Energy Harvesting: RF for RFID tag

by

Go Chang Hua

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical and Electronics Engineering)

MAY 2011

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Energy Harvesting: RF for RFID tag

by

Go Chang Hua

A project dissertation submitted to the
Electrical and Electronic Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL AND ELECTRONIC ENGINEERING)

Approved by,

____
(Dr. Rosdiazli Ibrahim)
Project Supervisor

Universiti Teknologi PETRONAS

Tronoh, Perak

May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

GO CHANG HUA

ABSTRACT

RFID is an acronym for Radio Frequency Identification, which is a wireless communication technology that enables users to uniquely identify tagged objects or people via radio frequency waves. It is rapidly becoming a cost-effective technology for various sectors like the supply chains, livestock management, military's weapon tracking and the medical industry. In general, there are two types of RFID tags – active and passive. Passive tag has a small physical form factor and does not have an on-board battery. It relies on the RFID reader to supply power to activate the tag. Active tag on the other hand has an on-board battery power which supplies continuous power to the tag. As such, it has greater capability and is advantageous compared to the passive tag. One of the most prominent advantages is in terms of its long range communication distance. However, battery depletes over time and replacing the battery can be tedious, time-consuming and costly. This project aims to enable active RFID tags to harvest energy from surrounding radio frequency (RF) to power and to recharge the on-board battery of the tag.

ACKNOWLEDGEMENTS

First of all, the author would like to thank the Almighty God for providing him with blessings, strength and health to work on the final year project. The whole experience would not be made possible without the guidance and protection from the Lord. Also, the author would like to thank his family members for all the support and encouragement throughout the one year experience.

The author is also grateful for the continuous supervision and support of Dr. Rosdiazli Ibrahim from the Electrical and Electronics Department of UTP as well as Pn. Hanita Daud of the Fundamental and Applied Science Department of UTP. In addition, he author would like to extend his gratitude to the lab technologists of UTP for their technical aid and support as well as the university for the facilities provided.

Last but not least, the author would like to thank the ELECTREX organizing committee as well as EDX organizing committee for their hard work and support in providing a platform to showcase the author’s project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background study

Radio Frequency Identification (RFID) is a wireless communication technology that enables users to uniquely identify tagged objects or people via radio frequency waves [1]. Its development took years before it matures to become a functional system and its basic principal is quite similar to that of the barcode technology. However unlike the barcode technology, RFID technology does not require line of sight or contact for communication.

RFID is also one of the most promising and growing segments of today's automatic identification and data capturing (AIDC) industry due to the various advantageous features it offers [2][3]. AIDC which includes technologies like bar code, magnetic ink character recognition, optical character recognition (OCR) and biometric identification has been in existence since 1930 [4].

In general, there are two types of RFID tags, which are the active and passive tags. Both tags have features and advantages that differ from one another. Despite the various downsides of passive RFID tags, they are still the most preferred type due to its relatively cheap cost and its small size. These two features alone are very attractive to industries or sectors which requires bulk usage or flexibility (able to fit in almost anywhere) of using the RFID technology.

The split of spend on RFID by value chain positioning in 2010 depicted below proves the popularity of passive tags:

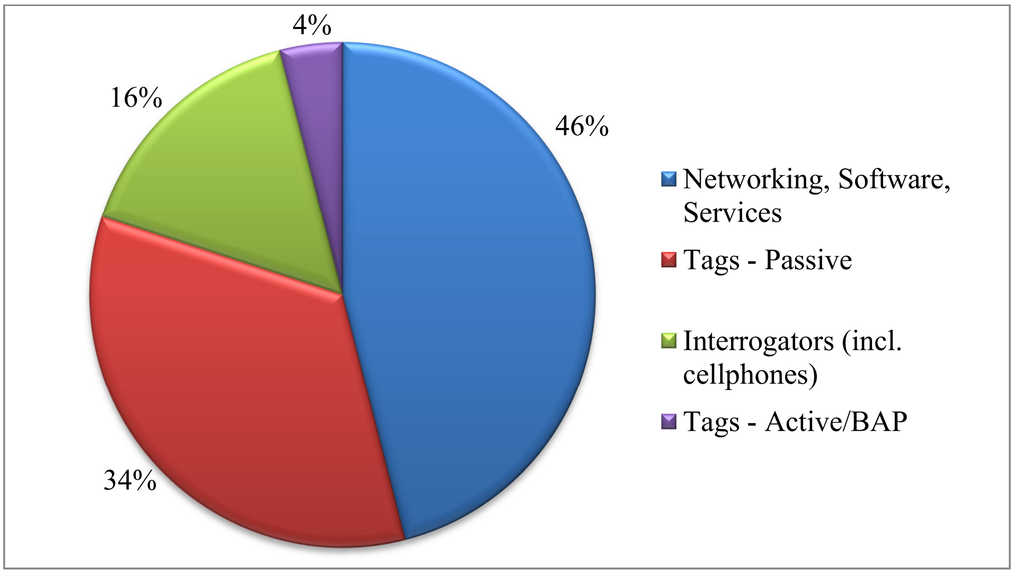


Figure 1: RFID Market by Value Chain Positioning

1.2 Problem Statement

Though passive tags may be the favourable RFID technology for various businesses and industries, it does lack a lot of advantages posed by active tags. Some of the challenges faced using passive tags are short communication range, poor performance in the presence of liquid or metals and its reliance on reader's high signal strength to power the tags. These challenges limit the potential of passive RFID tag.

Active tags on the other hand have long communication range and perform greatly compared to passive tags. This is achievable through the on-board battery which powers the active RFID tag. However, as we know, battery depletes over time and the battery on an active RFID tag can only last around 2 to 5 years. Thus, the battery needs to be replaced every few years once it has worn out. The process of replacing the battery can be very tedious, time consuming and costly especially when it involves hundreds and thousands of RFID tags. This limitation has been a main factor many industries are holding back from adopting active RFID technology, despite being obviously better than passive RFID tag.

Figure below shows the management effort required based on the number of RFID tags used increases. As the number of battery-powered active RFID tags used increases, the management effort exponentially increases due to the effort required for battery replacement.

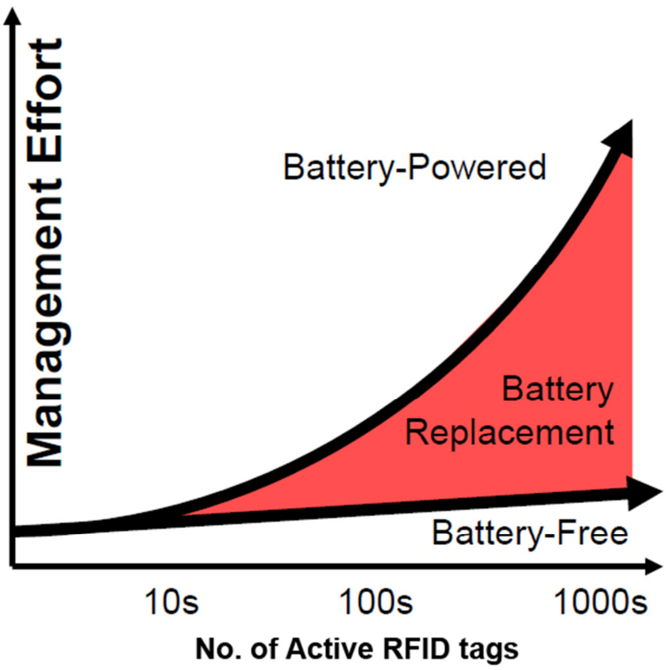


Figure 2: Management Effort vs. Number of Active RFID Tags

Therefore in order to overcome these challenges, an alternative energy source must be used to constantly power the active RFID tag or to create perpetual (or almost battery-free-like) active RFID tags. This project will look into the possibility of harvesting energy from surrounding radio frequency (ambient energy) particularly to recharge the on-board battery on active tag.

1.3 Objectives

The objectives of the project include:

a) To study on the feasibility of harvesting energy from surrounding radio frequency to recharge on-board battery of active RFID tags or to directly power active RFID tags.
b) To design and construct a mechanism to harvest energy from surrounding radio frequency for the application of active RFID tags.
c) To analyse the challenges faced through utilising the harvested energy for active RFID tags

1.4 Scope of Study

The project focuses on providing constant power for active RFID tags by studying the possibility of harnessing energy from the surrounding radio frequency (RF) signals to recharge battery on an active RFID tag as well as to power the active RFID tags directly. Energy may be harvested from ambient waves, for example mobile phone waves (GSM), broadcast radio waves, television microwaves, Wireless Fidelity (WiFi) or Bluetooth. Through this, the battery on the active tag will not need to be replaced every few years.

Table 1: RF selection for energy harvesting

Frequency	**Reason for frequency selection**
180 – 220 MHz	TV transmission
900 MHz	Global System for Mobile Communication (GSM)
915 MHz	License-free ISM band
2.4 GHz	License-free ISM band, Used for WiFi, Bluetooth

CHAPTER 2

LITERATURE REVIEW

2.1 Past, Present and Future of RFID

RFID technology is made possible through the discovery and understanding of electromagnetism and ways of controlling it more than a hundred years ago. James Clerk Maxwell, a Scottish mathematician and physicist published the first theories on electromagnetism back in 1873, which describes the phenomena of electromagnetic radiation. His formula is what we now known as the Maxwell equation. German physicist Heinrich Rudolf Hertz was then the first to prove Maxwell's equation and the existence of electromagnetic radiation in 1888, by creating a device that emits radio waves. In 1901, an Italian inventor and Nobel Laureate, Guglielmo Marconi, developed the first wireless telegraphy [5]. All of these discoveries, coupled with radio broadcasting and radar technologies, laid the foundation for development of radio frequency identification.

RFID technology was believed to be first implemented in the Identification, Friend or Foe (IFF) system during the World War II [6]. It was used by the British military to identify whether incoming aircrafts were allies or enemies. At that time, RFID was still a relatively expensive technology as well as limiting in business applications due to its size and cost.

It is only after the evolution in the field of electronics where RFID technology grows rapidly. The discovery of transistors in 1947 at Bells Labs by Walter Brattain, John Bardeen and William Shockley combined with the advancement in circuit etching paved ways for RFID to be developed smaller and more flexible at a much lower cost [6].

With more than 50 years of history, RFID is entering a new phase of existence, thanks to the Internet, mobile phone technology, cheaper computer chips and the efficiency of today's business process [7]. At present, it is a widely adopted technology used by organizations, businesses, and individuals all over the world. Some of the applications include:

1) Supply chain inventories tracking and management system.
2) Animal tracking devices.
3) Access control systems, such as contactless entry and staff identification system.
4) Automatic toll collection systems, such as SmartTag and Touch N' Go implementation in Malaysia [8].
5) Vehicle and asset tracking.
6) Infant ID and security wrist bands.
7) Point-of-sale applications such as Visa Wave.
8) Library books tagging.
9) Passport.

The numbers of applications continue to grow as RFID technology is being refined every day. There are many opportunities offered by RFID technology that has yet to be explored. In the future, the cost of RFID will be much lower and its functionality will be much more flexible to be adopted in various industries.

2.2 RFID: Active and Passive Tags

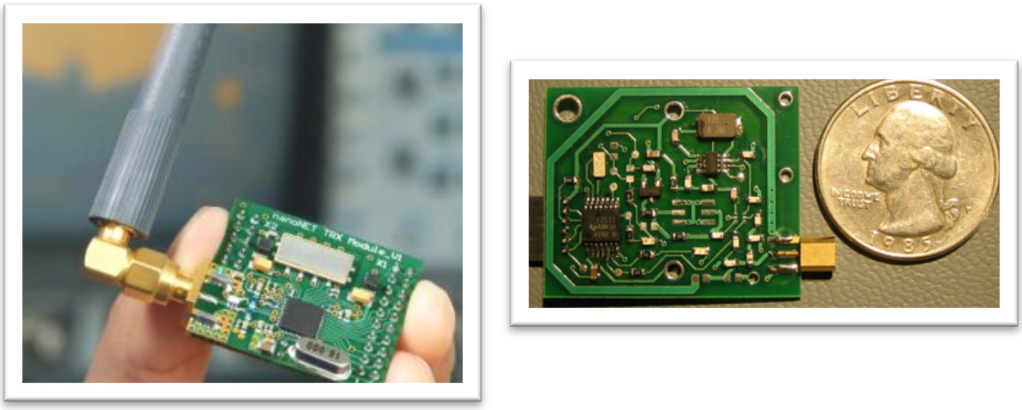


Figure 3: Active RFID tags

RFID tags can either be active or passive. An active tag has an on-board power supply (usually a battery) for reading or writing into the microchip and to communicate data with the RFID reader. The internal power source provides active tag a major advantage, whereby it can constantly emit frequency signals which can be detected more than 100m away from the reader.

However, it also poses a few disadvantages to it, mainly on the aspect of size and cost. The size and cost is significantly higher due to the need of a battery. Also, the lifespan of the battery is limited and must be replaced once it’s exhausted, usually after a short 2 to 5 years.

Figure 4: Passive RFID tag

Passive tag on the other hand does not have its own power supply. It depends on the radio frequency from its reader to provide the power. This enables passive tag to be produced in a much smaller size compared to that of an active tag. It is also significantly cheaper to be produced and thus a much preferred type when it comes to bulk usage like in the supply chain or manufacturing industries.

On the downside, a passive tag may only be detected within a very short range, usually only 3m or less. It also has much smaller data storage as well as performs poorly in the presence of liquid or metals. This limitation obscured the full potential and capabilities of a passive RFID tag.

The following table summarizes the differences between an active and passive RFID tag:

Table 2: Active vs. Passive RFID

	Active RFID	**Passive RFID**
Tag Power Source	Internal	Energy transferred from reader via Radio Frequency (RF)
Tag Battery	Yes (with limited lifespan)	No
Size	Large	Very small
Cost	Expensive	Very cheap
Availability of Tag Power	Continuous	Only within field of reader
Required Signal Strength from Reader to Tag	Very low	Very High (to power the tag)
Communication Range	Long range (>100m)	Short range (<3m)
Data Storage	Large read/write data storage (128KB) with sophisticated data search and access	Small read/write data storage (128 bytes)
Performance in the presence of liquids and metals	Good	Very bad
Tag power requirement	15mW – 300mW	100µW

2.3 Energy Harvesting

The concept of energy harvesting, also known as energy scavenging involves converting the surroundings ambient energy into electrical energy to power circuits and devices or stored them in the form of rechargeable batteries. The technologies of energy harvesting have been around for centuries in various forms, from the traditional windmill and watermills to modern-day solar cells and hydroelectric generator. These technologies contribute to the macro-scale energy harvesting.

While macro-scale energy harvesting technologies have pretty much matured by the 21st century, engineers are now turning their interest to micro-scale energy harvesting instead as the future of energy source. This is due the advantages offered by micro-scale energy harvesting which has the potential to contribute significantly for low-power devices. The technology will be especially useful for hard-to-reach battery-operated devices and for devices where it is almost impossible or impractical to change the batteries, such as the mass-implemented RFID tags.

