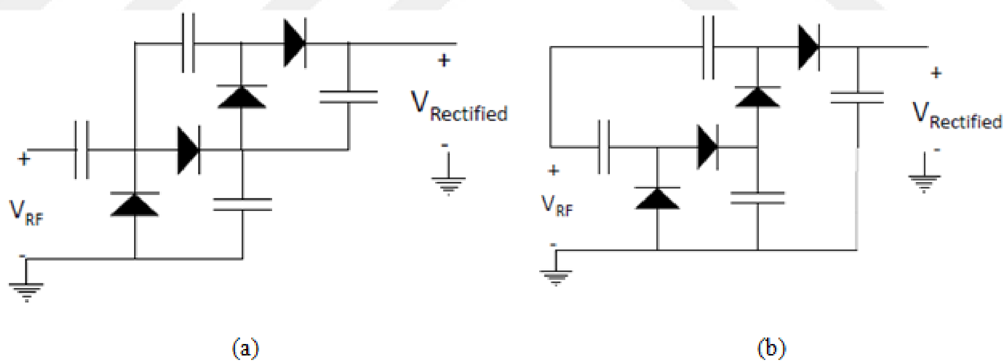

Figure 5: (a) Villard Rectifier (b) Dickson Rectifier [8].

It has been reported in [32] that HSMS-28XX Schottky diodes (shown in Figure 6) are the most preferable candidates for RF energy harvesting rectification circuitry. In [8], author has used HSMS-2850 Schottky diode because of its low capacitance and low forward voltage. Similarly, [3] shows the utilization of SMS7630 Schottky diode for WLAN energy harvesting system while low operating voltage HSMS-2860 Schottky diodes are been deployed in analogue TV harvesting system mentioned in

Figure 6: HSMS Schottky Diodes

[33] . Two Schottky diodes are used in each rectifier stage. The number of stages are another important consideration of rectifier circuit as mentioned in [5], [32]. Different number of stages are used in past research work depending upon the application and type of RF source.

2.3 Background Research About Non-Ideal Behaviour of Harvesting System

Modelling of all the losses and other non-idealities of ideal RF energy harvesting system is an important consideration. In chapter 4, detailed analysis of non-ideal model and its comparison with ideal circuit design will be discussed. As PCB losses will be considered so, it is important to consider some significant facts about transmission lines. Therefore, a short review has been done in this regard as well. PCB lines/ microstrip lines are used in circuit implementation, they carry and transmit RF/microwave signals. The physical parameters of these transmission lines are crucial and they vary according to the frequency of signal transmitting through them [23].

The past research work on PCB design of RF energy harvesting circuit and its implementation shows that, critical consideration of substrate and transmission lines is required [1]. Moreover, component losses are also taken into account to nearly estimate the total loss during the RF energy harvesting operation [9].

It is important to contemplate all PCB losses and other factors of non-ideal circuit, because actual incident RF power on antenna can be 0 dBm or even lower and after passing through the processing circuitry it may decreases further [8]. Consequently, there is a requirement of such an energy harvesting circuit that can work properly under all these constraints and realistic condition. In this regard, [7] shows the PCB implementation of RF energy harvesting circuit. Similarly, [9] explains the procedure of designing non-ideal PCB layout using S-parameter analysis of ADS software. In the presented work, the design, analysis and comparison of non-ideal circuit design has been discussed in detail. Moreover, our work includes the hardware implementation of RF energy harvesting circuit along with the receiving antenna, which is a novel aspect.

CHAPTER III

RF ENERGY HARVESTING FROM WLAN ACCESS POINTS

3.1 Design of System Architecture

This chapter explains the design and analysis of RF energy harvesting from dual WLAN frequency band. It includes the detail design procedure of receiving microstrip patch antenna, selection of stages in voltage rectifier and optimization of matching network. It will be shown later in this chapter, that the proposed circuit design can harvest energy from dual frequencies of WLAN. Moreover, the designed system is efficient enough to operate at dual frequency band and provide sufficient voltage, that may energize low power devices.

The overall RF energy harvesting system architecture comprises of two sub-systems namely RF signal transmitter/source and RF signal receiver. RF source generates and transmits the signal via pathloss channel, and signals are ultimately incident on receiving antenna [30]. The crucial challenge in harvesting RF energy is the path loss between source and the receiver. The Friis transmission equation (1) [34] relates the received (P_r) and transmitted source (P_s) powers with the distance R as:

$$P_r = P_s G_t G_r (\frac{\lambda}{4\pi d})^2 \tag{1}$$

Where G_t and G_r are antenna gains, and λ is the wavelength of the transmitted signal. The received RF power decreases with the square of the distance in free space environment, while it becomes worse in case of urban and rural environment. Thus energy harvesting circuit requires special design consideration and it becomes more critical issue when real time environment is considered which involves various channel conditions as shown in Figure 7.

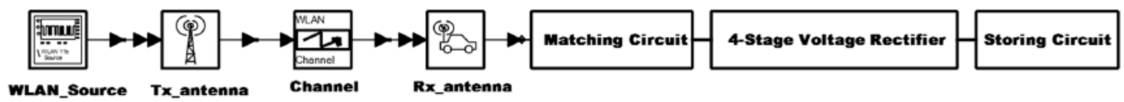

Figure 7: The proposed architecture

The proposed architecture is simulated on ADS Agilent software, which not only provides an option for WLAN source but also considers practical channel model including all the real time impairments. A frequency domain method of harmonic balanced analysis is used in this work since our ultimate goal is to compute the steady state solution of a non-linear circuit. The source power (P_s) of the transmitter and the distance (d) between the transmitting RF source and receiving antenna greatly affects the harvested energy [2]. RF signals are transmitted from WLAN 802.11a/b source via transmitter antenna and wireless channel, which are collected at the energy harvesting circuitry. The front-end of RF energy harvester is the receiving antenna, which converts the incident RF signal into AC voltages and currents.

The matching network ensures the maximum power delivery from antenna to voltage rectifier and increases the input power to the rest of the circuit. In our case 4-stage voltage rectifier has been used and LC matching technique is utilized for the design of matching circuit. The storing circuit at the end of system architecture allows uninterrupted power delivery to the load even when external energy is not available [16]. Figure 8 shows the proposed system architecture of receiving side of RF energy harvesting system. In RF energy harvesting, the amount of harvested energy depends on the transmitting power, frequency of the RF signals and the distance between RF signal source and the harvesting system.

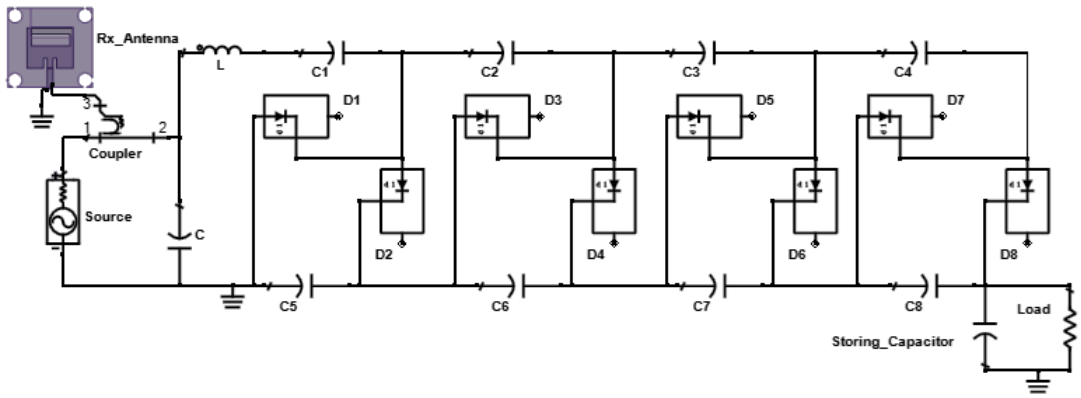

Figure 8: Schematic diagram of 4-stage WLAN energy harvesting system

3.2 Effect of Transmitting Source Power

Transmitting power has a significant effect on the total energy obtained at the output of circuit. WLAN source can operate at different RF power levels and with the change in P_s, the received RF power changes accordingly. In this regard, three realistic transmitter power levels are considered and simulations are performed to obtain the results in Figure 9 (a, b). Whereas, Figure 9 (a) reveals that for 2.4 GHz and at a fixed distance of 1 meter, almost 20 dBm, 15 dBm and 10 dBm power is collected on receiving antenna against P_s = 1 W, 500 mW and 200 mW respectively. By increasing source power, received power increases linearly, but increase is different for both WLAN frequencies i.e. received power for 2.4 GHz is more as compared to 5.8 GHz.

It also elaborates the fact that higher frequencies are more vulnerable to path-loss, that is the reason P_r at 5.8 GHz is less than 2.4 GHz for the fixed distance. By observing the above values of obtained P_r, rest of comparison and analysis considers P_r from -30 dBm to 30 dBm. Moreover, this received power is converted to total energy harvested at output of designed circuit in Figure 7. For different P_s levels, total harvested energy varies according to the fact that increase in source power leads to the exponential increase in total harvested energy with respect to time, as shown in Figure 10. It also elaborates the trend of harvested energy with source power, i.e. at fixed time instant of 8 ms and distance of 3 m, total harvested energy is 2.0 nJ and 4.0 nJ, when the source power (P_s) is 700 mW and 900 mW respectively.

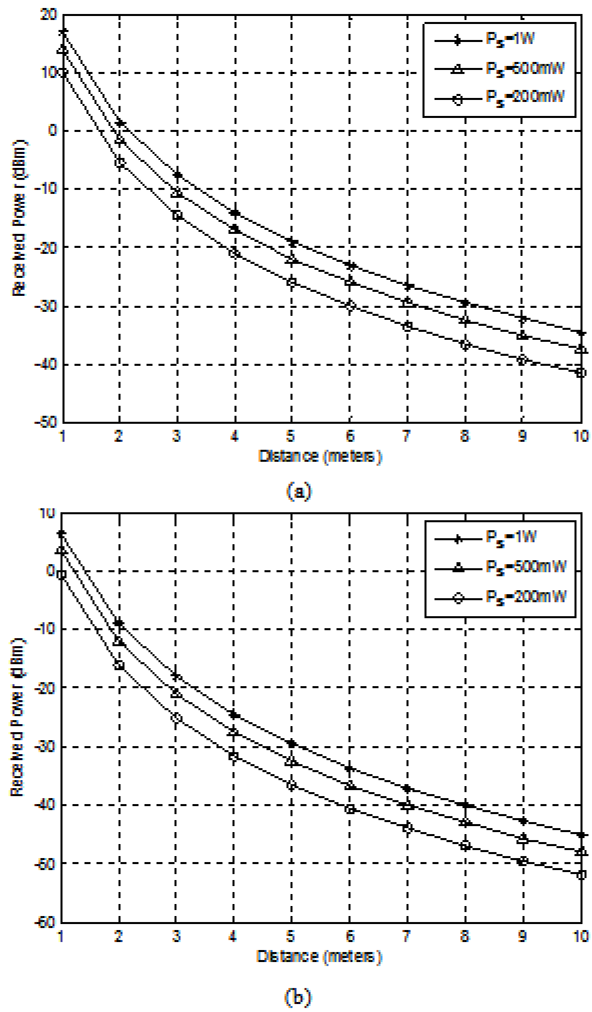

Figure 9: Effect of distance on received power at different transmitting power levels for Indoor Office Environment (a) at 2.4 GHz (b) at 5.8 GHz

3.2.1 Effect of Channel Conditions

The free-space model mentioned in equation (1) has the assumption that there is only one single path between a transmitter and a receiver. However, due to RF scattering and reflection, a receiver may collect RF signals from a transmitter via multiple paths.