Among the advantages of micro-scale energy harvesting include virtually inexhaustible source of energy which translates to unbounded lifetimes of the battery as well as having little or no adverse effect on the environment [13]. Though only low-power devices will benefit from the micro energy harvesting, the technology would also play a great part in saving cost when it comes to large scale implementation. The following table shows a comparison between macro and micro energy harvesting

Table 3: Macro vs. Micro-scale Energy Harvesting

	Macro	**Micro**
Energy Source	Renewable energy (e.g. solar, hydro and wind)	Ambient energy (e.g. mechanical vibration, RF)
Targeted application	Energy management	Low power devices
Ultimate goal	Reduce oil dependency	Perpetual devices

2.4 Energy Sources

There are various sources where energy can be harvested. The most familiar sources of ambient energy include solar energy, mechanical vibrations, thermal gradients as well as radio frequency (RF) [13]. The most challenging source to work on is the RF energy. This is because compared to the other three sources, the energy availability of RF is at least an order of magnitude less than them. In simpler term, it is trickier to harvest RF energy and most of the time the harvested energy is very low.

The following table compares the power generation potential of different ambient energy sources. The potential of each source is measured in terms of power density (power per area).

Table 4: Comparison of Power Generation Potential of Different Ambient Energy Sources [13][14][15]

Energy Source	**Power Density (μW/cm^2)**
Light	
Solar (outdoor)	12500 (Direct sun) 150 (Cloudy day)
Solar (indoor)	6
Vibration	
Piezoelectric	500
Electromagnetic	4
Electrostatic	3.8
Temperature	
Temperature Difference of 5°C	60
RF	
GSM (Global System for Mobile Communication)	0.1
Wi-Fi	1

Though it may be challenging to harvest RF energy, it is undoubtedly the best source of energy which is suitable for RFID applications. Therefore, this project will be looking into designs of energy harvester which will overcome the limitation of RF energy.

2.5 Radio (RF) Spectrum

As part of the electromagnetic spectrum, radio waves generally consist of electric and magnetic components. Radio waves travel through air in frequencies of within 3kHz to 300GHz and when on contact with a conductor, such as the transceiver or antenna on a RFID tag, electromagnetic induction occurs and this will induce current on the conductor's surface. The said phenomenon is known as the skin effect. This phenomenon allows the possibility of harvesting energy via radio frequencies to power low-power devices such as the RFID tags.

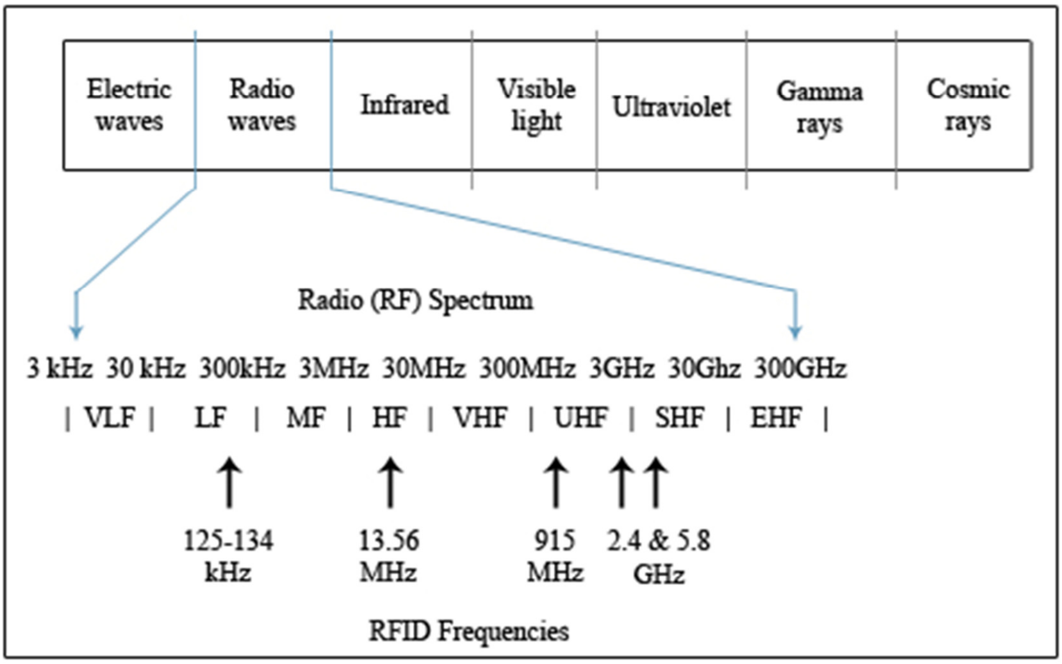


Figure 5: Radio frequencies (RF) and common RFID frequencies [2]

RF energy harvesting techniques can be employed for a wide range of radio frequencies. However, due to regulations, the common spectrum usually used for RF energy harvesting is 900 to 915 MHz and 2.4 to 2.45 GHz. These bands fall under the IEEE 802.15.4/ZigBee wireless personal area networks (WPAN) of the industrial, scientific and medical (ISM) radio bands [2]. Bluetooth and WiFi falls under 2.45 GHz bands. These bands can also be used to intentionally broadcast RF energy for wireless power system [17].

Another possible RF energy source which could be tap is via radio FM waves. In Malaysia, radio broadcast occupies RF spectrum between 87.7MHz to 107.5MHz.

The maximum theoretical power can be harvested from RF energy is 7.0µW and 1.0µW for 900 MHz and 2.4 GHz frequencies respectively over a free space (theoretically perfect vacuum) distance of 40 metres [16].

2.6 Theory of Inductive Coupling

It is possible to incorporate existing passive RFID inductive coupling technology for RF energy harvesting. Basically, an RFID reader communicates with RF tags to retrieve the data from the tag. The reader has an on-board power supply which enables it to transmit and receive data from the tags. For passive RFID tags, the reader will initiate radio transmission and sends a message to the tag indicating the beginning of communication [6]. Passive tags, which rely on the reader to provide sufficient energy, will then transmit data on the tags to the reader once it has enough energy to do so. This is made possible through the application of inductive coupling.

A summary of the operation of RFID [18] is as follow (passive RFID tag is used in the context):

i. RFID reader continuously emits RF signals and continuously observes the received RF signals data.
ii. If a tag is nearby, it will modulate the RF signal which will be detected by the reader.
iii. The tag will "absorb" a small portion of energy emits by the reader (through inductive coupling) and will start sending modulated data once it receives sufficient energy.
iv. The reader demodulates the signals emitted by the tag and decodes it to acquire the data.

Inductive coupling allows the transfer of energy wirelessly from one circuit to another through a shared magnetic field [2]. Current will be passing through the coil of the primary circuit (coil) and creates a magnetic field around it. This magnetic field will be captured by the secondary circuit (coil) and an electrical current will be induced in it, thus inducing voltage wirelessly at the second circuit.

The same concept can be used to harvest RF energy from the surrounding. Since radio waves, which comprises of electromagnetic field, is ubiquitous in our daily lives, it is possible to use the concept of inductive coupling to capture these magnetic field and turn it into DC current to power active RFID tags.

2.7 Backscatter modulation

Backscatter modulation is a form of Amplitude Shift Keying (ASK) and is widely used to modulate data on to RF carrier. In RFID, the term actually refers to the communication method implemented by passive RFID tags to send data back to the reader [2]. RF carrier refers to sine wave generated by the reader to transmit energy to the passive tags and to receive data from the tag.

Based on Harley Lehpamer, author of “RFID Design Principles”, in this type of modulation, the tag coil is repeatedly shunted through a transistor. By doing so, the tag can cause slight fluctuations in the reader’s RF carrier amplitude. The RF link behaves just like a transformer where whenever the secondary coil is momentarily shunted, the primary coil will experience momentary voltage drop. The reader must then peak-detect the data at around 60dB down. This kind of amplitude modulation loading of the RFID reader’s transmitted field provides a communication path back to the reader. The data will then be encoded, modulated and processed [2].

2.8 Voltage Multiplier (VM)

Voltage multiplier is an electrical circuit which can convert electrical power of a lower voltage value to a higher one. This can be achieved using a combined network of diodes and capacitors. Voltage multiplier is able to convert AC power to DC power, thus eliminating the need of a rectifier once energy is harvested from the receiving antenna. Due to these properties, it is one of the most important components in the design of RF energy harvesting circuit.

There are different types of voltage multiplier configuration. One of the popular ones is the Villard circuit. The figure below shows a simple Villard configuration.

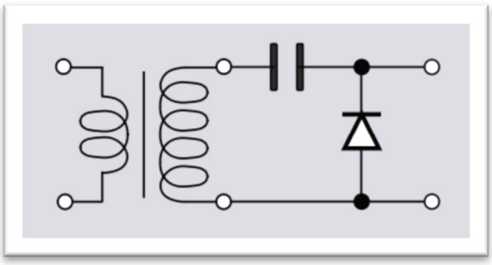


Figure 6: Villard circuit

Villard configuration may be combined to create multistage Villard voltage multiplier. An example of a multistage Villard configuration for RF energy harvesting is as depicted below:

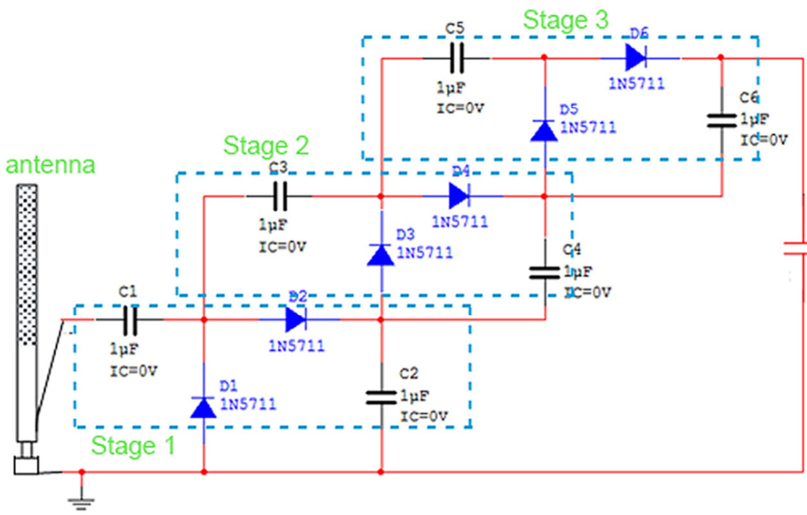


Figure 7: 3-Stage Villard Voltage Multiplier Circuit

While Villard configuration may be simple, the output produced may contain poor ripple characteristic. The Greinacher voltage doubler offer significant improvement compared to the Villard circuit but it is slightly more complex and involves more components, thus increasing the cost. The figure below shows the basic configuration of Greinacher voltage doubler.

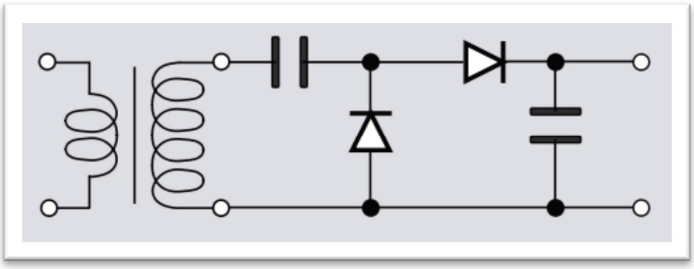


Figure 8: Greinacher Voltage Doubler

These configurations will need to be simulated in order to determine most suitable configuration for RF energy harvesting application. It is interesting to note that the input voltage for a voltage multiplier must be AC and the output voltage as mentioned earlier would be DC voltage. This property made it very suitable for the RF energy harvesting design.

2.9 Significance of the Project

The project poses various advantages that has not been realised before in the field of RFID. The advantages include:

1) Energy saving

By harnessing the energy from surrounding radio frequency, it is possible to do away with the battery for an active RFID to have continuous power supply. This breakthrough may even abolish the need for an active RFID, since passive RFID will be able to function just like its active counterpart.

This advantage is very significant to current global movement towards greener Earth by consuming less electricity and finding new source of energy.

2) Reduced maintenance cost for active RFID tags

As mentioned earlier, active RFID tags rely on on-board battery to power it. Once the battery wears off, the battery will need to be replaced manually. In industry or businesses, this involves a large-scale maintenance work which not only poses a high cost but also wasted significant amount of time.

Most of the time, these active tags are placed in hard-to-reach area which causes replacing of battery impossible. Through energy harvesting technology, the on-board battery can be recharged and the need to replace the battery can be abolished.

3) Create perpetual active RFID tags

This project and research may eventually lead to the creation of perpetual active RFID tag. In simpler term, this means that active RFID tags will never run out of battery and will always have the needed power supply. This is achieved by using the harvested energy to directly power the active RFID tags.

2.10 Feasibility study

2.10.1 Feasibility study on RFID industry

As quoted from Mark Roberti, founder and editor of RFID Journal, “Radio frequency identification is a powerful emerging technology that enables companies to achieve total business visibility.” Companies are able to optimize business processes and reduce operational cost by knowing the location, identity and conditions of its inventory, assets and people.

A study by AMR Research shows that early adopters of RFID technology manage to cut supply chain costs by approximately 3 – 5% while increasing its revenue by 2 – 7% [9]. By 2006, revenues for the RFID industry were predicted to reach $7.5 billion [11]. RFID-based solutions were also predicted to save more than $8 billion for the pharmaceutical industry [10].

During the 2007’s Smart Labels Conference, the CEO of IDTechEx, Raghu Das, estimated that the sales for RFID tags for 2006 would be around 1.3 billion tags [12]. Sales for 2007 alone exceeded 1.6 billion while it is forecasted that more than 1 trillion RFID tags will be shipped by 2015 [1]. These figures show that the growth of RFID technology will be significant in the next 5 years and would even be as pervasive as barcode technology in the near future.

Table 5: Comparison between RFID and Barcode technology [11]

System	Barcode	RFID
Data Transmission	Optical	Electromagnetic
Typical Data Volume *Data Modification*	1-100 Bytes Not possible	128-8K Bytes Possible
Position of Data Carrier for Read/Write	Visual contact	Non line of sight possible
Reading Distance	Several metres (line of sight)	From centimetres to metres (depending on the frequency and tags)
Access Security	Little	High
Environmental Susceptibility	Dirt	Very small
Anticollision	Not possible	Possible

With rapid advancements in RFID technology and benefits of RFID technology over traditional alternatives like barcode as shown in the table above, it is clear that RFID would be the major player in the AIDC industry in years to come.

Thus, the focus, research and development into RFID technology are very feasible and will have a great prospect not only to accelerate its growth, but the industry as a whole.

2.10.2 Feasibility study on RF energy source

Radio frequency (waves) is ubiquitous in our daily lives, be it in the form of signals transmission from mobile phone (GSM), Wireless LAN (WiFi, WiMAX), radio, TV, Bluetooth, etc. They are readily available as “free energy” to be harvested at almost anywhere and at any time.

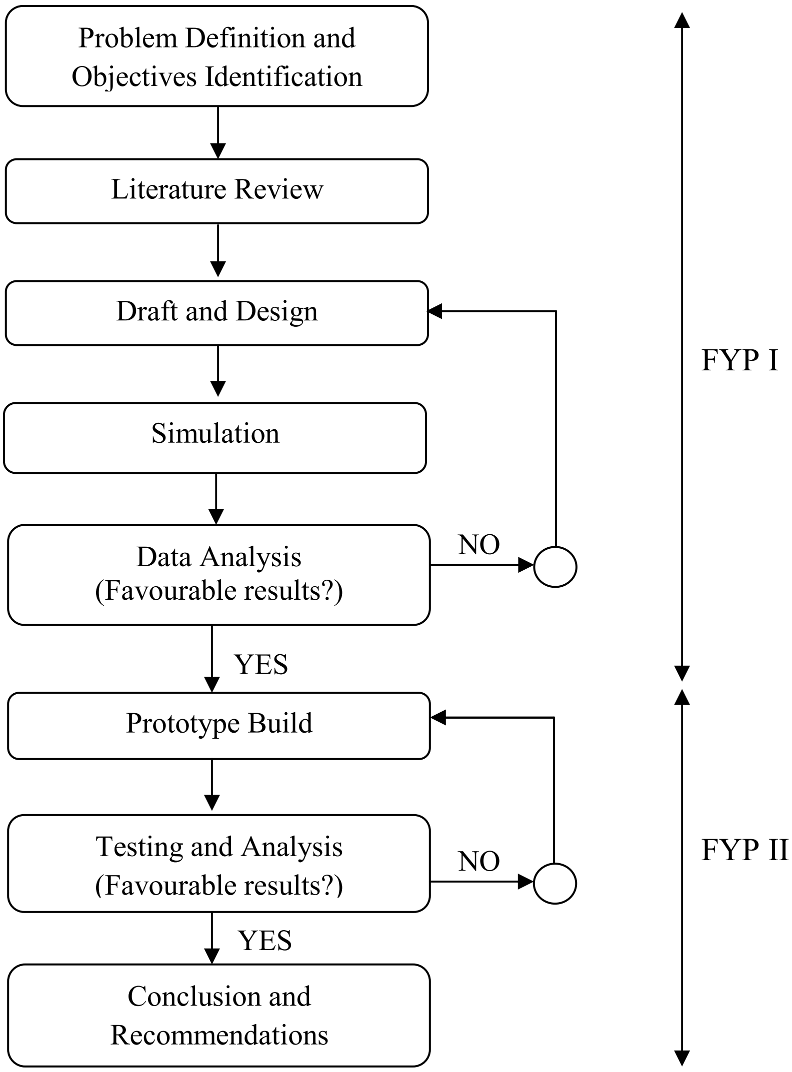
Therefore, RF energy source holds great potential of being the future source of energy. It is definitely worthwhile for the project to focus on RF energy as the energy source to power passive RFID.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

In order to achieve the project's objective, there are various steps that need to be executed. The procedures involved are shown as follow:



3.2 Tools & Equipment Used

The equipment used throughout the experiment can be categorized into the following:

a) Hardware
   - Electrical components (Project board, antenna, veraboard, wires)
   - Electronics components (capacitors, diodes)
   - Testing equipment (multimeter, AC function generator, DC power supply)
   - Personal computer

b) Software
   - Simulation software (Pspice, MultiSIM etc.)
   - Project management software (Microsoft Office suite)

3.3 Simulation Test Plan

Few stages of simulation are carried out prior to the prototype build phase in order to determine the most suitable configuration that can be applied for the prototype. The ultimate goal of the simulations is to find out:

a) The optimum configuration of voltage multiplier
b) The optimum number of stages for the voltage multiplier
c) The type of diode to be used
d) The value of capacitance to be used

Details of the simulation test plan are tabulated as follow:

Table 6: Simulation Test Plan

Test Name	Description	Variables
Simulation I Different configurations of voltage multipliers	To determine the most efficient configuration of voltage multiplier through a series of simulation	Voltage multiplier configurations (i.e. Dickson, Greinacher and Villard configuration)
Simulation II Silicon vs. Schottky diode	To determine the difference in performance between silicon and schottky diode implementation on circuit design	Type of diode (i.e. silicon and Schottky diode)
Simulation III Multiple stages Villard Voltage Multiplier	To analyse the DC output voltage yield by voltage multiplier of different stages	Number of stages for the voltage multiplier
Simulation IV Effects of different capacitor values	To find out the effects of using capacitors with different value of capacitance at a constant frequency as well as variable frequency	Values of capacitance and frequency of AC input

3.4 Prototype Build Test Plan

Prototype build test plan aims to find out the performance of the prototype created based on analysis of the simulation results. There are two phases for the prototype build testing. The first phase focuses on testing the performance of the prototype by using direct AC input generated using a function generator. This is carried out to ensure that the prototype works and behaves as it should be as shown in simulation results.

The second phase meanwhile focuses on testing the performance of the prototype using surround radio frequency waves. This is carried out to determine whether the prototype is able to harvest the surrounding radio frequency, which is the objective of the project. Details of the prototype build test plan are tabulated in the following table:

Table 7: Prototype Build Test Plan

PHASE 1		
Test Name	**Description**	**Variables**
Test I Verifying the performance of voltage multiplier circuit	To ensure that the initial prototype of voltage multiplier exhibit same behaviour as shown in simulation	3 kHz and 50 kHz AC input power (at different voltage and current)
Test II Determining the optimum number of stages for the prototype design	To determine the optimum number of stages for the prototype design by analysing the power loss and efficiency at multiple stages	Number of stages of the voltage multiplier
Test III Testing the performance of Germanium diode vs. Schottky diode	To find out the different in performance of prototype using germanium diode and Schottky diode	Type of diode (i.e. Germanium and Schottky diode)

PHASE 2		
Test Name	**Description**	**Variables**
Test IV RF energy harvesting from a 300MHz transmitter	To test the prototype's RF energy harvesting capability using a 300MHz transmitter	Distance between RF source and prototype
Test V RF energy harvesting from Global System for Mobile Communications (GSM) signal	To test the prototype's RF energy harvesting capability using a GSM a.k.a. mobile phone waves	Distance between RF source and prototype
Test VI RF energy harvesting from simulated TV transmission	To test the prototype's RF energy harvesting capability using an RF transmitter at 180 MHz simulating TV transmission RF waves	Distance between RF source and prototype
Test VII RF energy harvesting from Bluetooth signal	To test the prototype's RF energy harvesting capability using a Bluetooth transmission	Distance between RF source and prototype

CHAPTER 4

RESULT AND DISCUSSION

4.1 Overview of energy harvesting system

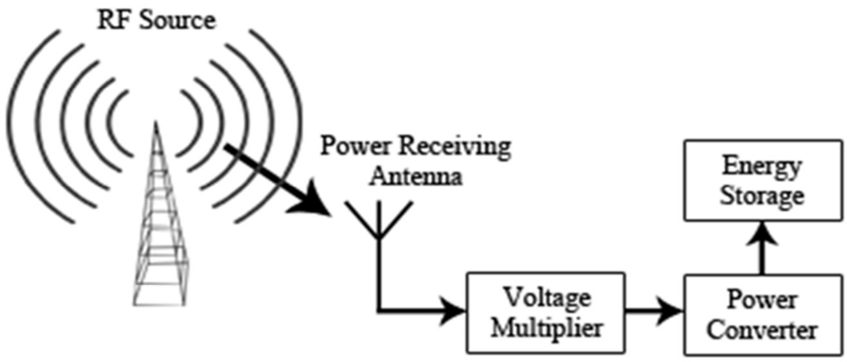


Figure 9: An Overview of RF Energy Harvesting System

The figure above provides overview of the planned energy harvesting system. It basically consist of a power receiving antenna which will be able to capture RF sources, such as radio waves from TV, radio broadcast, Wireless Local Area Network (WLAN), Wireless Fidelity (WiFi), Global System for Mobile Communications (GSM), Bluetooth etc.

Once this energy is harvested, it will pass through a system of rectifier which will convert alternating current (AC) to direct current (DC). The direct current will be fed through the voltage multiplier where the voltage will be stepped up to increase the output voltage.

If necessary, the harvested energy will also pass through a power converter, where it can be used to modify the voltage and frequency value of the harvested power before being supplied to the charger or energy storage device.

4.2 Results & Analysis

4.2.1 Simulation

4.2.1.1 Simulation I – Different configurations of voltage multipliers

This section contains the simulation results of 2-stage voltage multiplier for three different types of configuration of voltage multiplier. Theoretically, a 2-stage voltage multiplier can yield output voltage which is four times that of input voltage. This simulation aims to determine the most effective configuration of voltage multiplier for the RF energy harvesting design. Initial parameters used are as follow:

Table 8: Initial parameters for Simulation I

Voltage source (AC)	5V, 50kHz
Capacitor	1µF
Diode	1N3064 (small signal silicon diode)
Voltmeter (DC)	1MΩ

The results obtained from MultiSIM simulation are as follow:

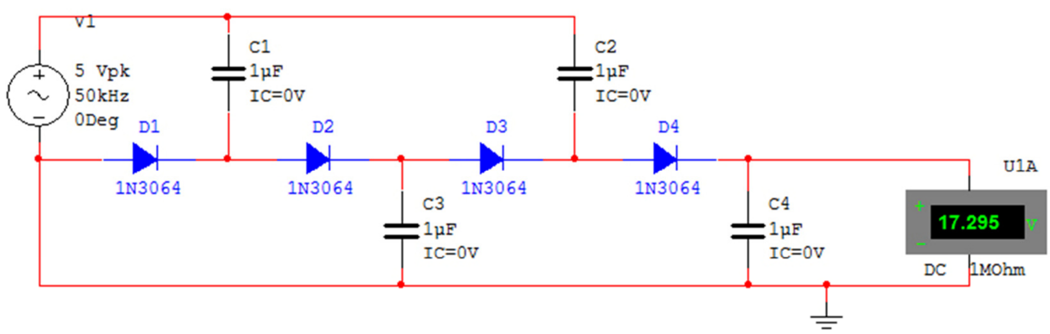


Figure 10: 2-Stage Dickson Voltage Multiplier

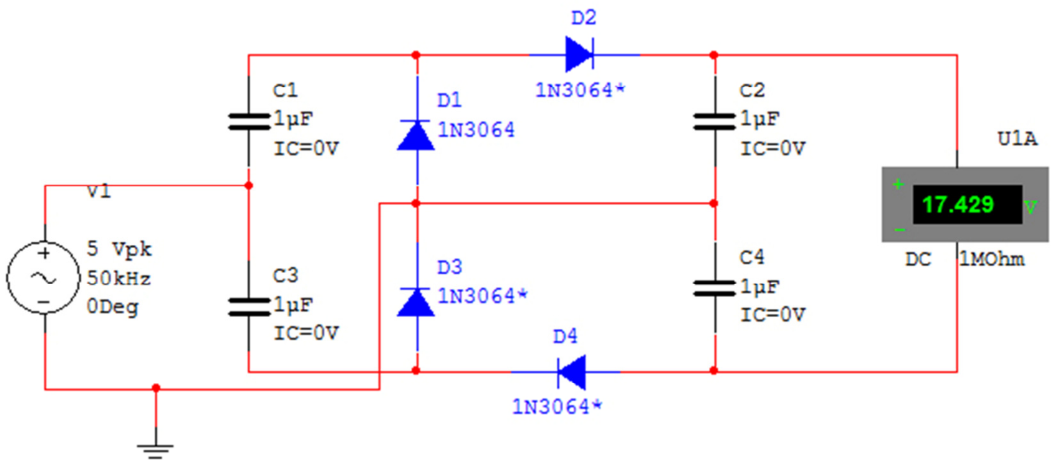


Figure 11: Greinacher Voltage Quadupler

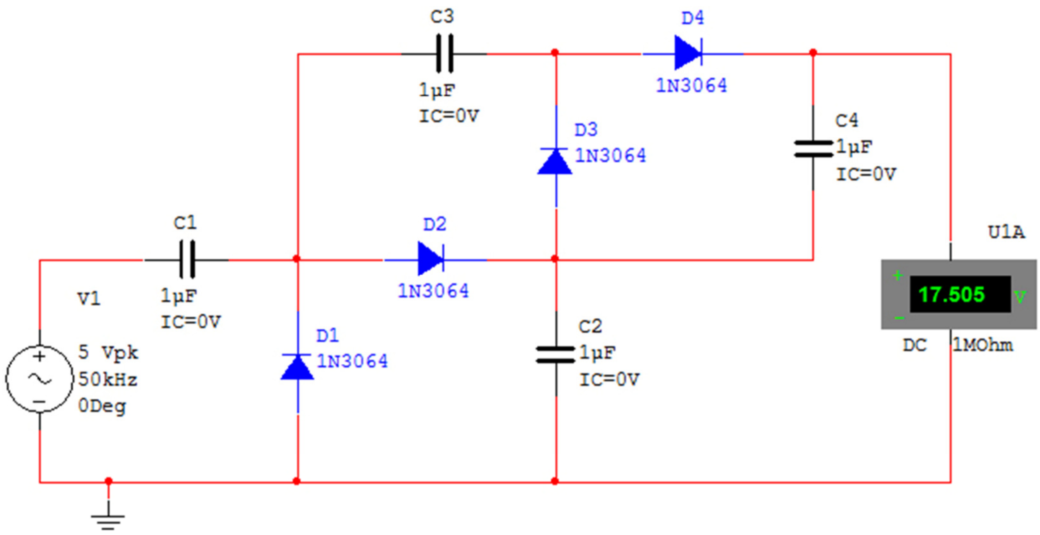


Figure 12: 2-Stage Villard Voltage Multiplier

Summary of the simulations above is as follow:

Table 9: Results of Simulation I

Voltage Multiplier Configuration	DC Output Voltage (V)
Dickson	17.295
Greinacher	17.429
Villard	17.505

The result shows that by using the same amount of diode and capacitor (same cost) as well as the same input voltage, the generated output voltage differs slightly from one another for the different types of voltage multiplier configurations. The Villard voltage multiplier configuration offers slight advantage over the other configurations since its output voltage is slightly higher than the others. Therefore, it is decided to implement Villard voltage multiplier configuration for the design.

4.2.1.2 Simulation II – Silicon Diode vs. Schottky Diode

The next simulation carried out is to evaluate the difference between the normal silicon diode with the Schottky diode. Schottky diode is known for its low forward voltage drop and fast switching action which poses to be of an advantage over normal silicon diode. Silicon diode usually has forward voltage drop of 0.6V to 1.7V while Schottky diode's voltage drop at forward biases of around 1mA is approximately 0.15V to 0.45V. Therefore, it is predicted that the performance of RF energy harvesting design using Schottky diode will be better than that using normal silicon diode.

The initial parameters used for this simulation are similar to that stated in Table 5, except that there will be three different diodes that were tested. The three diodes are:

i) 1N3064 (small signal silicon diode)
ii) 1SS241 (general purpose silicon diode)
iii) 1N5711 (small signal Schottky diode)
iv) 1N5712 (small signal Schottky diode)

The results of the simulation using MultiSIM can be seen in the following pages.