Moreover, in practical indoor environment channel is no more free space so wireless fading channel model of ADS, and realistic indoor office environment has been used in simulations.

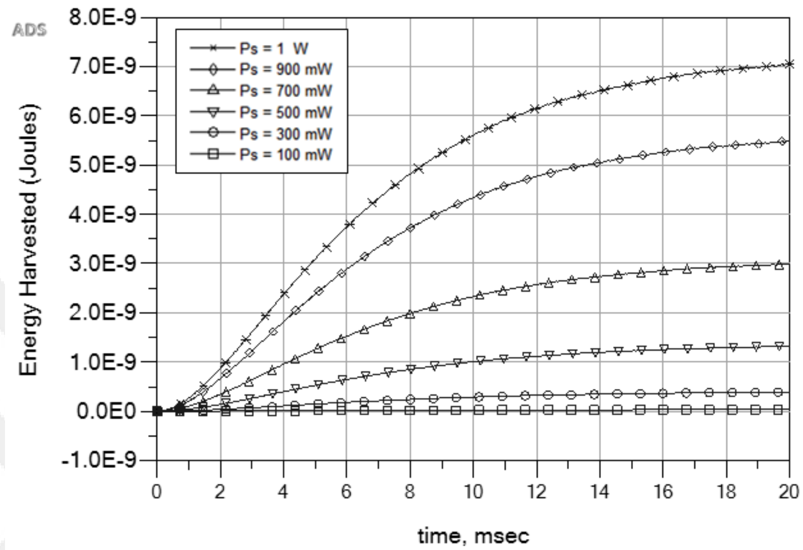

Figure 10: Effect of source power (P_s) on harvested energy

In order to investigate the effect of realistic channel model and power incident on receiving antenna for a range of distance, circuit shown in Figure 7 has been used. Whereas, receiving antenna is integrated with harvesting circuit which scavenges energy at dual frequencies of 2.4 GHz and 5.8 GHz. In simulations, distance is varied between 1 meter to 10 meters and corresponding received power (P_r) is measured at receiving antenna, the plot of received power versus distance is shown in Figure 9. The (P_r) diminishes with increase in distance between source and harvesting circuit.

3.3 WLAN Dual-Band Microstrip Patch Antenna

The antenna can be designed to operate on either single frequency or multiple frequencies, in which the system can harvest from a single or multiple sources simultaneously [24]. The efficient way of RF energy harvesting is to design an antenna that can operate on multiple frequency bands so that system can simultaneously harvest from a single or multiple sources [21]. In this regard, design of high directive dual band microstrip patch antenna has received much importance [6]. Moreover, such antennas have promising gain and bandwidth values [4].

In the presented work, our dual band microstrip patch antenna published in [], has been utilized as a receiving antenna to scavenge WLAN-RF signals from the environment. The designed antenna can simultaneously harvest energy from dual WLAN frequency bands i.e. 2.4 GHz and 5.8 GHz, and it is efficient enough to transfer maximum power from environment to the rest of processing circuitry. In the presented work, transmitted WLAN signals are received by patch antenna via wireless channel which are then converted to DC power by the voltage rectifier block after impedance matching.

3.3.1 Fabricated Antenna Results

In order to authenticate our simulated results mentioned in [], a prototype of the proposed antenna is implemented and fabricated on FR-4 epoxy substrate (ϵ_r=4.4, tanD=0.025) as shown in Figure 11.

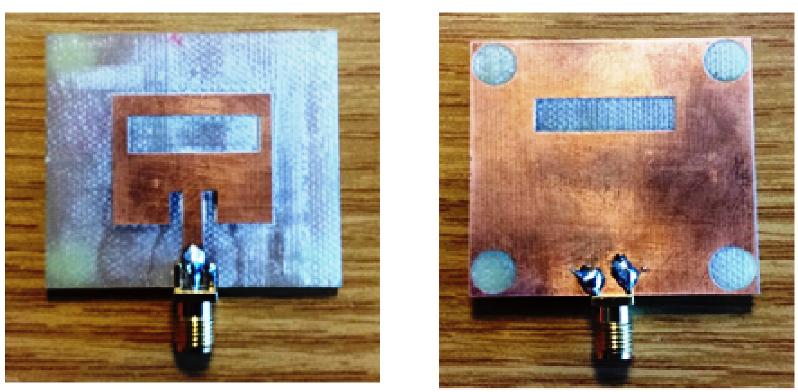

Figure 11: Fabricated prototype of designed WLAN microstrip patch antenna

The dielectric constant of the substrate is the most important parameter as it has a considerable role in the overall performance, width, length and resonant frequency of antenna [20], [24]. The physical dimensions of prototype are kept according to the equations mentioned in [23]. Whereas in general, microstrip antennas are $\frac{1}{2}\lambda$ structures; thus, they are easy to fabricate and their size make them preferable to be used in RF energy harvesting applications. [21].

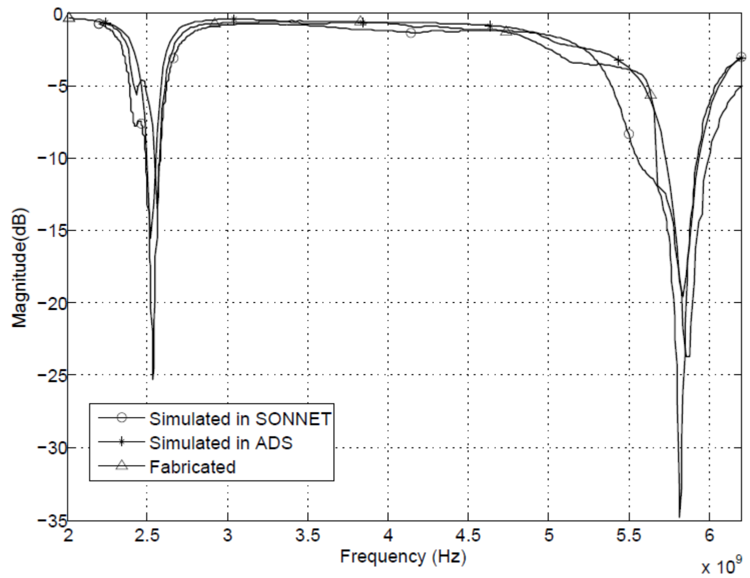

Figure 12: Simulated and fabricated reflection coefficient of proposed antenna

Figure 12 shows the simulated and measured results of the proposed antenna, it is clear that for 2.4 GHz, the 10 dB bandwidth is between 2.39-2.52 GHz, which covers the IEEE 802.11b frequency band. Similarly at 5.8 GHz, the bandwidth is between 5.65-5.85 GHz and reflection coefficient is as low as -35 dB. Thus, the proposed antenna receives all the frequencies of desired bands and attenuates the rest of unwanted frequencies. If measured results of antenna are compared with the simulated results, the measured reflection coefficient displays well agreement in resonance frequency bands and corresponding bandwidth. Later, in next chapter the antenna has been integrated with the rest of energy harvesting circuit using ADS momentum layout.

3.4 Matching Network

According to the operating frequency of RF source, the received RF power (P_r) is matched with the remaining circuit. Impedance matching is important in the design of energy harvesting system as it decreases the transmission loss between antenna and rectifier, thus increases the voltage for rectifier circuit [25].

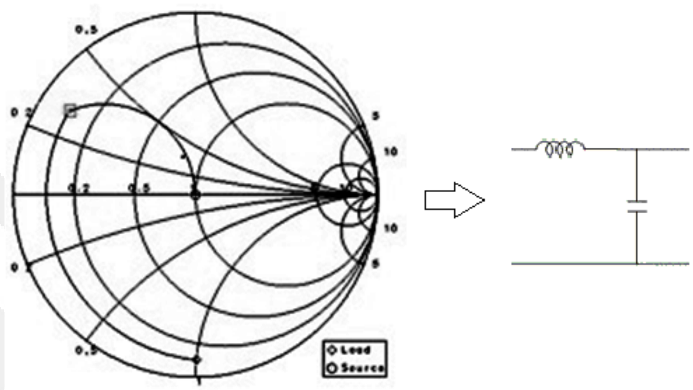

Figure 13: (a) ADS smith chart utility (b) The proposed LC matching network

The most commonly used impedance-matching technique for energy harvesting, is LC matching network. In the presented work, as shown in Figure 13 (a), ADS smith chart [8] is used to obtain two different LC matching networks for WLAN dual frequency bands with optimal values of inductor and capacitor, such that high RF-DC conversion efficiency is achieved. Firstly in ADS, the load impedance for matching circuit was simulated (shown by square on Figure 13 (a)) and then smith chart utility assistance was done to find the best power matching LC network, one similar to Figure 13 (b). For that perfect matching circuit, the impedance was matched to centre i.e. 50 ohms; which is shown by an arc extended from square to the centre of the smith chart. To verify the design of our matching circuit which is connected to the output of antenna, input and output voltage has been plotted in ADS. This is done in order to verify that matching circuit is providing the exact matched antenna to voltage rectifier, as shown in Figure 14.

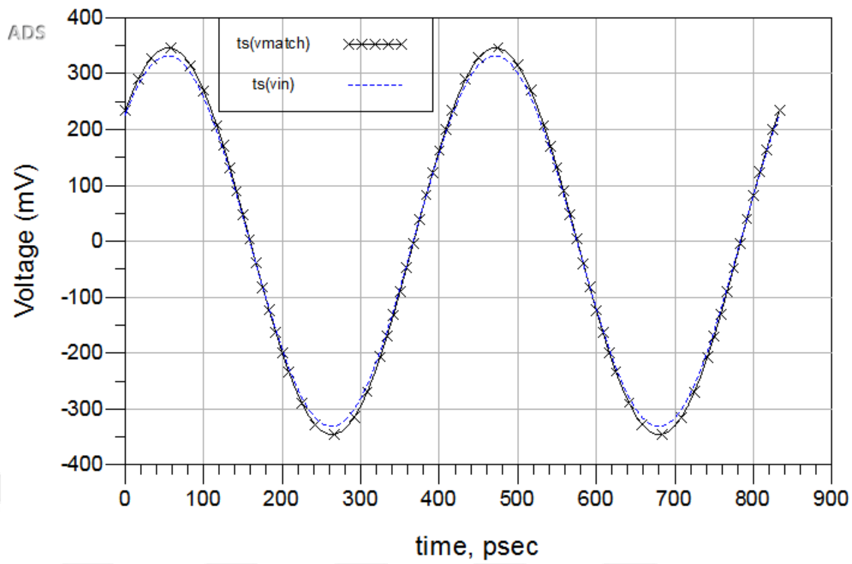

Figure 14: Output voltage of matching circuit

The above figure shows that input voltage (v_{in}) is matched to v_{match}, thus satisfying the purpose of impedance matching. In addition, it can also be seen that voltage is AC; which means that rectifier is needed to convert it to DC power. Small alterations in the matching circuit parameters can change the frequency range over which the power transfer is maximum [7]. The efficiency of the impedance matching is high at the designed frequency, that is why separate matching combinations are used for low and high WLAN frequencies. After matching circuit, signal is then fed to voltage rectifier which converts RF power to DC output voltage.