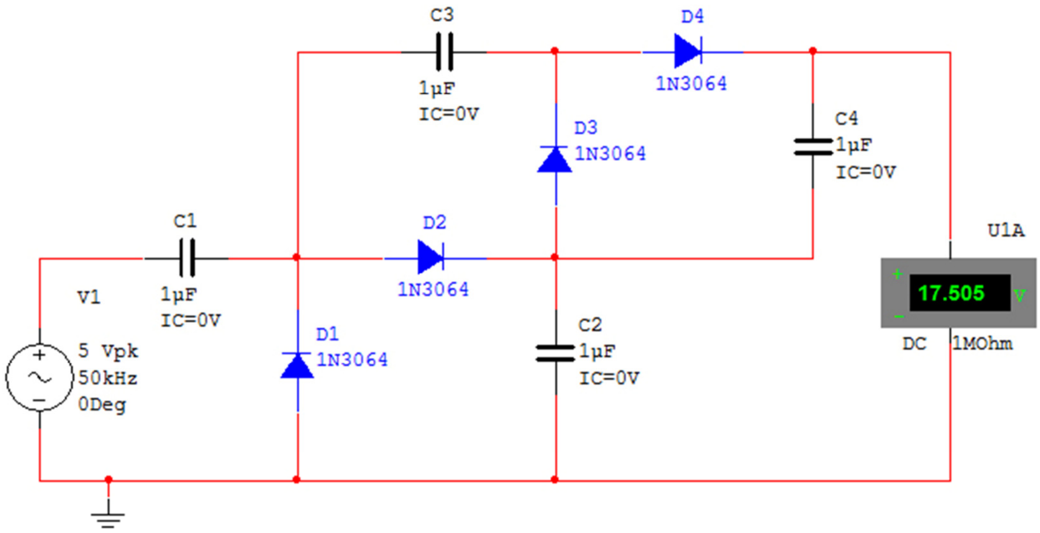


Figure 13: 2-Stage Villard Voltage Multiplier using 1N3064 diode

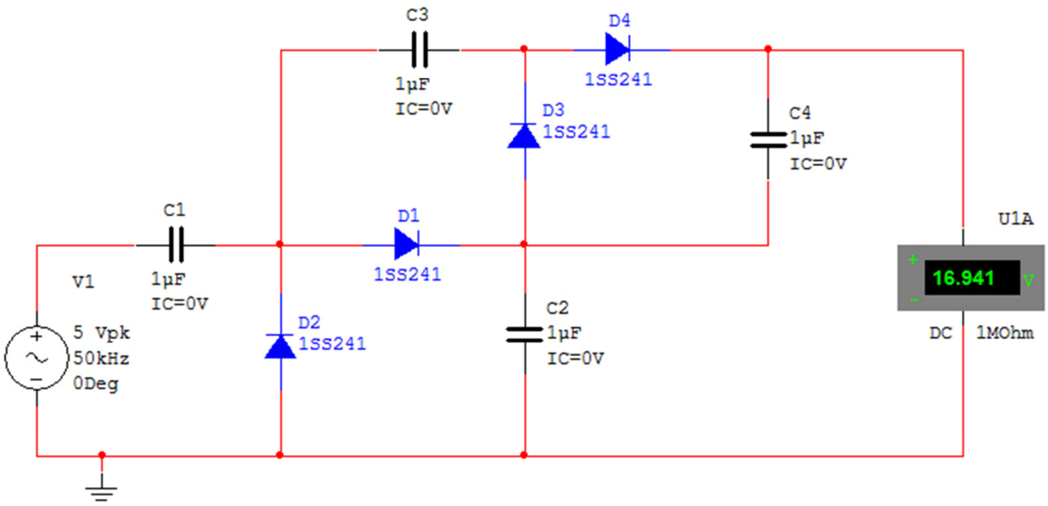


Figure 14: 2-Stage Villard Voltage Multiplier using 1SS241 diode

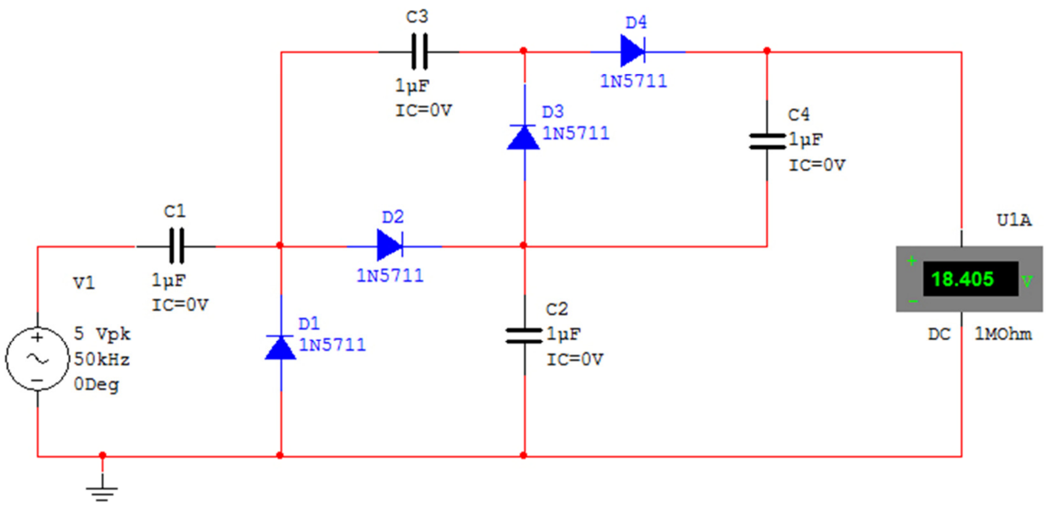


Figure 15: 2-Stage Villard Voltage Multiplier using 1N5711 diode

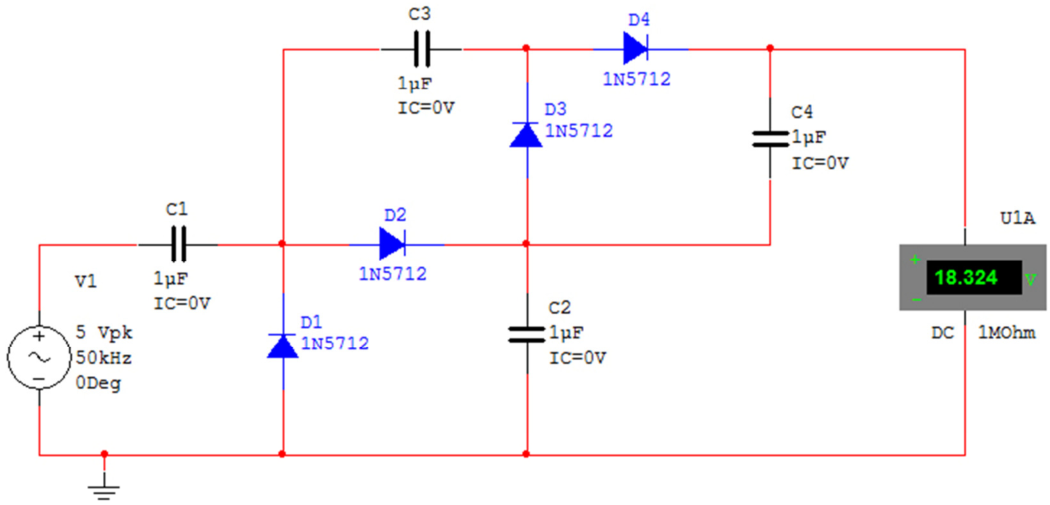


Figure 16: 2-Stage Villard Voltage Multiplier using 1N5712 diode

Summary of the simulations above is as follow:

Table 10: Results of Simulation II

Types of Diode	**Diode**	**DC Output Voltage (V)**
Silicon diode	1N3604	17.505
	1SS241	16.941
Schottky diode	1N5711	18.405
	1N5712	18.342

The results of the simulation reflects the prediction made earlier based on the fact that Schottky diode has a low forward voltage drop compared to normal silicon diode. It can be seen that the output voltage of the design using Schottky diode is higher than that of normal silicon diode, indicating a better performance. Small signal Schottky diode is commonly used in high frequency applications, thus making it suitable for RF energy harvesting design. Another type of diode (not included in the simulation but may have the potential to be considered as part of the design) is Germanium diode. Like Schottky diode, it has a low voltage drop of around 0.3V and it is much cheaper and easily available compared to Schottky diode.

4.2.1.3 Simulation III – Multiple stages Villard Voltage Multiplier

This round of simulation aims to determine the output voltage of multiple stages Villard voltage multiplier. It is known that increasing the number of stages of voltage multiplier will increase the output voltage, thus enabling the input voltage to be multiplied further. As seen in Simulation I and Simulation II, a 2-stage voltage multiplier are able to produce an output voltage of 3.5 times (theoretically 4 times) the value of input voltage. The initial parameters set for this simulation is as follow:

Table 11: Initial parameters for Simulation III

Voltage source (AC)	5V, 50kHz
Capacitor	1µF
Diode	1N5711 (small signal Schottky diode)
Voltmeter (DC)	1MΩ

A total of 5 simulations are carried out, which comprises of 1-stage, 2-stage, 3-stage, 4-stage as well as 5-stage voltage multiplier. The results of the simulations can be viewed in the figures below:

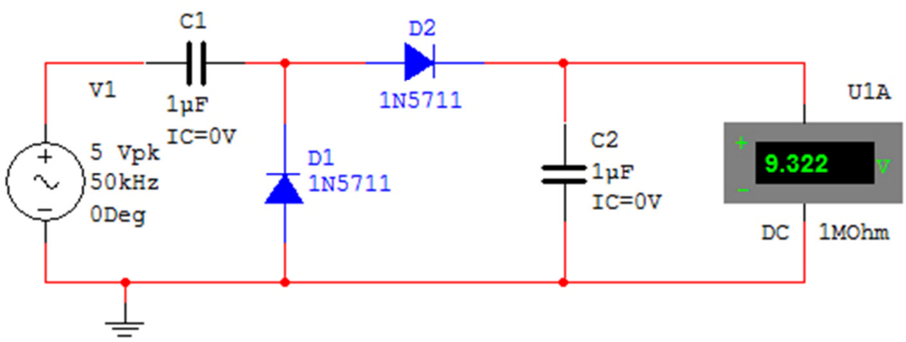


Figure 17: 1-Stage Villard Voltage Multiplier

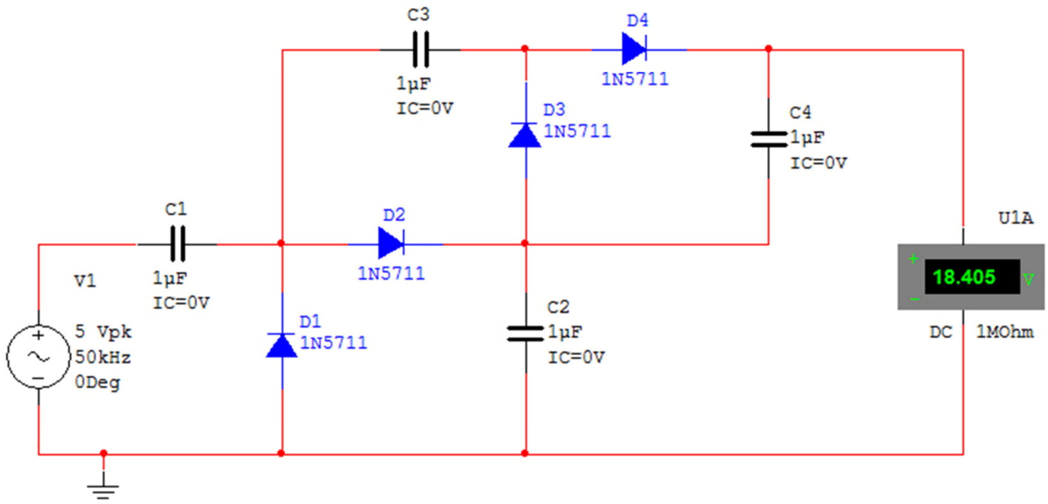


Figure 18: 2-Stage Villard Voltage Multiplier

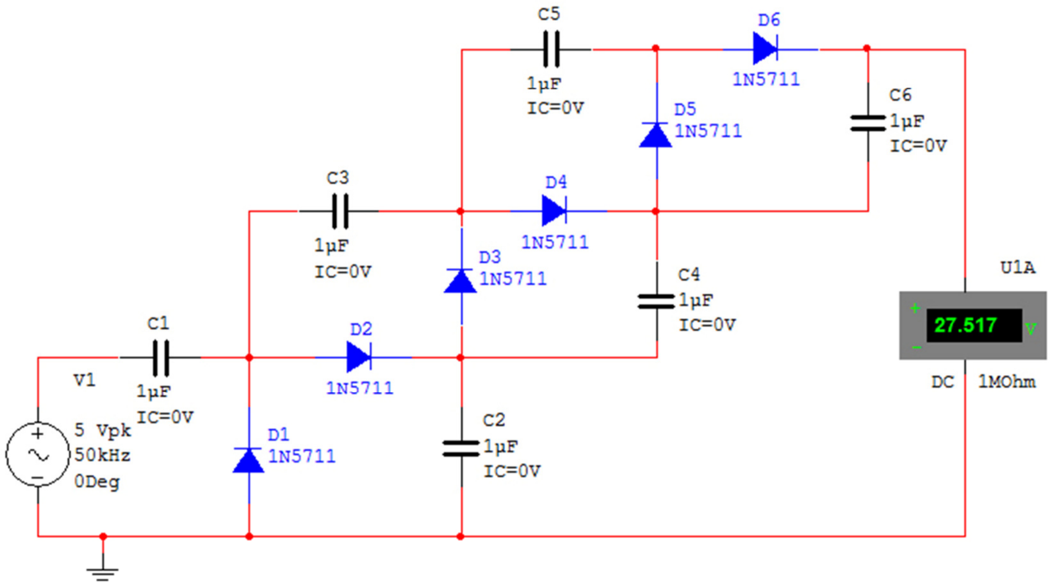


Figure 19: 3-Stage Villard Voltage Multiplier

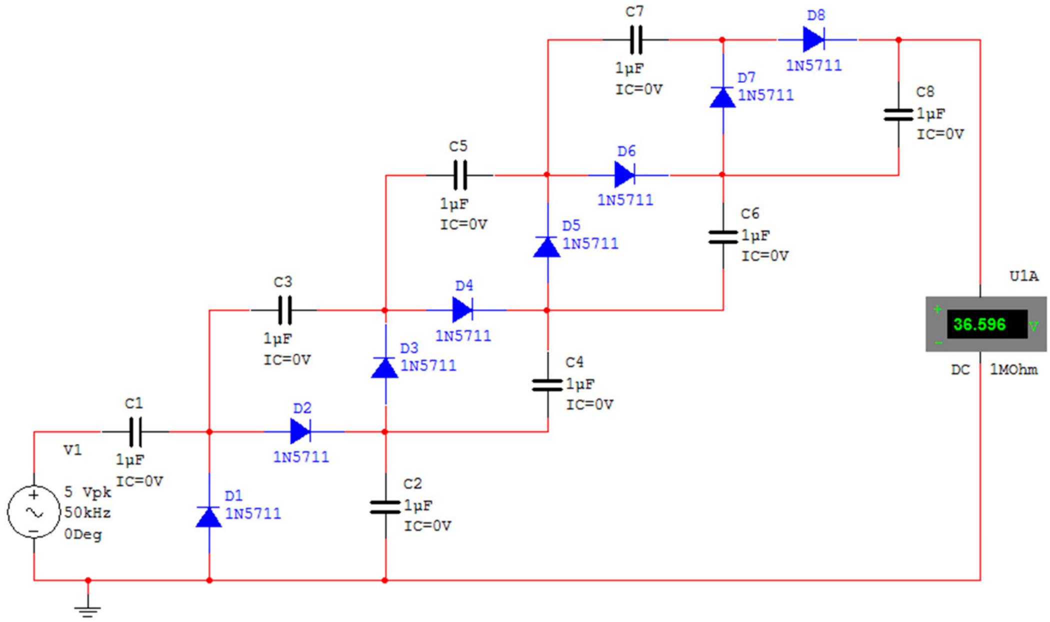


Figure 20: 4-Stage Villard Voltage Multiplier

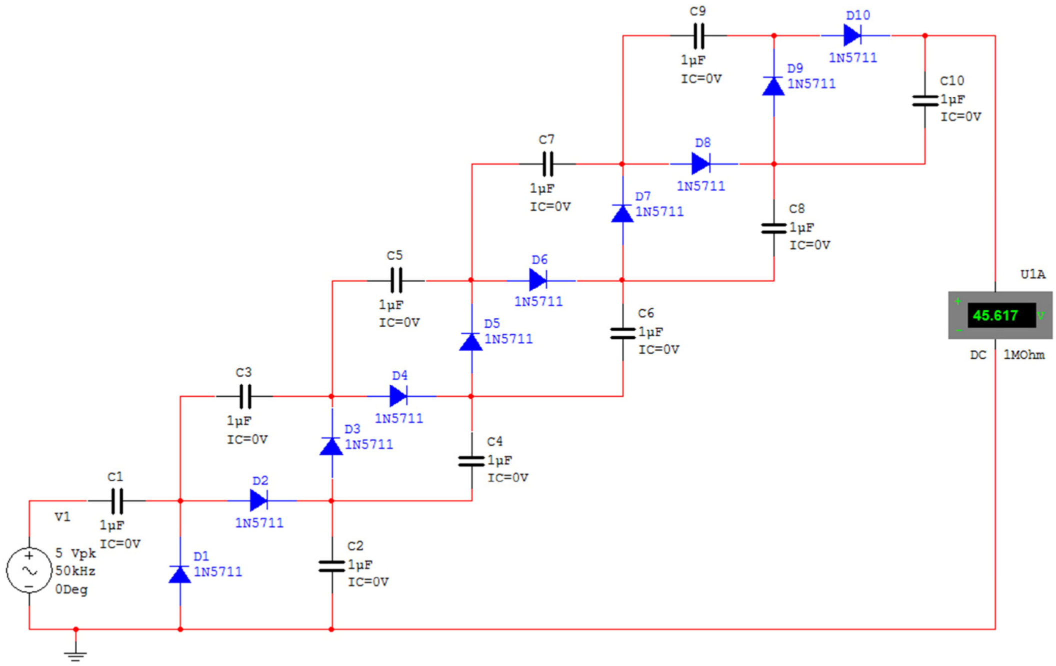


Figure 21: 5-Stage Villard Voltage Multiplier

Summary of the simulations above is as follow:

Table 12: Results of Simulation III

Number of Stages	DC Output Voltage (V)
1	9.332
2	18.405
3	27.517
4	36.596
5	45.617

From the results retrieved, it can be seen that increasing the number of stages of voltage multiplier will increase the DC output voltage. Analysis using a graph as shown in Figure 20 shows that the increment is in a linear form. Increasing the number of stages will increase the number of components (diodes and capacitors) used, thus increasing the cost of the design. It can be seen that the number of components also increase linearly as the number of stages increases.

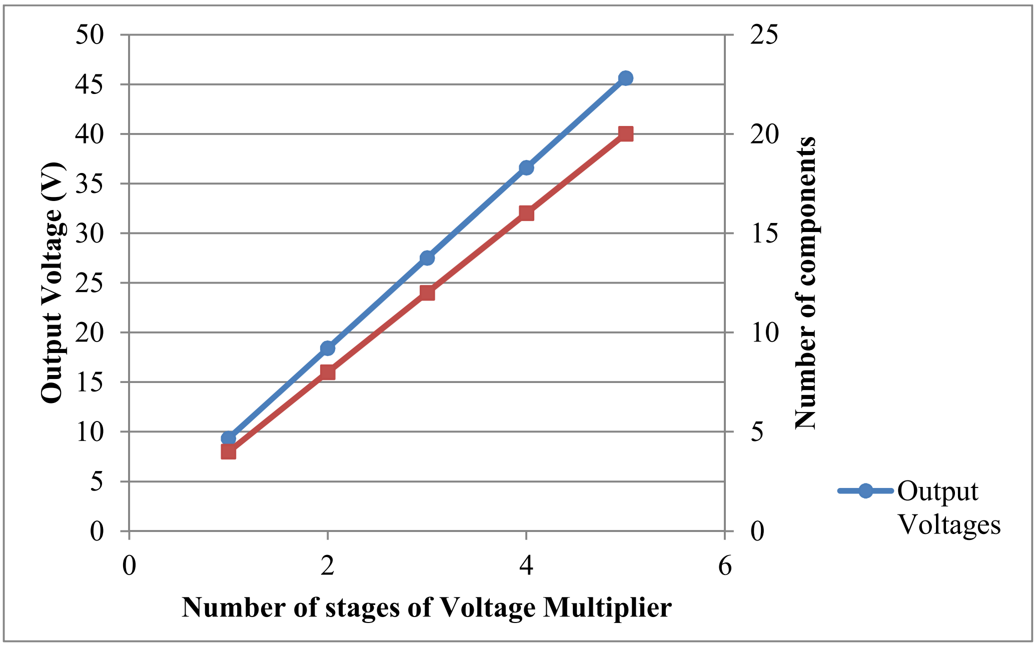


Figure 22: Graph of Output Voltage and Number of Components vs. Number of Stages of Voltage Multiplier

Based on Simulation III, it can be concluded that the number of stages and cost must be taken into consideration in the design of RF energy harvesting voltage multiplier circuit. The number of stages required will be heavily dependent on the obtained input voltage and the desired output voltage from it.

4.2.1.4 Simulation IV – Effects of different capacitor values

The next simulation aims to determine the effects of different capacitance to the output voltage, thus aiding the decision on choosing the appropriate value of capacitors used in the circuit design. Since RF energy sources (i.e. radio FM broadcast, WiFi, Bluetooth and TV transmission) are available at different frequencies, the value of capacitors must to be varied accordingly.

Two cases as described below are simulated and are discussed seperately. For simplicity, two-stage voltage multiplier with input voltage of 5V is used throughout the simulation.

CASE 1: Frequency is fixed at 50 kHz with value of capacitor varied.
CASE 2: Frequency is increased and value of capacitor is varied.

For the first case, the frequency is set to be 50 kHz. The value of capacitor is varied between 1 mF, 1 μF and 1 nF. Transient analyses are carried out to analyse the characteristics of using different values of capacitors. Results of the simulations can be viewed in the following figures.

Simulation using 1 mF capacitor (3.5 seconds):

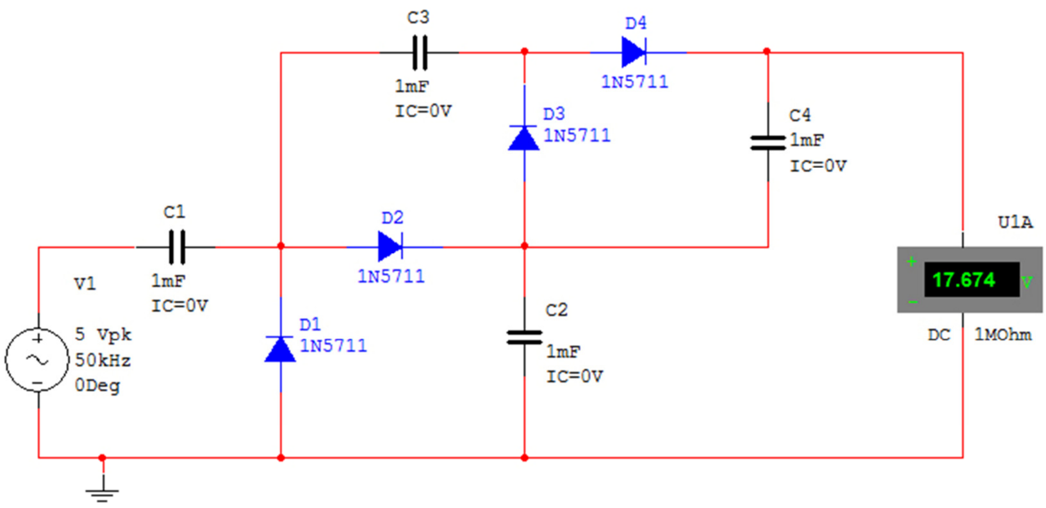


Figure 23: Simulation using 1 mF capacitor for 3.5 seconds

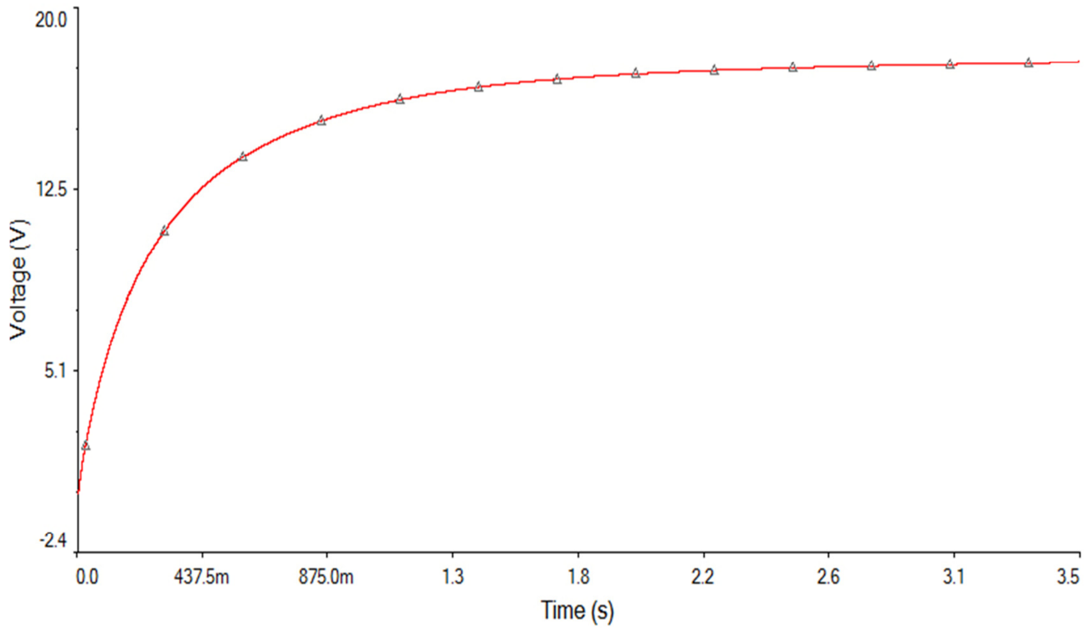


Figure 24: Transient analysis of simulation using 1 mF capacitor for 3.5 seconds

Simulation using 1 μF capacitor (0.04 seconds):

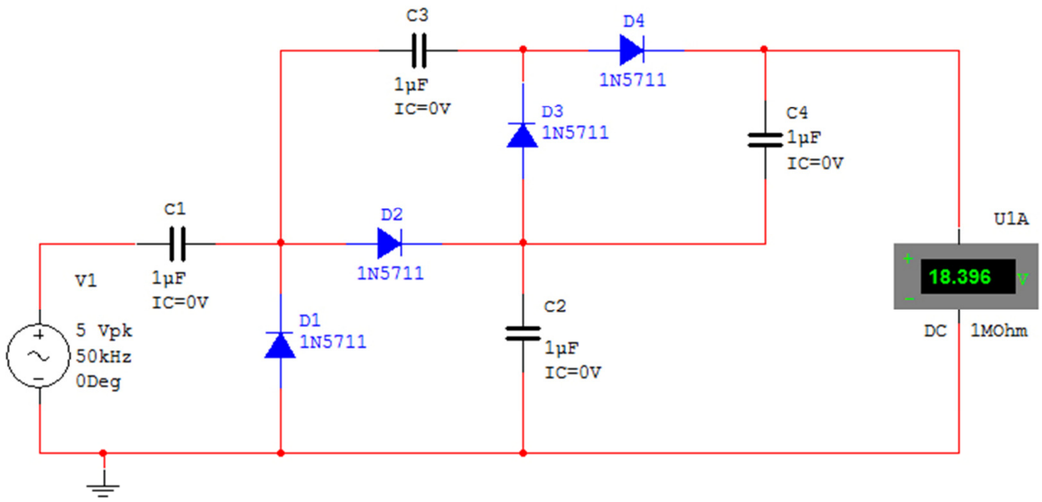


Figure 25: Simulation using 1 μF capacitor for 0.04 seconds

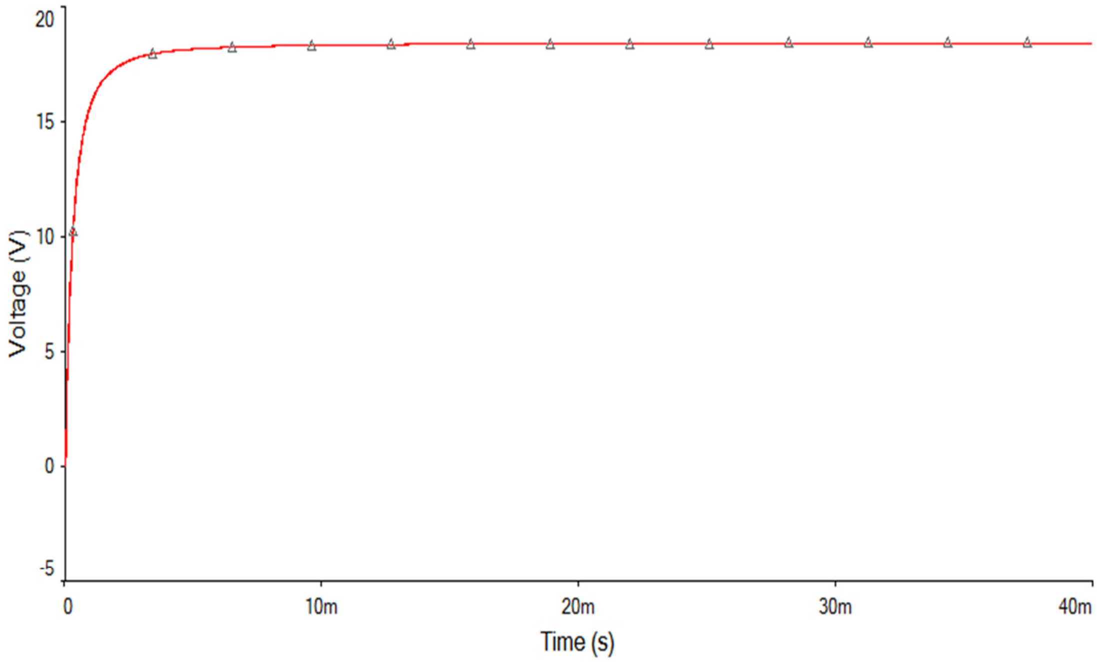


Figure 26: Transient analysis of simulation using 1 μF capacitor for 0.04 seconds

Simulation using 1 nF capacitor (0.04 seconds):