As it is already mentioned that, two matching networks are designed for dual WLAN frequencies and they are integrated one by one with the rest of the circuit to obtain the results. However for practical prototype, two complete separate circuits are needed to evaluate the corresponding results. To fix this critical issue, two separate bandpass filters can be deployed at the output of matching networks as mentioned in [9]. The twofold reason of each bandpass filter is: that it allows the frequency band to pass, whose power transfer is being maximized by the respective impedance matching network e.g in case of 2.4 GHz matching network is connected to bandpass filter which only allows this lower WLAN band. The second most important consideration, is to reject the high-frequency components which consequently results in the undesired harmonic re-radiation and electromagnetic (EM) interferences [9].

3.5 Voltage Rectifier

The main component of the rectifying circuit are diodes, which transforms RF signals into DC voltage [20]. Single stage voltage rectifier consists of stage capacitors and diodes as shown in Figure 15. Whereas, multistage rectifier design is recommended for an increased efficiency of energy harvesting system. Generally, higher conversion efficiency can be achieved by diodes with lower built-in voltage [5]. In the presented work, 4-stage voltage rectifier is used, while topology is Grainacher voltage doubler [3] which provides enough and smooth voltage supply to operate low power wireless system.

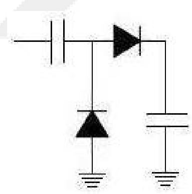

Figure 15: Single stage voltage rectifier

3.5.1 Choice of Non-Linear Components

The selection of non-linear component diode is of significance importance, as it determines the conversion efficiency of system [1]. Conversion efficiency is defined as a ratio of DC output power to incident power on receiving antenna. It is of paramount importance to measure the efficiency of designed system [33].

$$\eta = \frac{DCOutputPower}{InputRFPower} \tag{2}$$

In designing RF energy harvesting circuit, it is desirable to attain higher conversion efficiency so low built in voltage diodes are preferred. HSMS-285x family of zero

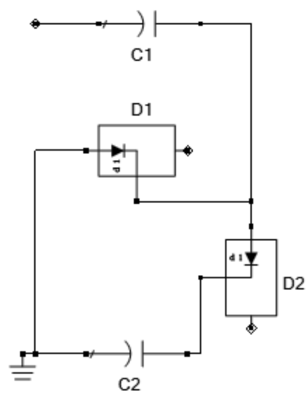

Figure 16: Voltage Rectifier with Schottky Diode

bias Schottky detector diodes has been designed and optimized for use in circuits where input power may be as low as -20 dBm. They are ideal component for RF-ID applications [22]. Moreover, these microwave detector diodes from Avago technologies are preferred because of its low forward voltage as well as its ability to perform up to 5.8 GHz RF frequencies. High frequency diode (HF) vendor library in ADS provides an option to select HSMS-2850 diode which not only increases the low built in voltage but also provide low substrate losses [32]. Single stage voltage rectifier shown in Figure 16, is made up of two HSMS-2850 diodes and two stage capacitors of same values. Whereas, if high voltage diodes are used it results in significant increase of harmonics due to the nonlinear behaviour of the diode; consequently, it decreases the conversion efficiency of rectifier circuitry [22], [15]. There is another critical parameter i.e. saturation current, which has impact on the efficiency of diodes. In designing RF energy harvesting circuit, it is preferred that diodes should have high saturation current, low equivalent series resistance (ESR) and low junction capacitance [32].

3.5.2 Effect of Number of Stages

The number of rectifier stages has a major influence on the output voltage of the energy harvesting circuit. Selection of number of rectifier stages should be done carefully such that output voltage can be enough to energize low power devices.

Optimal number of stages should be added to the system because parasitic loss of non-linear devices increase by increasing number of stages which effects the overall performance and efficiency of system [3], [8].

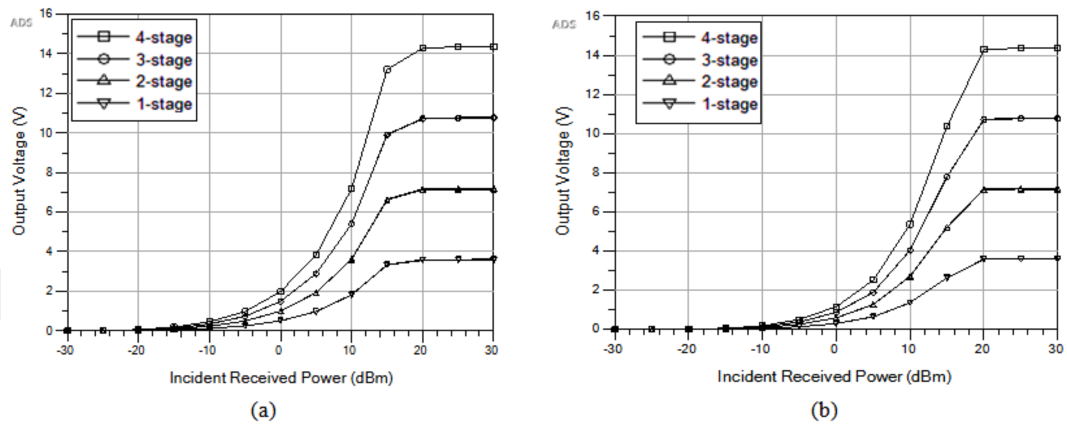

Figure 17: Stored voltage versus input RF power for different rectifier stages (a) at 2.4 GHz (b) at 5.8 GHz

Voltage stored at the storing capacitor has a direct relation with number of stages i.e. voltae stored is directly proportional to the number of stages. By increasing number of stages, output voltage increases but after certain number of stages, efficiency of system decays down. In the designed system, 4-stages of voltage rectifier are cascaded in series with each other. Figure 17 and Figure 18 show the effect of number of stages on output voltage stored at capacitor and overall efficiency of system respectively. The designed system can provide voltage of 7 V across 10 kΩ load for an input power of 10 dBm, given that signal transmitting frequency is 2.4 GHz as shown in Figure 17 (a). In ADS simulations for input RF power, parameter sweep of -30 dBm to 30 dBm has been used and number of rectifier stages are varied from 1 to 4. Moreover, it can also be seen that voltage increases exponential and saturates after 12 dBm because at this point capacitor fills up and reaches its saturation level.

It is clear from Figure 17 and Figure 18 that, the number of stages are directly proportional to the output voltage and the efficiency of the energy harvesting system.

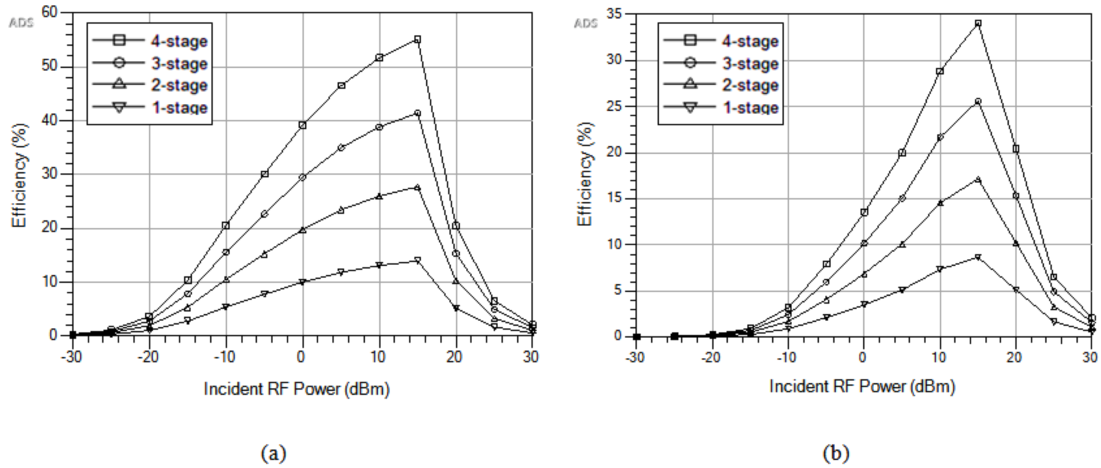

Figure 18: Efficiency versus Incident RF Power at different rectifier stages (a) For 2.4 GHz (b) For 5.8 GHz

However, losses due to the nonlinear components in each rectifier stage limit the number of stages in the designed system. Therefore, if the number of rectifier stages are increased further, the voltage gain and overall efficiency would decrease. Thus, this aspect make it necessary to choose such number of stages which can provide sufficient voltage for WSNs applications. According to [33], turn-on voltages of typical sensor nodes are in the range of 1.8 V - 3.6 V, thus our proposed system of 4-stages is suitable to provide the maximum required voltage for sensors node applications. Moreover,the highest efficiency of 57% is achievable at an input power of 15 dBm for 2.4 GHz, after that it decreases as shown in Figure 18 (a). It can be inferred that increase in RF input power is relatively higher than increase in respective output DC power; therefore, over all efficiency decreases after certain threshold power level as shown in Figure 18 (a, b).

3.6 Storage Circuit

In storing circuit optimum capacitor should be used which can store enough charge to power the intended application such as wireless sensor nodes. Our proposed circuit design includes a capacitor across the load to store and provide DC output voltage (shown in Figure 19). The output is not a good DC signal without a capacitor across the load [4], so it is optimized to store sufficient amount of charge.

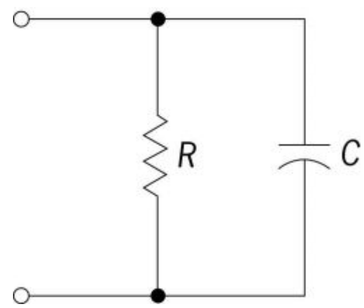

Figure 19: Storage Circuit

3.6.1 Selection of Capacitor

The reasonable value of capacitor can be used to store enough energy for the intended applications. In Figure 20, the voltage on the storage capacitor as a function of time is plotted for a range of capacitance values. In addition, charging time is also of

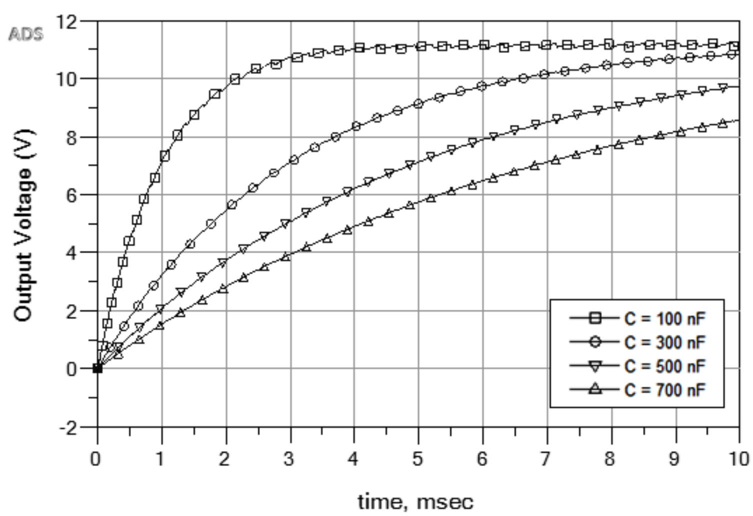

Figure 20: Output voltage versus time at different storage capacitors.

paramount importance while selecting a storage capacitor, because if it is too short the output at the node may experience energy shortage; whereas if it is too long, an additional amount of energy will be lost due to leakage in capacitor [33]. Among the tested values of capacitors, 700 nF has more charging time as compared to 100 nF as shown in Figure 20; for example, 100 nF capacitor saturates at 3 ms, while 700 nF is still in charging state even at 10 ms. Therefore, optimum capacitors should be chosen according to the requirement of application. There are some applications where capacitors may not be able to store enough charge, then a battery or a super capacitor can be deployed as an alternative [1].