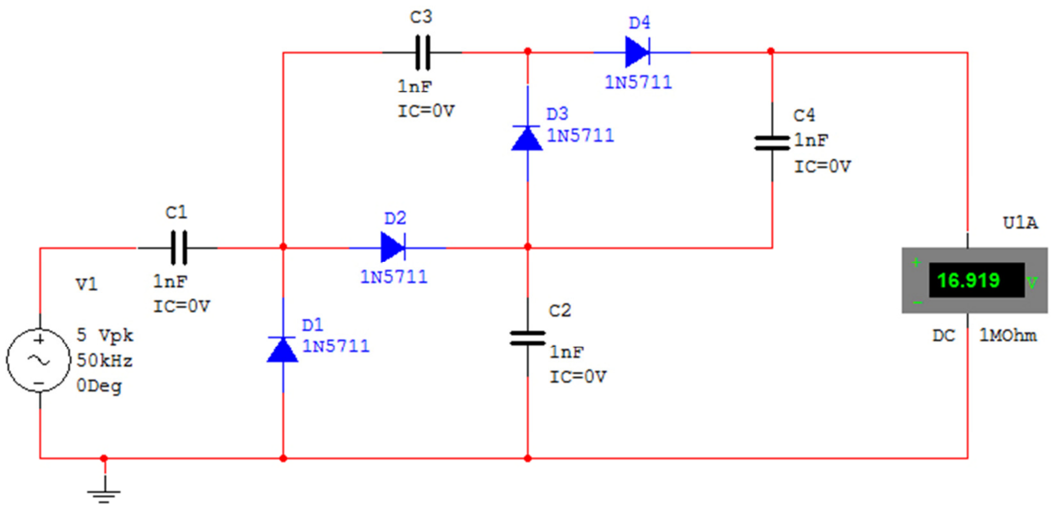


Figure 27: Simulation using 1 nF capacitor for 0.04 seconds

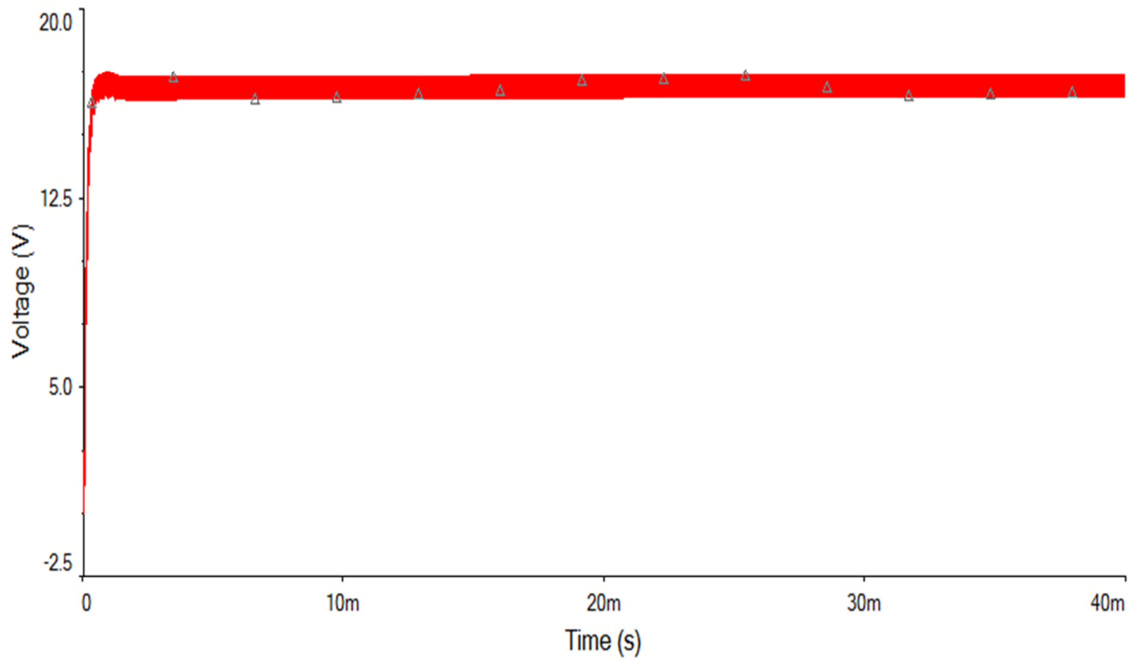


Figure 28: Transient analysis of simulation using 1 nF capacitor for 0.04 seconds

From the results above, it can be seen that by using 1 mF capacitor, it takes a longer time for the output voltage to reach its peak value as compared to using 1 μF and 1 nF capacitors. It is only after 3.5 seconds the output voltage reaches the value of 17.674V.

On the other hand, using 1 nF capacitor yield maximum output voltage of around 17.3V in a very short time (approximately 0.0005s) but the output voltage drops slightly after. It also produces unstable (ripple) output voltage. The output voltage fluctuates between 16V to 17V.

In comparison, it can be observed that utilizing 1 μF capacitor appears to be the best choice among the three, as it produces maximum output voltage of 18.396V in a very short time and it does not contain ripple. As a conclusion, different values of capacitor will have different effects on the output voltage generated by the voltage multiplier circuit. Therefore, the design must take into consideration the value of capacitors used in order to produce optimum results.

The next simulation (case 2) will look into the effects different capacitor values for the input voltage at increased frequency. From the previous simulation, we have already seen the effects on 50 kHz input voltage. This part of simulation meanwhile will focus on input voltage at 1 MHz and 10 MHz.

The following figures show the result of simulation using the capacitors of 1 μF and 1 nF respectively.

Simulation of input voltage at 1 MHz (using 1 µF capacitor):

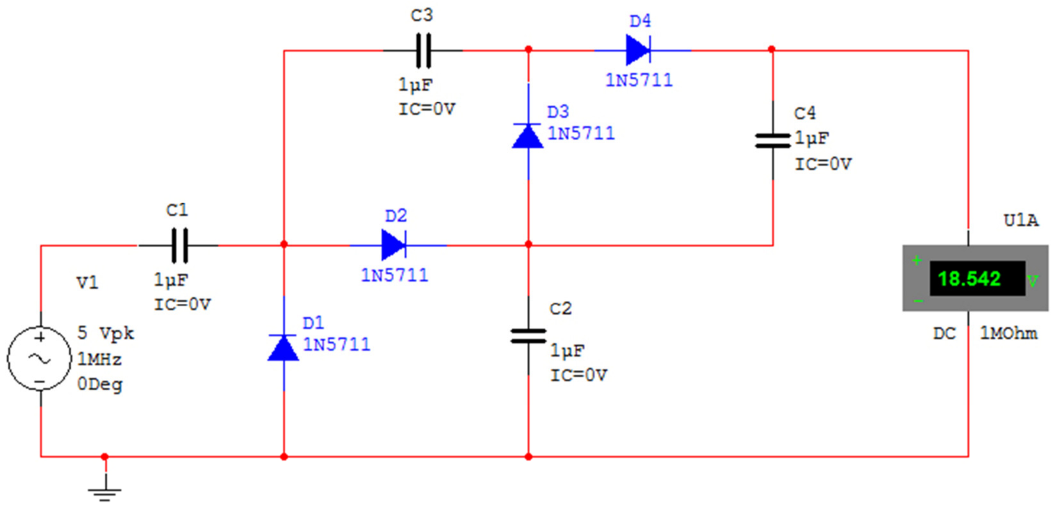


Figure 29: Simulation using 1 µF capacitor for 0.04 seconds at 1 MHz

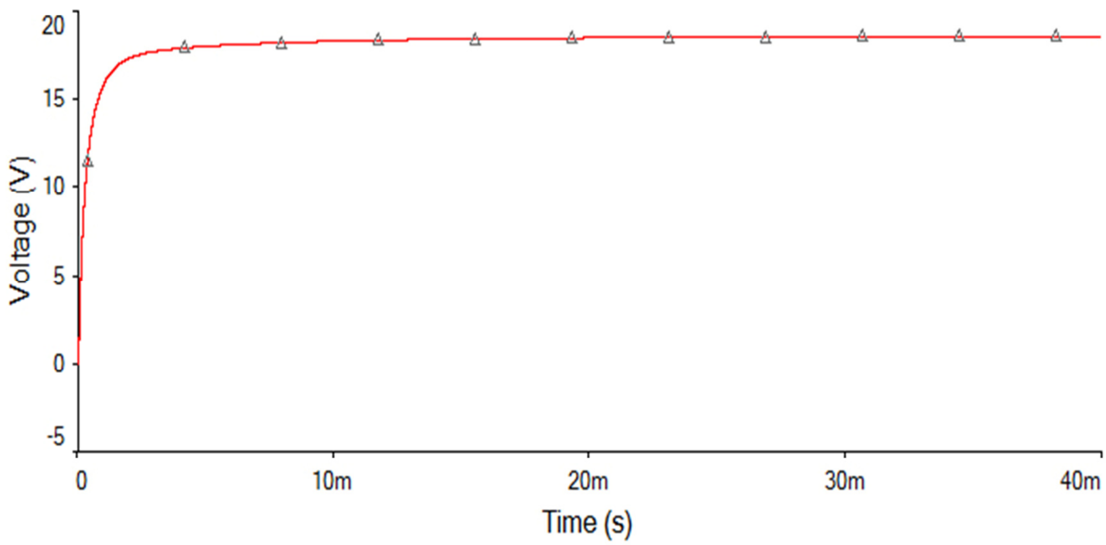


Figure 30: Transient analysis of simulation using 1 µF capacitor for 0.04 seconds at 1 MHz

Simulation of input voltage at 1 MHz (using 1 nF capacitor):

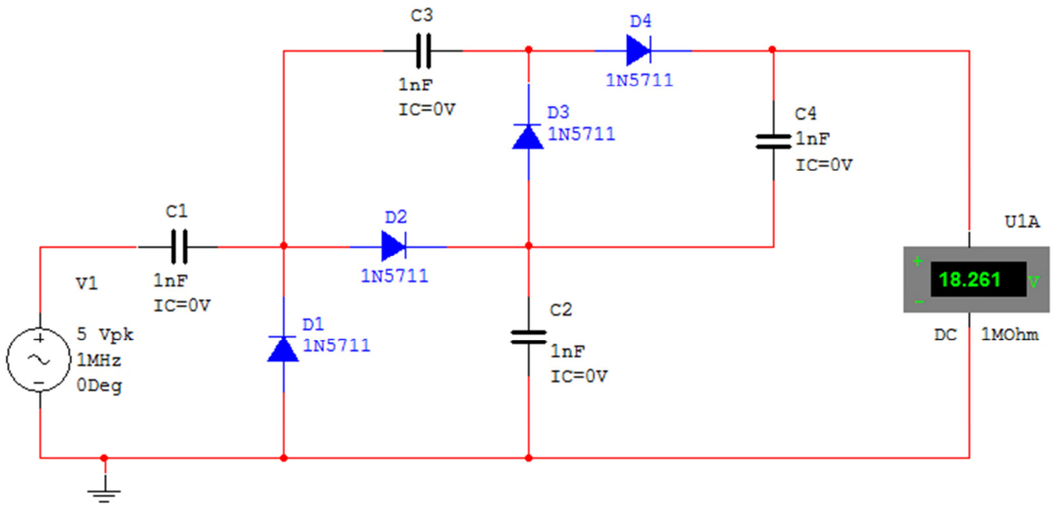


Figure 31: Simulation using 1 nF capacitor for 0.04 seconds at 1 MHz

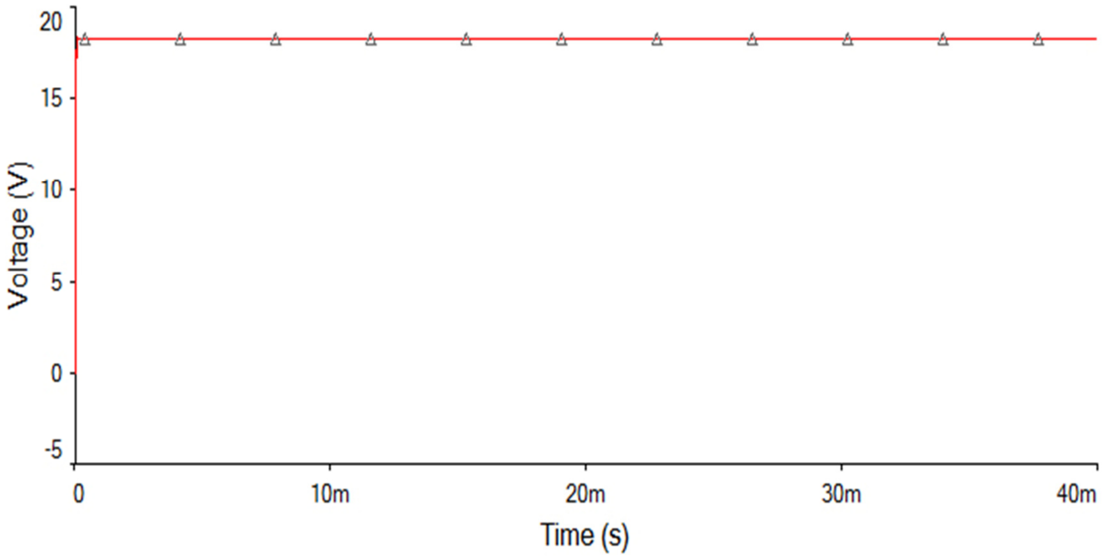


Figure 32: Transient analysis of simulation using 1 nF capacitor for 0.04 seconds at 1 MHz

Simulation of input voltage at 10 MHz (using 1 µF capacitor):

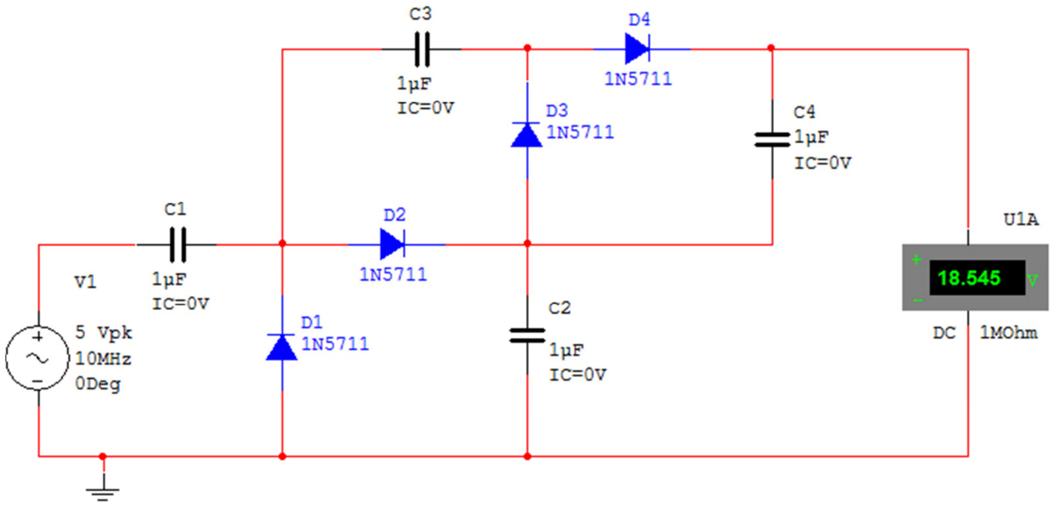


Figure 33: Simulation using 1 µF capacitor for 0.04 seconds at 10 MHz

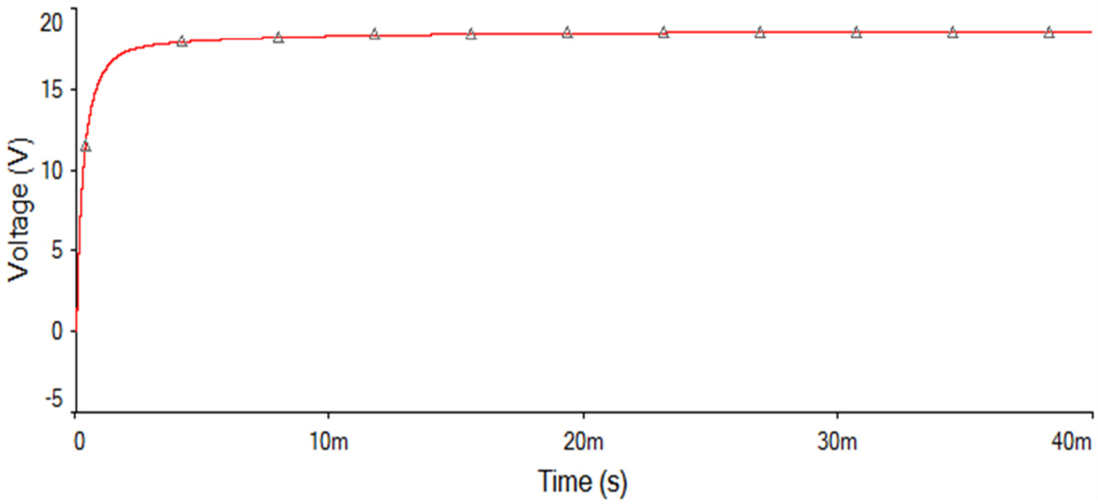


Figure 34: Transient analysis of simulation using 1 µF capacitor for 0.04 seconds at 10 MHz