3.6.2 Effect of Load Resistor

In ADS effect of load resistor has been simulated using parameters sweep of -30 dBm to 30 dBm for RF input power and 10 kΩ to 160 kΩ for load resistor. It is clear from Figure 21, that the circuit yields the optimized value of efficiency at a particular load, or we can say that efficiency decreases if either load value is too high or it is very low. It can be observed that among the tested loads, resistor of 10 kΩ provides the maximum attainable efficiency in case of both 2.4 GHz and 5.8 GHz, i.e. our system works efficiently if load value is 10 kΩ as in Figure 21 (a, b).

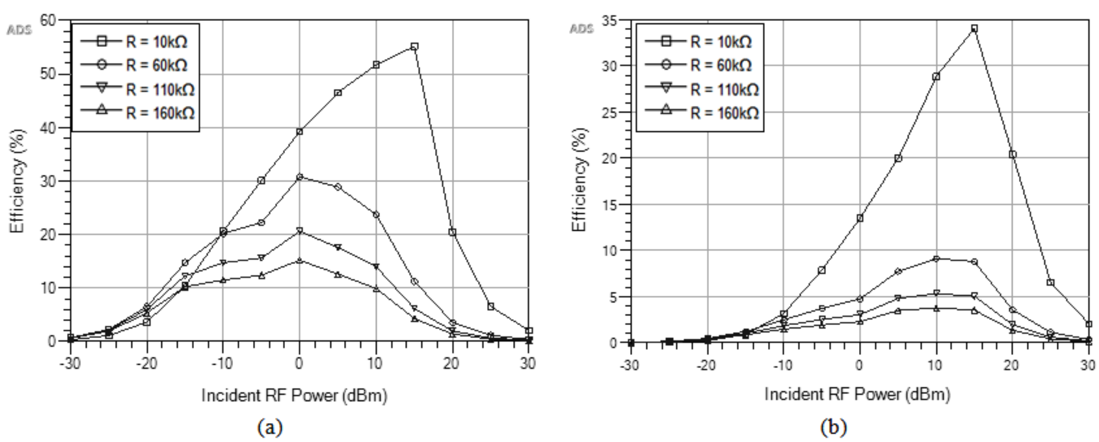

Figure 21: Efficiency versus incident RF power at different loads (a) for 2.4 GHz (b) for 5.8 GHz

However when received power is lower, i.e. from -30 dBm to -15 dBm then 60 kΩ load provides the maximum efficiency. The amount of total charge stored in capacitor at output end of circuit also depends on the transmitting frequency of source. WLAN dual frequencies provides different efficiencies and voltages as shown in Figure 18 and Figure 21. Low transmitting frequency provides overall efficiency of 57% while at 5.8 GHz, the efficiency decreases to 35%. Similarly, the voltage obtained at the output of the circuit also decreases at high transmitting frequency as shown in Figure 18 (a, b). For example, at P_r= 10 dBm, maximum voltage for 2.4 GHz and 5.8 GHz is 7 V and 5 V respectively.

3.7 Impact of Channel Impairments on Harvested Energy

The total amount of energy harvested depends on the number of factors as mentioned in previous section. We know that, the wireless radio channel offers fundamental limitations to the performance of any wireless communications systems. Moreover, radio channels are very random, thus their effect is not easy to analyze [34]. Such channel impairments e.g. path-loss and different fading models drastically effects the total amount of harvested energy.

3.7.1 Effect of Path-Loss

Impact of fading model or impairment conditions of a channel on the total amount of harvested energy is shown in Figure 23. In the designed system, energy collected at the output storing capacitor varies with the distance between transmitter and receiver. Path-loss is directly proportional to the distance between source and receiver, because path loss of the channel is the ratio of transmitted power to the received power; whereas, received power varies with the distance [34].

Therefore, it is an important parameter which not only effects the total received power at the front-end of receiving antenna, but also total harvested energy. Energy harvested is plotted on log scale as a function of time for a range of distance as shown in Figure 22. It is noticeable that energy increases exponentially with time but decreases as an inverse function with increase in distance, e.g. at 5 ms energy obtained at 1 meter is greater than energy collected at a distance of 10 meters. The exponential increase is because of the fact that energy stored is function of voltage collected at capacitor which has exponential relation with time.

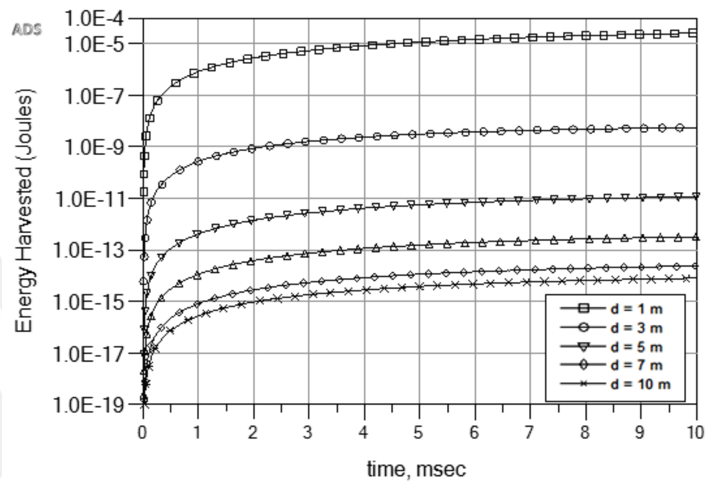

Figure 22: Energy harvested versus time for range of distance from transmitter

3.7.2 Effect of Different Fading Models

A fading model is a statistical model to include the effect of a propagation environment on RF signals [35]. In simulation, ADS Agilent provides an option of channel model type which can be changed as an no fading, rayleigh faded or rician faded. Energy as a function of time varies according to the type of channel selected as shown in Figure 23.

It can be clearly seen that at a fixed distance of 1 m and a constant P_s of 1 W, energy harvested from rayleigh faded channel is less than no fading and rician channel. It is because of the fact, that in rayleigh fading there is no line of sight (LOS). Signal in this case is obtained via reflected paths, thus received signal becomes more distorted and faded as compared to rician where there is one or more LOS [34].

The result shown in Figure 23 satisfies the basic wireless communication channel

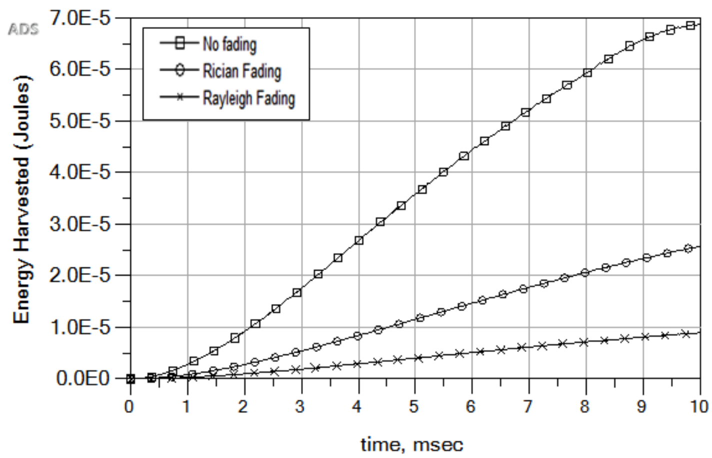

Figure 23: Energy harvested versus time at different fading models

modelling approach i.e. the output of: $Rayleigh\ Channel < Rician\ Channel < Nofading\ Channel$ [35]. The performance of rayleigh fading channel is the worst, as bit error rate (BER) of this channel is much affected by noise [35]. In addition to the channel impairments, there are other important factors which can greatly effects the output. These constraints mainly are component losses and PCB fabrication losses, which will be discussed in next chapter.

CHAPTER IV

MODELLING OF NON-IDEALITIES IN RF ENERGY HARVESTING SYSTEM

This chapter focuses on modelling and analysis of non-idealities in WLAN-RF energy harvesting system. The previous chapter explains the design methodology for ideal harvesting system and provides the analysis under the influence of different constraints. As described earlier, RF energy harvesting system constitutes of some important components, that includes receiving antenna, impedance matching network, voltage rectification circuit and load branch; which can be a wireless sensor network e.g. sensor-node or some IoT applications.

The main goal is to analyze and discuss the non-ideal behaviour of RF energy harvesting circuit. For this purpose, we need to understand the factors that are responsible for non-ideal behaviour of any circuit. In this regard, the two important parameters that should be taken into account are, the practical losses of components and the fabrication losses. In this work, ideal schematic mentioned in chapter-3, is transformed to non-ideal design by doing the following steps and procedure:

1. Ideal components are replaced by the non-ideal vendor based components as shown in Figure 24.

2. The traces of transmission lines are placed around each component to include the conductor and dielectric losses [7].

Further details of above two steps are mentioned in the next sections. Moreover, non-ideal circuit has been modified in ADS Agilent schematic and for its S-parameters analysis, layout momentum design has been generated corresponding to schematic (shown in Figure 25). This chapter shows the non-ideal circuit design for 2.4 GHz and 5.8 GHz, while design procedure for only low frequency has been reported in this thesis. Similar procedure is adopted for designing 5.8 GHz non-ideal circuit.

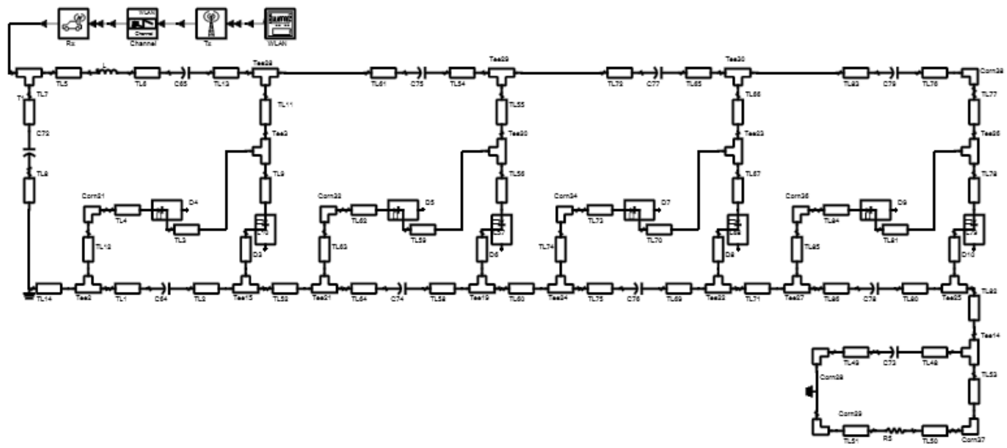

Figure 24: Schematic design of non-ideal circuit for WLAN energy harvesting.

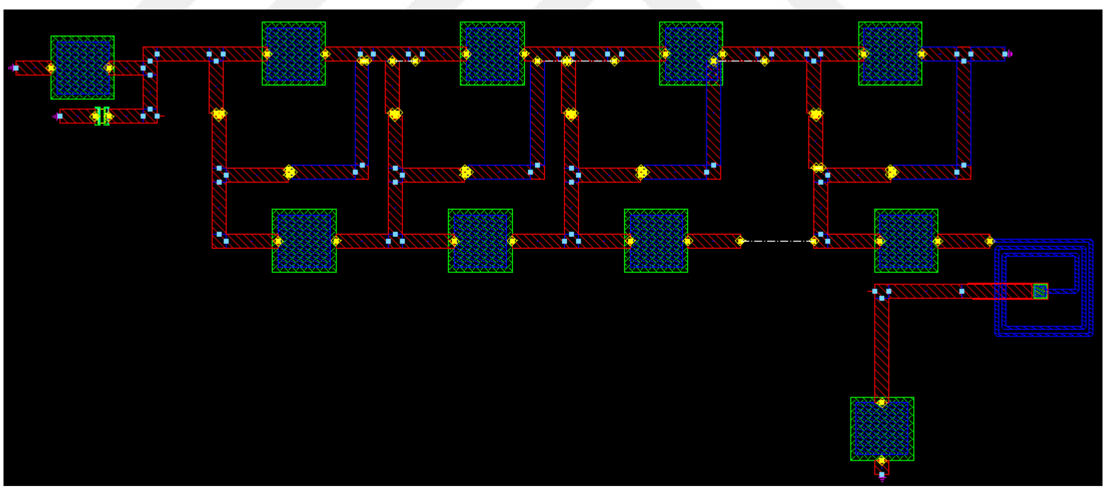

Figure 25: PCB Layout of non-ideal circuit for WLAN energy harvesting.

4.1 Circuit Design and Analysis

In previous simulations and analysis, we assumed that all the components except Schottky diodes exhibit ideal behaviour. The results obtained under this ideal assumption, reveals specific efficiency, output voltage and ultimately total energy harvested at different times and for a range of input RF power. To analyze and compare the similar results for non-ideal design, inclusion of parasitic effects and losses from non-ideal components should be considered. Moreover, it is significantly important to incorporate all related practical models of components and substrate losses in the simulations.

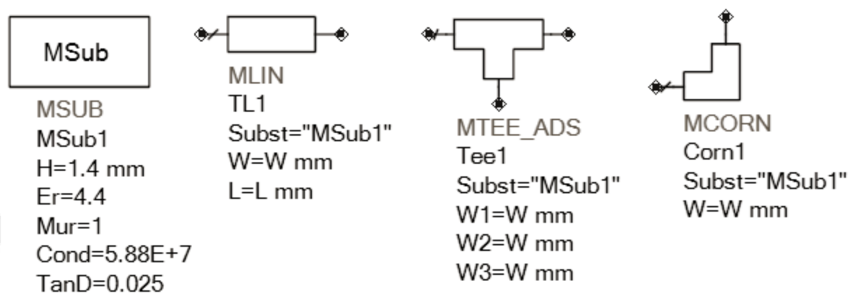

Figure 26: MSUB, MLIN, MTEE and MCORN modules of ADS

Therefore, Agilent ADS ideal case simulations have been repeated after incorporating the microstrip transmission line (MLIN), to include the Printed Circuit Board (PCB) losses i.e conductor and dielectric losses. In other words, connecting lines are now replaced with straight MLIN, cross shape, tee and corner junctions shown in Figure 26. The dimensions of transmission lines are calculated using line calculator [9] tool of ADS, which provides an option to calculate the length and width of line against receiving frequency, relative permittivity and substrate thickness .

Moreover ADS substrate module, MSUB is used to define the dielectric parameters, i.e. ϵ_r and tanD. In addition, ADS vendor supplied component libraries are used to model the components for circuit design as shown in Figure 24. It not only provides a closer result to that of the practical system, but also anticipate the maximum achievable efficiency and total harvested energy. In addition, the design also elaborates the integration of WLAN source, transmitter, wireless channel and receiving antenna to the PCB layout.

4.1.1 Inclusion of PCB Losses

With the effect of PCB included, one can estimate the losses due to the dimensions of traces and substrate leakages of a practical prototype [8]. According to the specific design, the alteration of substrate characteristics can be performed by the option provided by MSUB block shown in Figure 26. MLIN are placed around each lumped components to incorporate the PCB traces loss in practical scenario as depicted in Figure 24.

The substrate definition has been provided, which is FR-4 epoxy substrate with ϵ_r equal to 4.4 and tanD of 0.025. Whereby, in Figure 26 'H' is cover height and 'Mu' is relative permeability. Secondly, the microstrip line is configured by defining length and width according to results of line calculator [17]. After defining substrate and trace characteristics, the transformed circuit has been integrated to channel model via receiving antenna, to include the effect of channel impairments on the total harvested energy.

4.1.2 Influence of Components Losses

It is known that each component in practical circuit has some losses which depends upon the value and the physical size of component. To incorporate this type of losses, vendor component library of ADS has been used. Instead of using ideal lumped component as for the ideal circuit design mentioned in previous chapter, vendor defined components has been integrated in the schematic.

Consequently at this stage, our designed RF energy harvesting circuit not only considers the practical losses due to PCB fabrication, but also estimates the losses due to components themselves. The explanatory flow chart for the complete procedure of non-ideal circuit analysis has been shown in Figure 27.

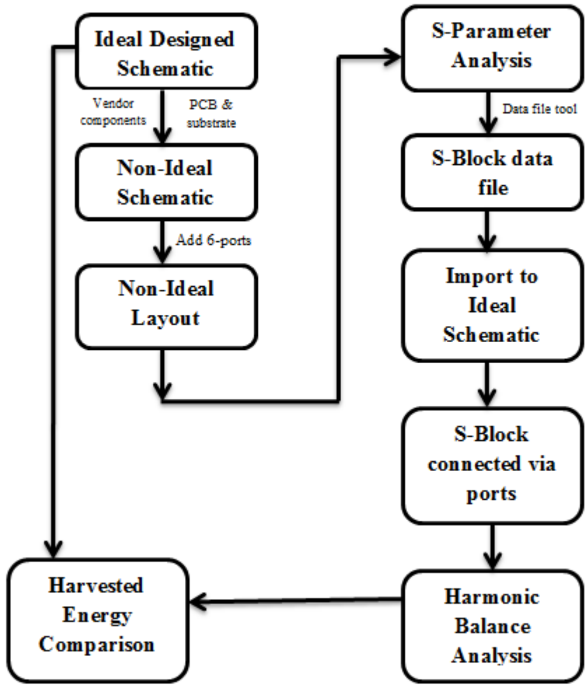

Figure 27: Flow diagram of non-ideal circuit design and analysis

4.2 S-parameter Analysis of Non-Ideal Design

According to RF/microwave concept in [23], transmission coefficients and reflection coefficients are of significant importance to explain the behaviour of PCB design towards high frequency RF signal. For this purpose, S-parameters should be calculated against each subsection of circuit i.e matching network, voltage rectifier and storage circuit.

4.2.1 Layout Generation

ADS momentum tool has been used to generate the layout and the corresponding substrate has been defined in ADS emulation setup category as shown in Figure 25. The first step is to define the PCB layers in layout window. For layer disposition definition, momentum functionality available in layout window has been selected. In the next step, integration of all the parts and placing of some essential simulation points, known as ports, is performed. Ports must be placed around matching network, voltage rectifier and storage circuit, in order to estimate the S-parameters of each sub-component. The output frequency plan of S-parameter analysis is defined with a linear sweep type and with a range of 0 to 5 GHz in steps of 0.1 GHz. S-parameters simulations are performed and corresponding data set is obtained as a touchstone file, which will be used in the schematic simulation later.

4.2.2 S-Block Schematic

S-parameters are necessary to make an accurate simulation of the PCB, that is why layout was generated. Whereas, creating another S-block schematic is essential in order to evaluate the non-ideal circuit behaviour [9]. Harmonic balance (HB) method is configured, while maintaining the same parameters as mentioned in chapter-3. For this purpose, a S-parameter file based block having number of ports equal to ports in layout design, is imported and placed in schematic as shown in Figure 28. If we push into this block, it should provide the PC directory link for S-parameter data file. In our layout design there were six ports, two ports for input and output of matching circuit. Similarly, 2 ports for the rectification block and last two for storage circuit.

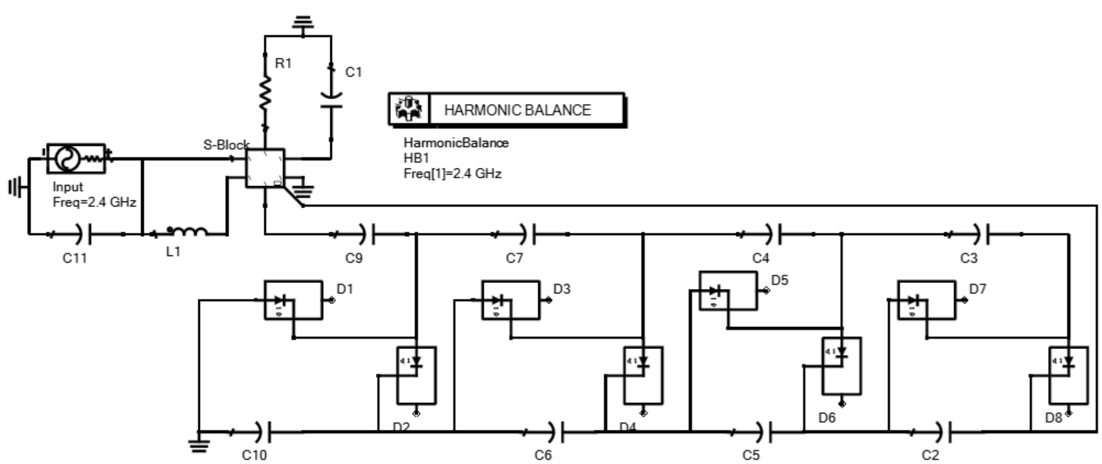

Figure 28: ADS S-parameter block schematic design.