Simulation of input voltage at 10 MHz (using 1 nF capacitor):

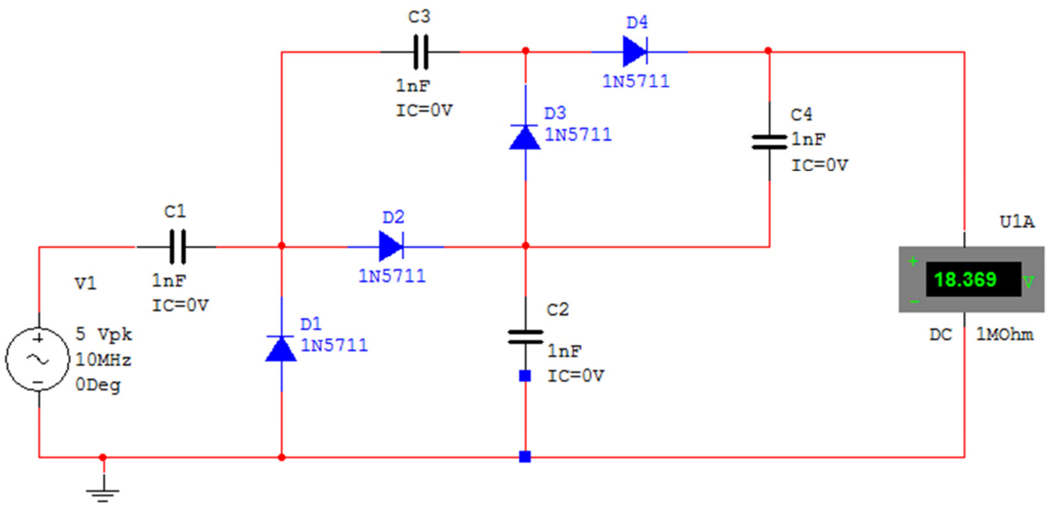


Figure 35: Simulation using 1 nF capacitor for 0.04 seconds at 10 MHz

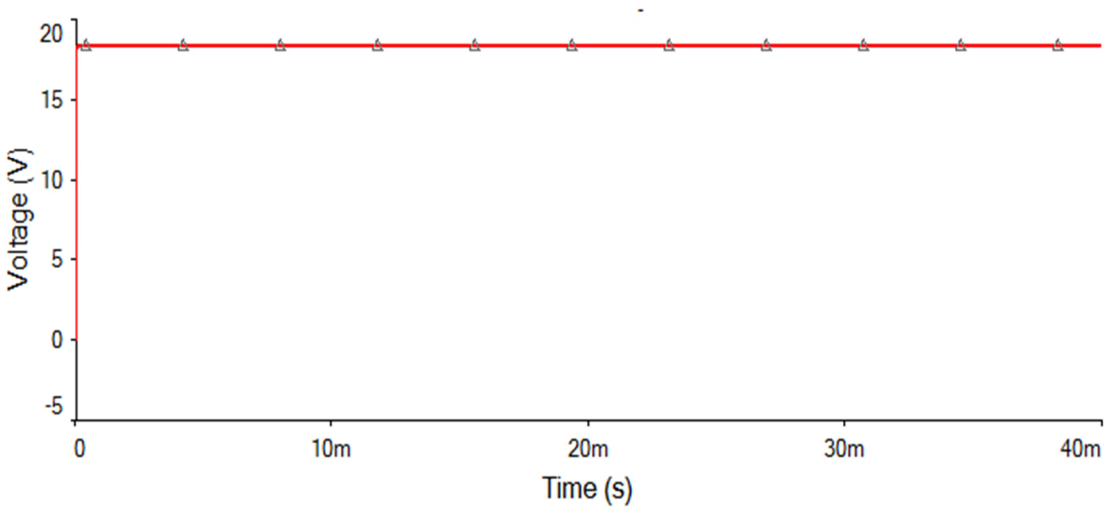


Figure 36: Transient analysis of simulation using 1 nF capacitor for 0.04 seconds at 10 MHz

Case 2 of simulation IV shows that for increased value of frequency, the transient characteristic for the respective capacitance is similar to one another. Utilizing 1 μF capacitor appears to be the most appropriate choice out of the three values of capacitor, since it yield the highest and most stable output voltage within a short range of time. This statement appears to be true for all three simulations involving frequencies of 50 kHz, 1 MHz and 10 MHz.

4.2.2 Prototype build and test

4.2.2.1 Test I - Verifying the performance of voltage multiplier circuit

Once the voltage multiplier prototype circuit was built, its performance was tested using direct AC input generated with a function generator. This part of testing is to verify that the voltage multiplier prototype works as specified in theory and simulation. Due to the unavailability of Schottky diode, the initial design utilized the next best diode which is the Germanium diode. This is based on the fact that Germanium diode also has low voltage drop of 0.3V compared to 0.2V for Schottky diode. Below are the specifications and the figure of the prototype build:

Table 13: Specifications for voltage multiplier prototype #1

No. of stages	3
Type of capacitor	1μF, 50V rating
Type of diode	OA90 (Germanium)

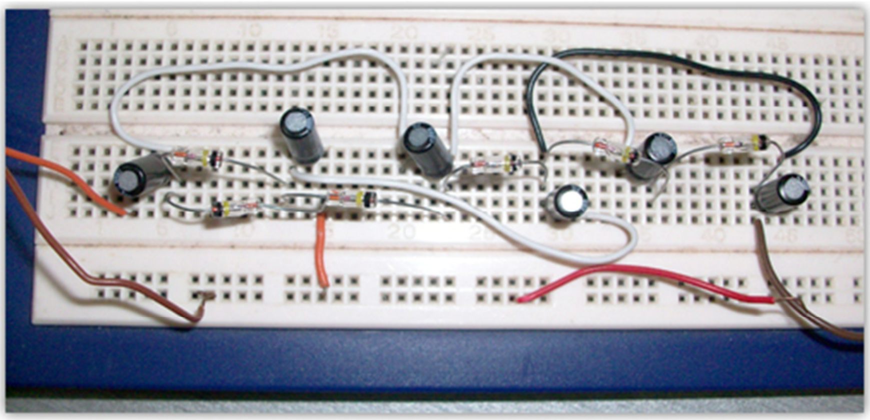


Figure 37: 3-Stage voltage multiplier prototype #1

It is worthy to note that the higher number of stages used will produce a higher output voltage but may also result in more power loss within the components. Therefore, based on a few rounds of preliminary testing, the prototype design will initially proceed with implementing 3-stages voltage multiplier.

On the capacitance side, the decision to use 1µF capacitors is based on the simulations results obtained earlier. It is known from the simulations that different capacitance does not have much impact on the output voltage yield. Preliminary testing has also confirmed this.

Two sets of testing is done to verify the circuit design whereby one utilized a 3kHz AC input while another using a 30kHz AC input. The results are tabulated as follow:

Table 14: Results of voltage multiplier prototype #1 verification testing

$V_{in, AC}$ (V)	$I_{in, AC}$ (mA)	$V_{out, DC}$ (V)	$I_{out, DC}$ (mA)
PART 1 - 3kHz AC input			
1	20.0	9.59	1.1
2	39.5	17.53	3.2
3	57.8	23.87	6.7
4	69.8	27.46	10.5
5	86.3	30.84	14.4
PART II – 50kHz AC input			
1	19.4	8.95	1.8
2	32.5	17.01	4.2
3	48.9	34.92	6.5
4	66.9	29.43	9.0
5	80.2	33.27	13.2

Comparing the above results with the simulation results, it can be concluded that the voltage multiplier circuit has been verified to be working properly. Therefore, further testing can be carried on using this circuit design.

4.2.2.2 *Test II – Determining the optimum number of stages for the prototype design*

Theoretically, as the number of stages cascaded in the voltage multiplier increases, the output DC voltage also increases. This is also proven in the simulation results. Logically, having the highest output DC voltage may be a desirable condition for the RF energy harvesting circuit design, thus having an infinite number of stages (or a very large number of stages) would be desirable. However, when we take into account the output current and the efficiency of the circuit design (power loss etc.), the number of stages has a particular limit.

This part of the testing aims to determine the optimum number of stages that can be implemented for the prototype design. The results are tabulate as follow and the conditions for testing are self-explanatory from the table below:

Table 15: Results of using different number of stages at varying input voltages

	$V_{out, DC}$ (V)	$I_{out, DC}$ (mA)	$P_{out, DC}$ (mW)	**Power Loss** (%)
AC Input: 1 V @ 20.00 mA (20.00 mW)				
1-STAGE	3.42	4.80	16.42	17.92
2-STAGE	6.72	2.55	17.14	14.32
3-STAGE	9.79	1.98	19.38	3.08
4-STAGE	11.03	0.32	3.53	82.35
AC Input: 2 V @ 38.57 mA (77.14 mW)				
1-STAGE	6.80	10.74	73.03	5.33
2-STAGE	13.69	5.99	82.00	-6.30
3-STAGE	19.27	4.48	86.33	-11.91
4-STAGE	22.96	1.00	22.96	70.24
AC Input: 3 V @ 60.60 mA (181.80 mW)				
1-STAGE	10.65	18.54	197.45	-8.61
2-STAGE	21.16	9.76	206.52	-13.60
3-STAGE	27.24	7.49	204.03	-12.23
4-STAGE	31.33	2.20	68.93	62.09

From the results above, it can be seen that stage 3 has the lowest percentage of power loss when tested with 1V, 2V as well 3V AC input voltages. At 4th stage (and beyond), the power loss increases exponentially, making it not ideal for the prototype design. Thus, 3-stage design is optimum number of stages.

4.2.2.3 Test III – Testing the performance of Germanium diode vs. Schottky diode

The third part of the prototype testing involves testing the performance of prototype based on Germanium diode as well as prototype using Schottky diode which is later acquired from an electronics store. In general, based on the observations on electronics store around Malaysia, Schottky diode is much more expensive compared to a Germanium diode. A 1N5711 (Schottky) diode cost RM4 each while a OA90 (germanium) diode cost RM0.80 each. Therefore, it is crucial to determine which diode is more cost-effective to be implemented to the prototype design. The table below shows configuration of the circuit used for the testing.

Table 16: Voltage multiplier circuit configuration for Prototype Test III

	Circuit #1	Circuit #2
No. of stages	1	
Type of capacitor	1µF, 50V rating	
Type of diode	OA90 (Germanium)	1N5711 (Schottky)

The findings are tabulated as follow:

Table 17: Results of Germanium diode vs. Schottky diode prototype testing

	Circuit #1 (Germanium)			**Circuit #2 (Schottky)**		
$V_{in, AC}$ (V)	**$V_{out, DC}$ (V)**	**$I_{out, DC}$ (mA)**	**$P_{out, DC}$ (mW)**	**$V_{out, DC}$ (V)**	**$I_{out, DC}$ (mA)**	**$P_{out, DC}$ (mW)**
1	3.19	5.27	16.81	3.00	3.77	11.31
2	6.20	13.48	83.58	6.14	9.00	55.26
3	9.09	22.32	202.89	8.96	13.93	124.81
4	9.86	30.92	304.87	9.64	18.87	181.91

From the results, it is obvious that the circuit design with Germanium diodes fared better than the one with Schotty diodes. Therefore, the prototype design will remain using Germanium diodes, as in Prototype #1.

4.2.2.4 Test IV - RF energy harvesting from a 300MHz transmitter

This part of the prototype testing involves radio frequency energy harvesting from the electromagnetic waves produced by a 300MHz transmitter. As its name implies, the transmitter is able to produce a 300MHz signal. It is assembled as follow:

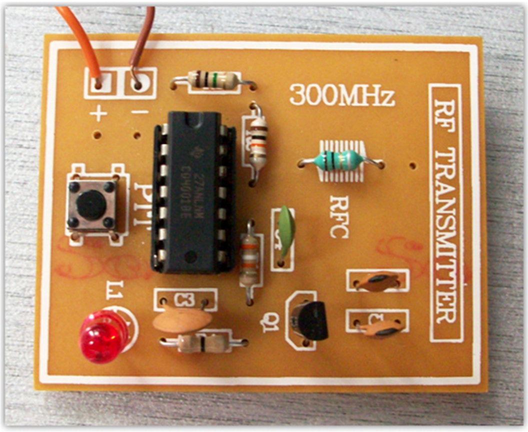


Figure 38: 300MHz RF transmitter

The circuit shown above consists of a push-to-transmit (PTT) button/switch that will enable 300MHz RF transmission when pushed (closed circuit). The red light emitting diode (LED) will be turned on when PTT is pushed, indicating that it is transmitting. In order to capture the transmitted RF energy, the voltage multiplier circuit tested earlier is coupled with a monopole antenna. The configuration of the circuit can be seen as follow:

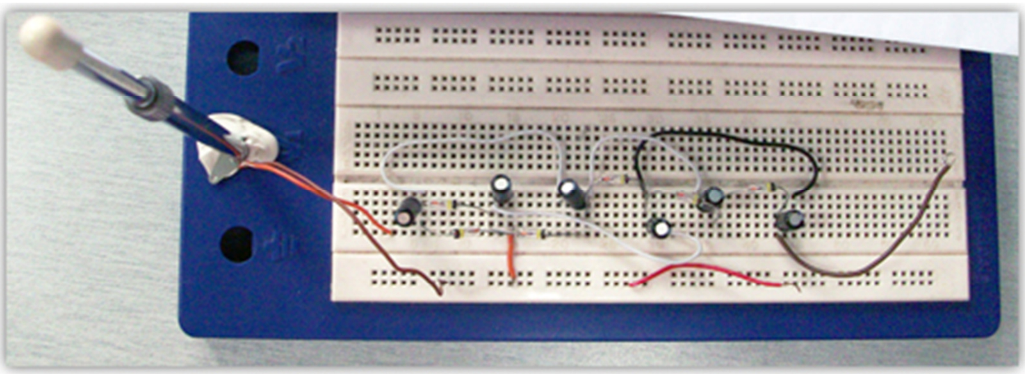


Figure 39: 3-Stage voltage multiplier prototype #1 with antenna

The experiment started off by supplying a 9V DC power to the 300MHz RF transmitter. The transmitter is then brought close to the receiving antenna of the 3-stage voltage multiplier. The output of the voltage multiplier is fed into a multi-meter to measure the generated output voltage and output current when the transmitter is turned on. The experiment setup is as follow:

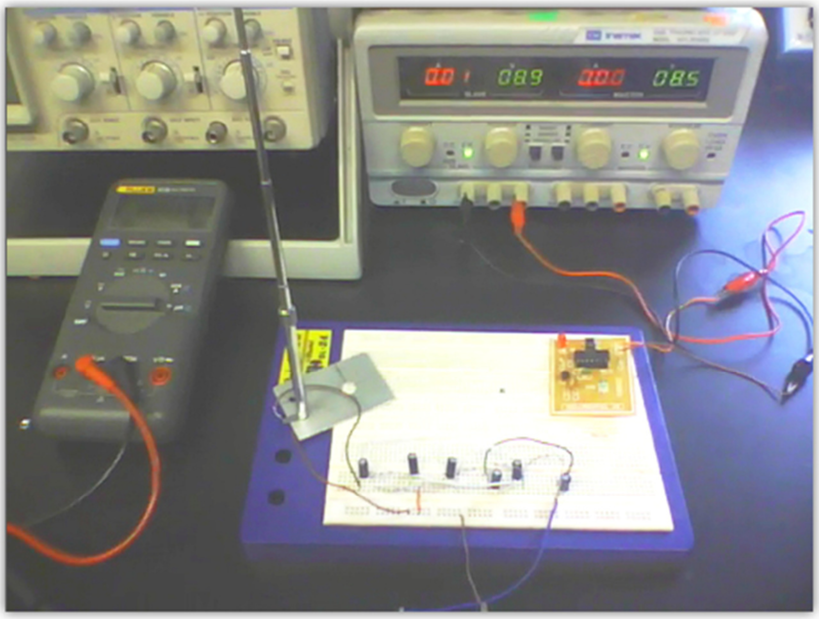


Figure 40: 300MHz RF energy harvesting experiment setup

A 300 MHz RF receiver is also used to verify that the 300 MHz radio frequency wave is present then the 300 MHz RF transmitter is ON.