Since the S-parameters are calculated using these ports, so pre-defined three sections

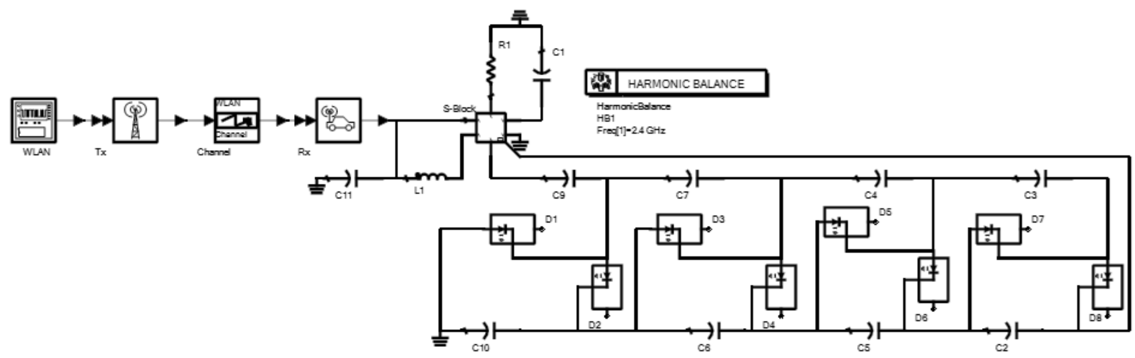

Figure 29: ADS S-parameter block schematic design with channel.

of ideal circuit should be situated between the same port number as they were in layout. It can be observed from Figure 28, that now ideal circuit is no more ideal, in fact it includes the PCB and component losses in the form of S-parameter file. Therefore, all the simulations have been repeated with this circuit design to analyze the behaviour of our actual circuit.

Similarly, channel model, WLAN source and receiving antenna model can be integrated in the place of simple source as shown in Figure 29. To incorporate the channel impairments and transmitting source attributes, the wireless channel model has been integrated with the circuit. Moreover, Figure 29 also provides us with some important outcomes i.e. total energy harvested under various channel conditions and at different levels of source power P_s, for non-ideal circuit design. The details of results and their analysis are mentioned in the next section.

4.3 Simulation and Results

The detailed analysis for designed non-ideal system has been performed which includes the comparison of total output voltage versus input RF power incident on receiving antenna. In addition, we have also calculated efficiency of a system at dual frequencies i.e. 2.4 GHz and 5.8 GHz and compared it with ideal system overall efficiencies as shown in Figure 31 and Figure 32. As we know that, interfacing channel with the receiving section has significant effect on the total energy harvested. Therefore, channel has been incorporated with WLAN source at one side and receiver circuit at the other. For a fixed distance of 1 meter, total harvested energy versus time has been calculated at different source power as shown in Figure 30. The details of theses results are mentioned in next subsections.

4.3.1 Comparison between Ideal and Non-Ideal Design

Our main goal is to calculate the total harvested energy under different constraints and conditions. Therefore, ideal and non-ideal circuit design has been compared in the light of energy harvested at different source powers, at multiple time instances and for a range of distance from source to receiver; whereas, distance range is shown in terms of power received at input antenna.

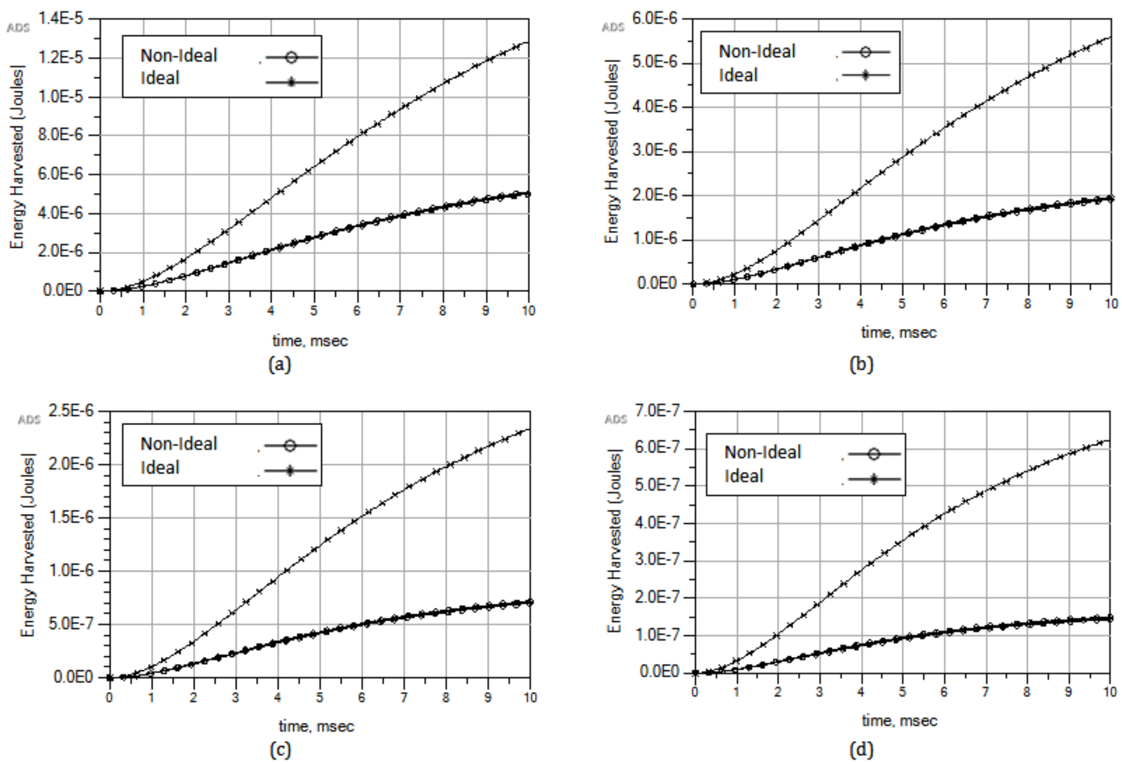

Figure 30: Energy versus Time for Ideal and Non-Ideal Case at (a) P_s = 1 W (b) P_s = 500 mW (c) P_s = 250 mW (d) P_s = 100 mW

It is therefore, assumed that for a particular distance, specific amount of power is incident on receiving antenna. It can be observed from Figure 30, that the energy harvested from non-ideal circuit is relatively less as compared to the energy harvested from ideal energy harvesting circuit. The decrease in energy is due to the fact, that now the circuit is more practical, since it includes parasitic losses and PCB dielectric losses. However, energy curve follows the same trend with time as that of ideal energy graph. Moreover, it has been shown that energy increases exponentially with time. It is because of the fact that voltage stored on capacitor has exponential relation with time i.e. expected charging characteristic of a capacitor. The harvested energy has been calculated by the following formula:

$$E_{stored}(t) = \frac{1}{2} C V_{stored}^2(t) \tag{3}$$

Where $'C'$ is the capacitance of storage capacitor which is chosen under the criteria as mentioned in previous chapter. Another important information, that can be inferred from the results is the increasing trend of harvested energy with increase in source power and it is also valid in both ideal and non-ideal cases; the respective result has been explained in next subsection.

4.3.2 Effect of Non-Ideal Behaviour on the Efficiency

It is clearly observable that, at 2.4 GHz output voltage and overall efficiency of a system is more than 5.8 GHz. Another important result, we can infer from these results is that output voltage for ideal case is clearly more than non-ideal circuit because of PCB losses and vendor (non-ideal) component inclusion in circuit schematic. Ideal and non-ideal both circuit design give maximum efficiencies at 15 dBm for 2.4 GHz and same for 5.8 GHz. Whereas, at 2.4 GHz voltage becomes saturated when input RF power exceeds 15 dBm; but in case of high frequency same stable voltage condition is achieved at almost 18 dBm as shown in Figure 31 and Figure 32. For example, in Figure 31 (b) at 2.4 GHz maximum efficiency of 60% is obtained in ideal

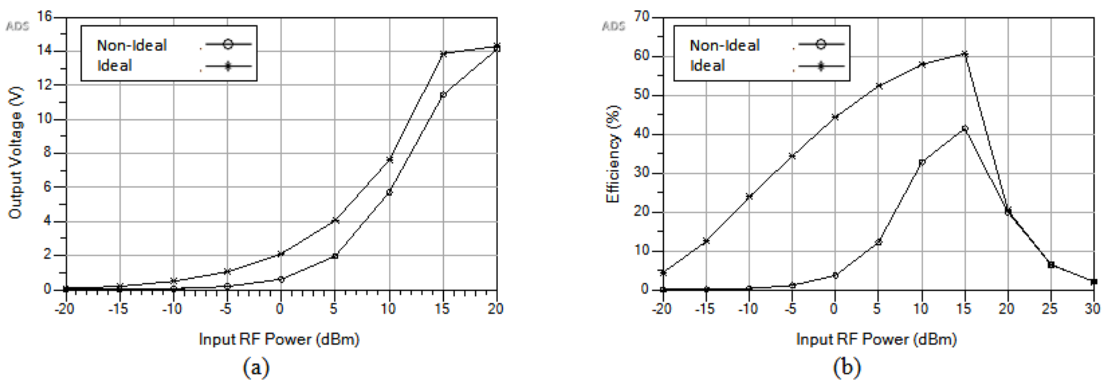

Figure 31: At 2.4 GHz (a) Output Voltage versus Input RF power (b) Efficiency versus Input RF power

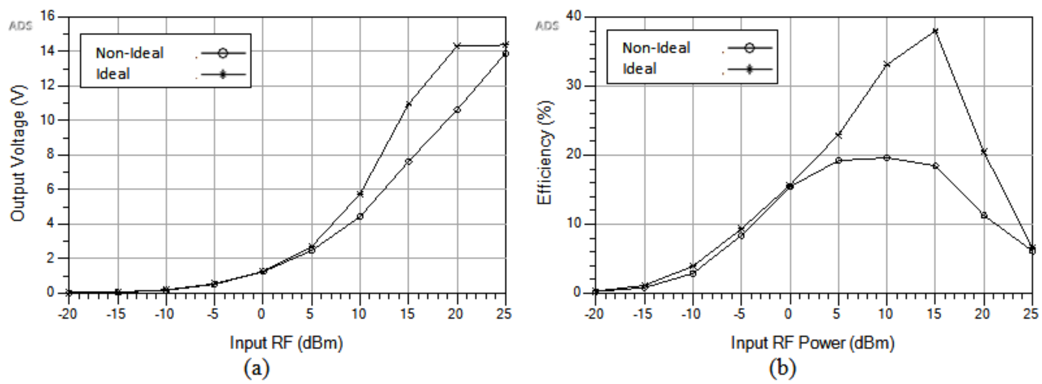

Figure 32: At 5.8 GHz (a) Output Voltage versus Input RF power (b) Efficiency versus Input RF power

scenario whereas; almost 40% efficiency is obtained for corresponding non-ideal case while the incident RF power is considered between -20 dBm to 25 dBm. The efficiency achieved in the simulation of the ideal system is quite higher, since the characterization of S-parameter has not been done; likewise, the dielectric and conductor losses were not been taken into account.

4.3.3 Effect of Source Power at different time instances

The transmitting power (P_s) of WLAN router has significant effect on the total output obtained in RF energy harvesting circuit. Therefore, energy comparison between ideal and non-ideal design has been performed, to investigate the effect of P_s. If the channel

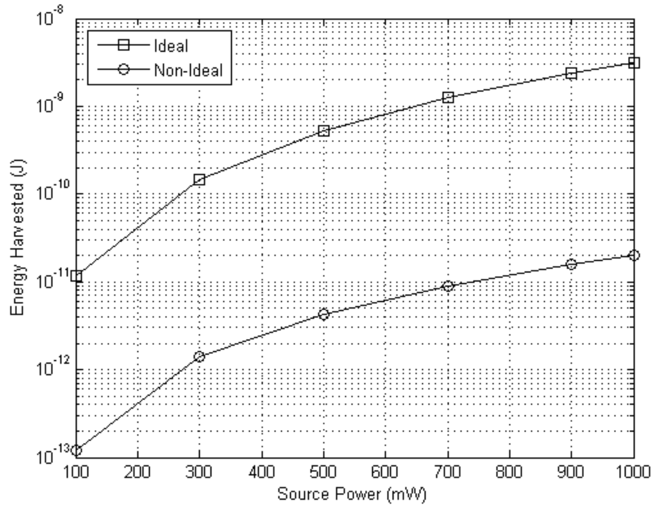

Figure 33: Energy harvested versus source power at t = 5 ms

model is assumed to be no fading and path-loss has been included, energy harvested increases exponential with increase in P_s for both ideal and non-ideal design for a fixed distance of 3 meters (shown in Figure 33, Figure 34 and Figure 35).

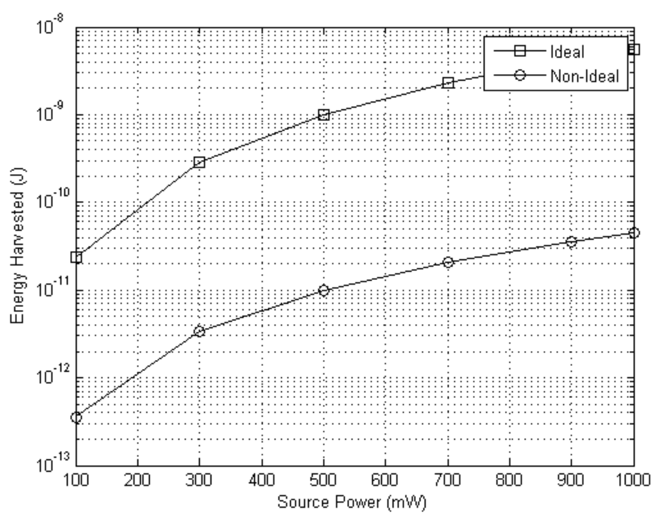

Figure 34: Energy harvested versus source power at t = 10 ms

Another considerable important parameter is the time instance at which particular amount of energy is harvested e.g. E_{stored} at 5 ms, 10 ms and 15 ms. Figure 33 shows the energy collected at time equal to 5ms. Similarly, Figure 34 and Figure 35 shows total harvested energy at t = 10 ms and t = 15 ms respectively, for a fixed distance of 3 meters in both ideal and non-ideal cases. This shows that PCB losses and individual component energy dissipation, significantly decreases the efficiency and total amount of energy harvested. It may not be possible to attain same energy for both the cases, but improved design considerations can be considered and utilized. One of the important consideration can be the reduction of transmission line lengths. This leads to minimization of the undesired parasitic inductance offered by copper traces in PCB [7], [9]. It can be inferred from these figures, that energy harvested increases linearly with the increase in source power for a fixed time instance.

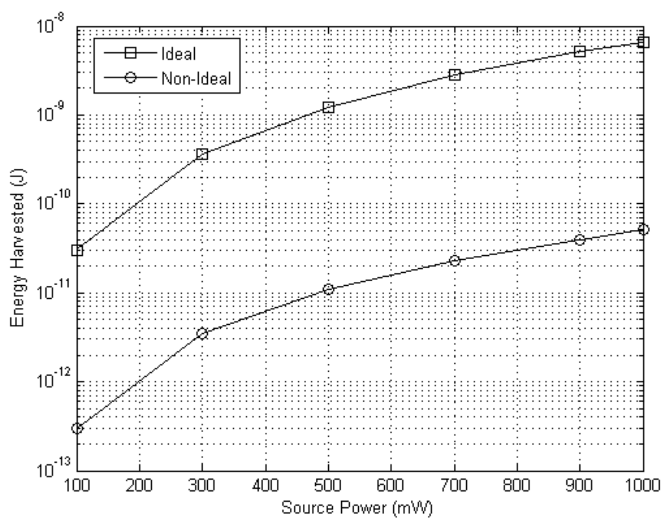

Figure 35: Energy harvested versus source power at t = 15 ms.

In other words, we can say that if source power becomes double the energy harvested becomes twice as well. For the constant time and source power, energy harvested in non-ideal case is less than the ideal one as shown in the respective figures.

4.4 PCB Fabrication and Measurement

It is known that practical implementation of PCB for designed circuit is an important step to investigate the real time practical constraints. As it is mentioned earlier, that PCB layout has been generated on FR4 substrate, now next step is to integrate our designed microstrip patch antenna with the rest of processing circuitry. For this purpose, we combined the two layouts i.e. combine antenna front plane with the circuit layout and ground plane with the ground plane of energy harvesting circuit.

The next important step is to print PCB, it requires generation of a machine language files, known as Gerber [7]. The number of Gerber files are equal to the layout layers. Figure 36 shows the PCB gerber files with all the layers included. There are two holes present in harvesting circuitry side, which are used to ground the circuit with a common bottom ground plane.

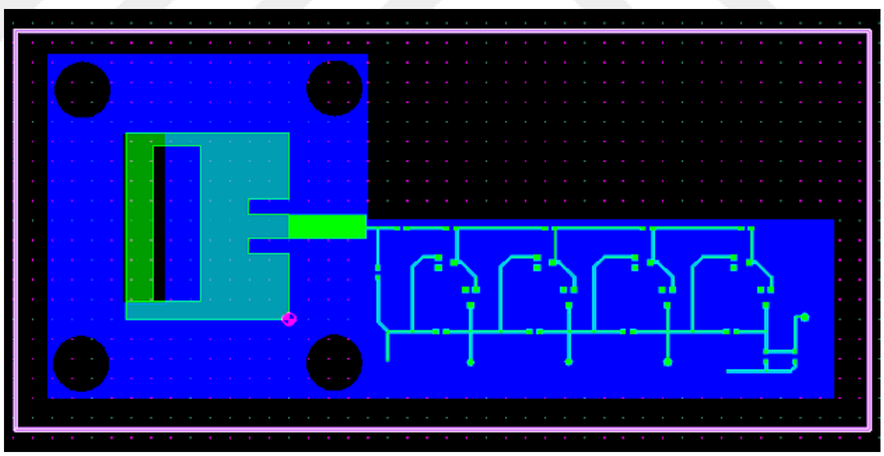

Figure 36: Gerber File For Printing of RF Energy Harvesting PCB.

4.4.1 PCB Fabrication and Components Selection

The PCB is printed on double layered FR-4 epoxy glass substrate, where one of the layer serves as a ground plane which has been made common with the antenna ground plane. Moreover, antenna can be seen on the top side of the Figure 36, which is integrated to the input of energy harvesting processing circuit from direct feed.

Another important consideration is selection of components, as we have selected the optimized components for our simulation. In this regard, we selected components with such values and performance parameters which are as close as possible to ones used in simulations. For example, instead of using HSMS-2850 schottky diode we deployed BAS70 schottky diode (SOT-23 package). It has low capacitance of 2 pF and low built in voltage characteristics, which is an important requirement of our RF energy harvesting circuit. Moreover, storage capacitor of 0.68 μF has been connected with the load resistor of 10 kΩ, which will be used to measure output voltage.

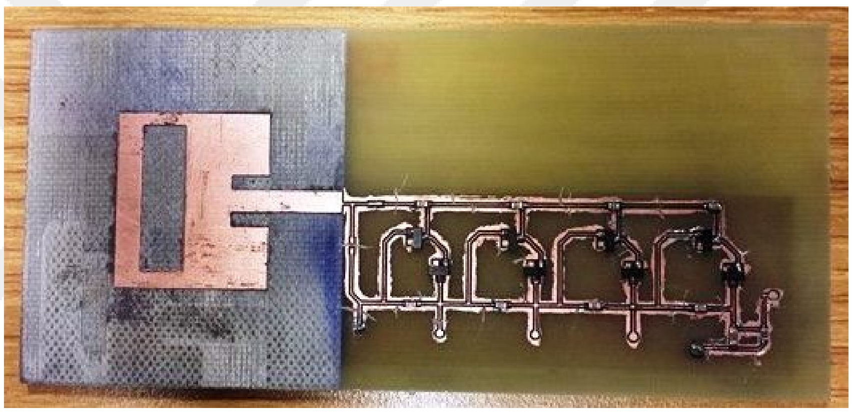

Figure 37: Prototype of WLAN-RF Energy Harvesting PCB.

4.4.2 Experimental Setup for Measurement

After the components have been assembled on PCB and respective soldering procedure has been done, the next step is to take the measurement from the circuit. For this purpose, WiFi router has been used as RF source for energy harvesting PCB. The physical prototype PCB of WLAN-energy harvesting circuit has been shown in Figure 37; its output voltage has been measured at different distances from the WLAN router, using Keysight 34411A Digital Multimeter.

The complete experimental setup has been shown in Figure 38. The harvesting PCB has been placed in the vicinity of WLAN RF signals. Moreover, additional WiFi router is also placed at a certain distance from the harvesting circuit which transmits

RF signal at power level of 100 mW. We know that WiFi signals are omnipresent in the lab environment, so antenna of harvesting PCB is also collecting RF signal of 2.4 GHz/5.8 GHz from the surrounding as well.

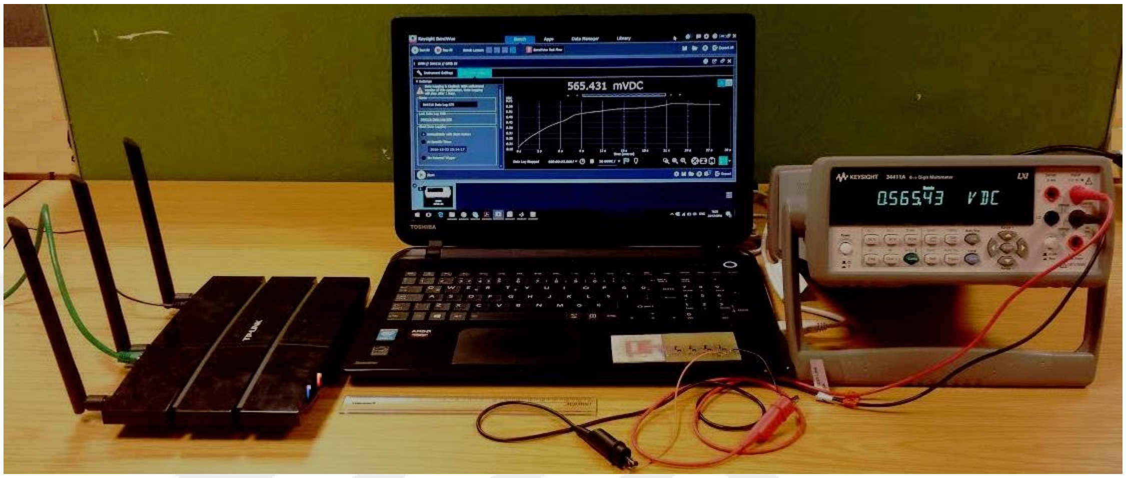

Figure 38: Prototype of WLAN-RF Energy Harvesting PCB.

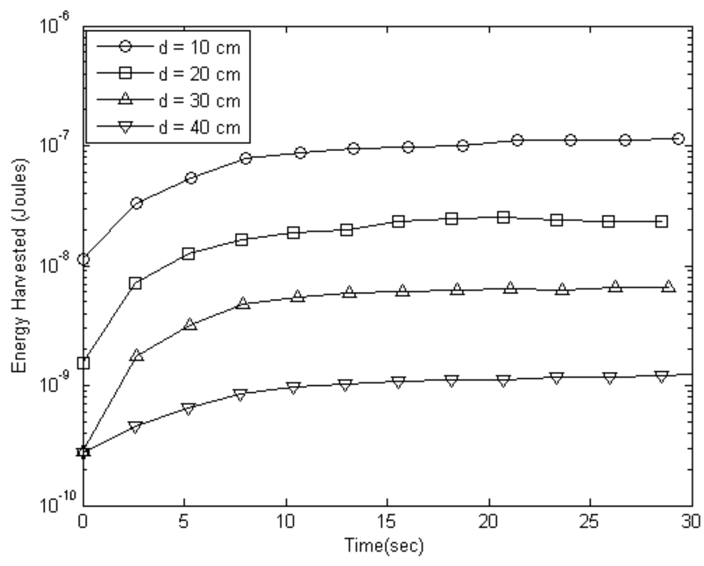

Figure 39: Prototype of WLAN-RF Energy Harvesting PCB.

In the experiment, the real time simulation has been plotted using data logger of BenchVue software on PC which is later exported to Matlab for better visualization of results. By using high performance digital multi-meter, we have measured the charging voltage of a storage capacitor with respect to time, which gives almost 0.6 volts or in terms of energy it is approximately 12.5 μJ at a fixed distance of 10 cm.

Moreover, the corresponding distance between router and PCB has also been varied to observe the effect of distance on total harvested energy as shown in Figure 39. It is evident from the graph that at a fixed time instant, energy harvested decreases with increase in distance. In other words, if the harvesting device is placed far from the WLAN source, the obtained energy decreases. Another important result is the exponential increase in energy with time as energy is measured across storage capacitor, which is in well agreement with the simulations and expected results.

CHAPTER V

CONCLUSION AND FUTURE WORK

In the presented work, dual-band RF energy harvesting system for WLAN frequency has been designed on ADS software and its prototype has been fabricated. The proposed system includes the design and fabrication of microstrip patch antenna, matching network and 4-stage voltage rectifier. It has been shown that the proposed system can harvest energy simultaneously from both 2.4 GHz and 5.8 GHz. Our system shows 57% and 35% efficiency for 2.4 GHz and 5.8 GHz respectively, such that 15 dBm power is incident on receiving antenna. The novel aspect is the integration of wireless channel model and actual WiFi source with the harvester circuitry and total amount of harvested energy has been calculated under different channel conditions and at various source power levels.

Moreover, for inclusion of the PCB losses and parasitic losses to the designed circuit, ADS vendor components library and microstrip transmission lines are deployed in the circuit design. To model the non-idealities S-parameter analysis has been performed such that losses are incorporated and their effect on total harvested energy has been calculated. The detailed comparison between ideal and non-ideal circuit has been explained which shows that non-ideal circuit provides 35% efficiency at 2.4 GHz. To better investigate the actual circuit outcomes, PCB of the energy harvesting circuit has been designed and fabricated on FR4 substrate. The SMD components are mounted on the printed board and the results are calculated. The experimental setup involves the placing of PCB near 2.4 GHz Wi-Fi routers, to verify that the designed harvester has the ability to harvest ambient RF energy and can process this signal to charge a capacitor. Our actual processing circuitry is able to provide voltage in order of few milli-volts.

In future to make our designed circuit more efficient and reliable, the following potential modifications to the design will be considered for the designed system: efficient impedance matching between the antenna and the rest of circuit and the minimization of losses due to PCB traces. Moreover, the presented work will be extended to combine the RF energy harvester with low power wireless sensor network. Therefore, instead of relying on batteries, the wireless devices will used the energy harvested by the energy harvester.

Bibliography

[1] D. Pavone, A. Buonanno, M. D. Urso, and F. D. Corte, "Design considerations for radio frequency energy harvesting devices," *Progress In Electromagnetics Research Journal*, vol. 45, pp. 19 – 35, Oct. 2012.

[2] X. Lu, P. Wang, D. Niyato, D. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Communications Surveys and Tutorials*, vol. 17, pp. 757 – 789, Nov. 2014.

[3] J. H. Kim, J. Bito, and M. Tentzeris, "Design optimization of an energy harvesting rf-dc conversion circuit operating at 2.45ghz," *IEEE International Symposium on antennas and Propagation and USNC/URSI National Radio Science Meeting*, July 2015.

[4] N. M. Din, C. K. Chakrabarty, A. B. Ismail, K. K. A. Devi, and W. Y.Chen, "Design of rf energy harvesting system for energizing low power devices," *Progress in Electromagnetics Research Journal*, vol. 132, Sept. 2012.

[5] S. W. Munir, O. Amjad, E. Zeydan, and A. O. Ercan, "Optimization and analysis of WLAN RF energy harvesting system architecture," *IEEE 2016 International Symposium on Wireless Communication Systems (ISWCS)*, Oct. 2016.

[6] Z. Zakaria, N. A. Zainuddin, M. N. Husain, M. Abidin, A. Aziz, M. Mutalib, and A. Othman, "Current developments of RF energy harvesting system for wireless sensor networks," *International Journal on Advances in information Sciences and Service Sciences(AISS)*, vol. 5, June 2013.

[7] D. J. Lpez, "Powering autonomous sensors by RF harvesting," tech. rep., Department of Electrical Engineering, Universitat Politcnica de Catalunya, Barcelona, Spain, Sept. 2013.

[8] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design optimization and implementation for RF energy harvesting circuits," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 2, pp. 24 – 33, Feb. 2012.

[9] B. Schauwecker, "Design of processing circuitry for an rf energy harvester," tech. rep., University of Arkansas, Fayetteville, Fayetteville, USA, May 2016.

[10] R. Balakumar, V. Vaidehi, and P. Balamuralidhar, "Solar energy harvesting for wireless sensor networks," *The 1st International Conference on Computational Intelligence, Communication Systems and Networks*, July 2009.

[11] N. Guilar, A. Chen, and R. A. T. Kleeburg, "Integrated solar energy harvesting and storage," *The 2006 International Symposium on Low Power Electronics and Design*, Oct. 2006.

[12] J. A. Paradiso, "Systems for human-powered mobile computing," *Design Automation Conference*, July 2006.

[13] R. Torah, . Glynne-Jones, M. Tudor, T. O. Donnell, S. Roy, and S. Beeby, "Self-powered autonomous wireless sensor node using vibration energy harvesting," *Journal on Measurement Science and Technology*, Oct. 2008.

[14] M. M. Tentzeris and Y. Kawahara, "Novel energy harvesting technologies for ict applications," *IEEE International Symposium on Applications and the Internet*, 2008.

[15] S. Paradan, Seong-Ro, L. S. K. Noh, and D. Y. Choi, "Comparative study of rectenna for electromagnetic energy harvesting," *International Journal of Control and Automation*, vol. 7, Dec. 2014.

[16] M. Arrawaita, M. S. Baghini, and G. kumar, "RF energy harvesting systems from cell towers in 900 mhz band," *IEEE-Conference In Communications*, Jan. 2011.

[17] D. R. Lewis, "Circuit design for energy harvesting from digital TV band," tech. rep., The Department of Electrical and Computer Engineering, Northeastern University, Northeastern, USA, July 2012.

[18] A. M. Z. et al., "Radio frequency energy harvesting and management for wireless sensor networks," tech. rep., available on-line at arXiv:1208.4439, 2012.

[19] H. Ostaffe, "Ambient rf energy harvesting for wireless sensors," *http://powercastco.com/PDF/ Power-Out-of-Thin-Air.pdf*, 2010.

[20] F. Alneyadi, M. Alkaabi, S. Alketbi, S. Hajraf, and R. Ramzan, "2.4ghz wlan rf energy harvester for passive indoor sensor nodes," *IEEE- International Conference on Semiconductors Electronics*, Aug. 2014.

[21] S. Shrestha, S. Noh, and D.Choi, "Comparative study of antenna designs for rf energy harvesting," *International Journal of Antennas and Propagation*, Jan. 2013.

[22] A. Georgiadis, G. Andia, and A. Collado, "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (em) energy harvesting," *IEEE Journal on Antennas and Wireless Propagation Letters*, vol. 9, Sept. 2010.

[23] C. Balanis, *Antenna Theory: Analysis and Design*. Newyork, USA: John Wiley and Sons, Inc., 2nd ed., 1998.

[24] M. Hoang, H. Phan, T. Q. V. Hoang, and T. P. Vuong, "Efficient compact dual-band antennas for gsm and wi-fi energy harvesting," *IEEE International Conference on Advanced Technologies for Communications*, Oct. 2014.

[25] V. R. Nag and G. Singh, "Design and analysis of dual band microstrip patch antenna with microstrip feed line and slot for multiband application in wireless communication," *IRACST - International Journal of Computer Science and Information Technology and Security (IJCSITS)*, vol. 2, Dec. 2012.

[26] Z. W. Sim, "Compact patch antenna design for outdoor rf energy harvesting in wireless sensor networks," *Progress In Electromagnetics Research*, vol. 105, July 2010.

[27] K. Lee, S. Yang, and A. kishk, "Dual-and multiband u-slot patch antennas," *IEEE Antennas wireless propagation Letter no. 7*, Nov. 2008.

[28] C. Hsieh, Tchiu, and C. Lai, "Compact dual-band slot antenna at the corner of the ground plane," *IEEE Transaction on Antenna propagation*, Oct. 2009.

[29] K. K. A. Devi, N. Md.Din, C. K. Chakrabarty, and S. Sadasivam, "Design of an RF - DC conversion circuit for energy harvesting," *IEEE International Conference on Electronics Design, Systems and Applications (ICEDSA)*, Sept. 2012.

[30] T. R. Ansari, A. Khan, and I.Ansari, "Wireless charging of mobile battery via optimization of rf energy harvesting system," *International Journal of Scientific and Engineering Research*, vol. 6, July 2015.

[31] F. Bouabdallah, N. Bouabdallah, and R. Boutaba, "On balancing energy consumption in wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 5, Sept. 2008.

[32] Y. hou, B. Froppier, and T. Razban, "Schottky diode rectifier for power harvesting application," *IEEE International Conference on RFID -Technologies and Applications (RFID - TA)*, May 2012.

[33] R. Shegita, T. Sasaki, D. M. Quan, Y. Kawahara, R. J. Vyas, M. M. Tentzeris, and T. Asami, "Ambient rf energy harvesting sensor device with capacitor-leakage-aware duty cycle control," *IEEE Sensors Journal*, vol. 13, Aug. 2013.

[34] W. C. Jakes, *MICROWAVE MOBILE COMMUNICATIONS*. Newyork, USA: John Wiley and Sons, Inc., 2nd ed., 1974.

[35] N. T. Awon, M. Rahman, M. A. Islam, and A. Islam, "Effect of AWGN and fading (raleigh and rician) channels on BER performance of a WiMAX communication system," *International Journal of Computer Science and Information Security*, vol. 10, Aug. 2012.