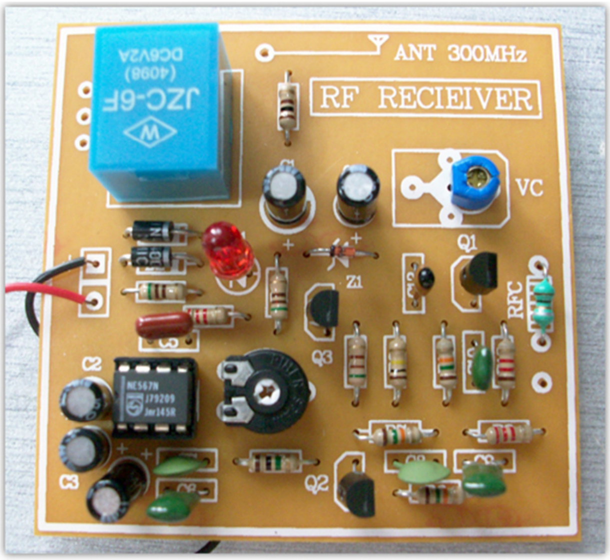


Figure 41: 300MHz RF receiver

The initial reading of the multi-meter is at 0 V. Once the transmitter is close enough to the antenna (assuming 0 cm), the PTT button is pushed and it can be observed that there is a spike in the output voltage reading, which is from 0V to around 7V. When the PTT button is released, the multi-meter reading will slowly return to 0V. The experiment is repeated by moving the transmitter away from the antenna 1 cm at a time. The readings for the generated output voltage are captured and tabulated in the following table:

Table 18: Output voltage of RF energy harvesting from 300MHz transmitter

Distance (cm)	**$V_{o,\,dc}$ (V)**			**Average $V_{o,\,dc}$ (V)**
	Trial #1	**Trial #2**	**Trial #3**	
0	6.34	7.35	7.08	6.92
1	6.12	5.96	6.32	6.13
2	5.64	4.52	5.737	5.30
3	4.28	3.73	4.76	4.26
4	3.10	2.95	3.20	3.08
5	1.97	1.75	2.22	1.98
6	1.05	1.04	1.08	1.06
7	0.83	0.68	0.63	0.71
8	0.64	0.35	0.38	0.46
9	0.49	0.24	0.30	0.34
10	0.31	0.22	0.17	0.23
11	0.14	0.13	0.09	0.12
12	0.06	0.12	0.08	0.09
13	0.08	0.10	0.07	0.08
14	0.02	0.08	0.06	0.05
15	0.02	0.06	0.04	0.04
16	0.02	0.04	0.02	0.03
17	0.01	0.03	0.01	0.02

Like the output voltage, the output current also decreases with distance. The maximum achievable output current recorded is at 78μA. Therefore, at very near distance, the maximum power harvested can be roughly equated as follow:

$$
\begin{aligned}
P_{max} &= V_{max} \times I_{max} \\
&= 6.92\ \mathrm{V} \times 78\ \mu\mathrm{A} \\
&= 540\ \mu\mathrm{W}
\end{aligned}
$$

Given that the power generation potential of radio frequency is around 0.1 to 1 $\mu W/cm^2$, the obtained results looks promising.

4.2.2.5 Test III - RF energy harvesting from Global System for Mobile Communications (GSM) signal

The next experiment carried out is to test the capability of the prototype to harvest RF energy from mobile communication (GSM) signals. In order to test this out, two mobile phones are utilized whereby one acts as a caller with the other acts as a receiver. These two phones are placed near to the antenna of the prototype, thereby enabling RF energy harvesting during phone call sessions, if there's any. The setup of the experiment is shown in figure below, with the results recorded in the following table. Note that the result reflects the maximum voltage achieved during the test.

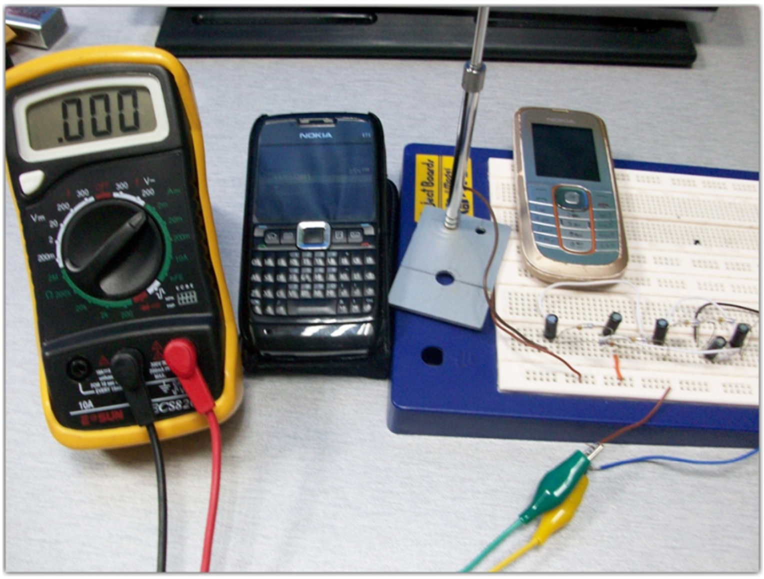


Figure 42: GSM RF energy harvesting experiment setup

Table 19: Output voltage and current of RF energy harvesting from GSM signal

Distance (cm)	**Trial #1**		**Trial #2**		**Trial #3**		**Average**	
	V_o (V)	**I_o (µA)**	**V_o (V)**	**I_o (µA)**	**V_o (V)**	**I_o (µA)**	**V_o (V)**	**I_o (µA)**
0	8.31	137	9.43	133	9.20	135	8.98	135
5	2.23	51	2.17	70	1.78	63	2.06	61
10	1.58	22	1.38	27	1.45	23	1.47	24

From the results, it can be seen that the maximum achievable output power is as follow:

$$P_{max} = V_{max} \times I_{max}$$

$$= 8.98\ \text{V} \times 135\ \mu\text{A}$$

$$= 1.21\ \text{mW}$$

The result above shows that RF energy harvesting from GSM wave is indeed very promising, with an achievable output power within milli-watt range. This range of output power can be used to power low power devices, i.e. the active RFID tags.

Prior to the experiment, the 900 MHz GSM wave is analyzed using a spectrum analyzer to found out the energy level of the wave. This is to determine the AC input power. The setup and result are shown in the figures below:

Figure 43: 9 kHz – 3 GHz Spectrum Analyzer

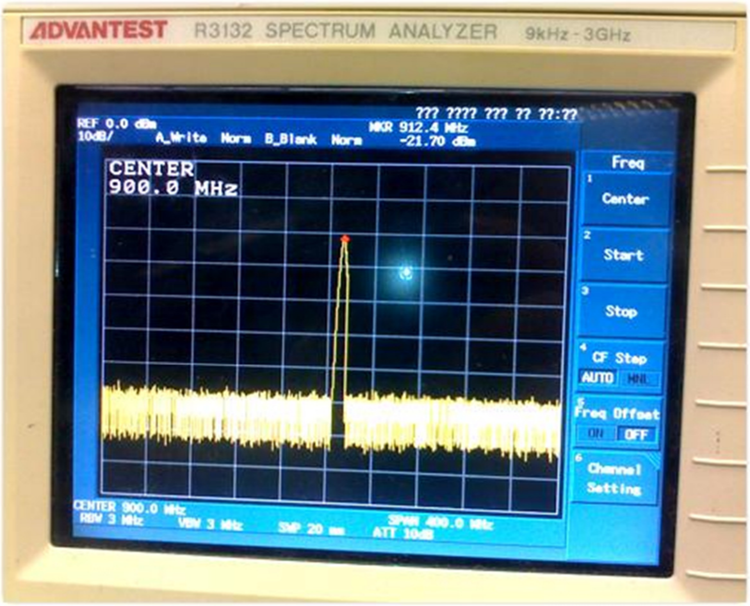


Figure 44: 900 MHz spectrum analysis and result

From the analysis, it is determined that the AC input power is around -19 dBm to -22 dBm. Converting this to milliwatt, the AC input power of GSM wave is roughly in the range of 6.3 µW to 12.6 µW. [$Formula{:}P_{milliwatt} = 10^{(\frac{dBm}{10})}$]

This shows a behavior of the prototype design whereby it is able to produce a much higher DC output power (1.21 mW) compared to its AC input power (6.3 µW). Such behavior has been tested and verified in the design simulation shown in the following figure (note that the AC input power reading by XMM2 is lower than the DC output power reading by XMM1):

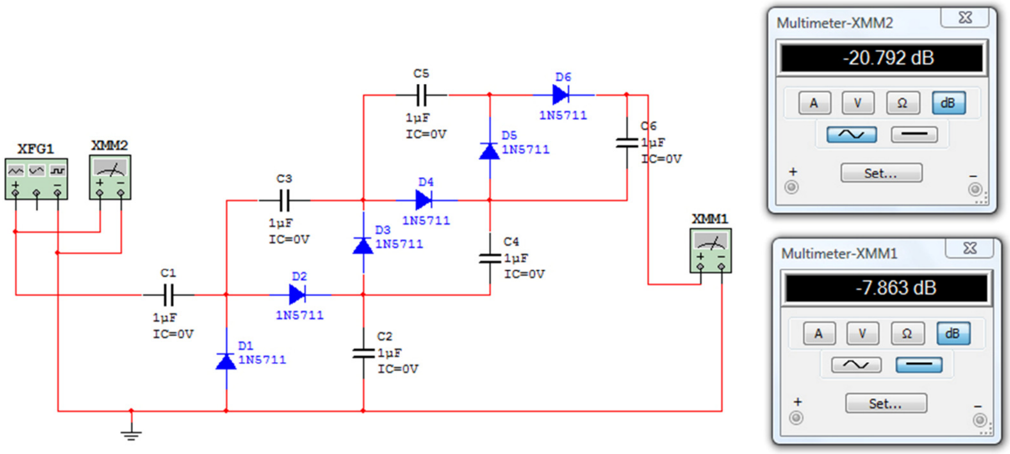


Figure 45: Simulation result to verify DC output hike from AC input

4.2.2.6 Test VI - RF energy harvesting from simulated TV transmission

This part of the experiment is carried out to test the capability of the prototype to harvest RF energy from TV transmission radio frequency waves. An RF transmitter is used to simulate the condition at 180 MHz. Following is the setup of the experiment:

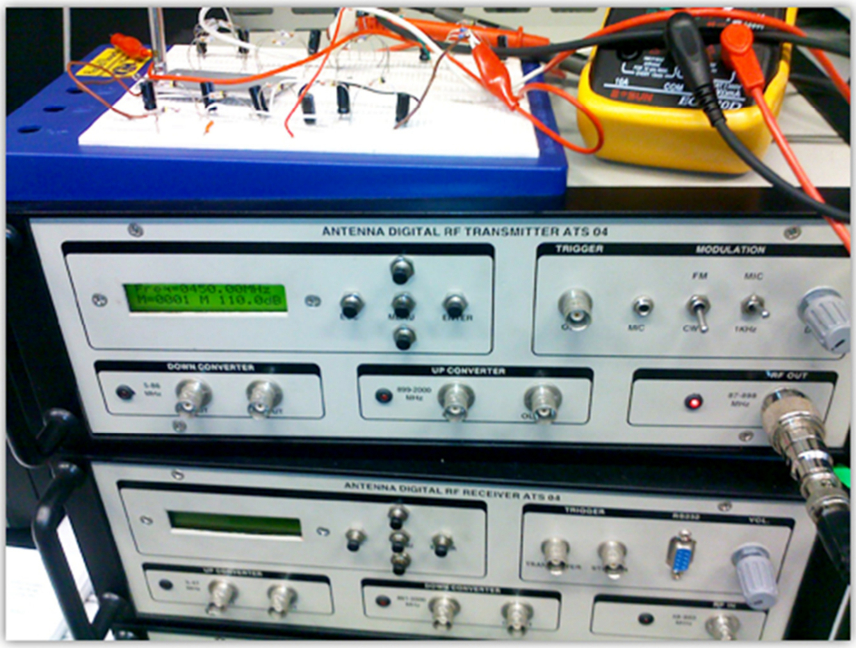


Figure 46: Simulated TV transmission energy harvesting experiment setup

Results from the experiment are as follow:

Figure 47: Measured voltage at near-distance for simulated TV transmission experiment

Table 20: Output voltage and current of RF energy harvesting from simulated TV transmission signal

Distance	DC Output Voltage (V)	DC Output Current (µA)
0	1.87	10
5	0.53	1
10	0.06	0.4

4.2.2.7 Test VII - RF energy harvesting from WiFi & Bluetooth signal

This part of the experiment is carried out to test the capability of the prototype to harvest RF energy from WiFi and Bluetooth signals. Both WiFi and Bluetooth operate at 2.4 GHz frequency. In order to test this out, a laptop and a mobile phone are deployed, whereby both will act as a receiver and sender. Throughout the experiment, files are sent from the laptop to the mobile phone via Bluetooth and vice versa. They are placed near the antenna of the prototype, thereby enabling RF energy harvesting during the file transfer session, if there's any. The setup of the experiment is shown in the figure below.

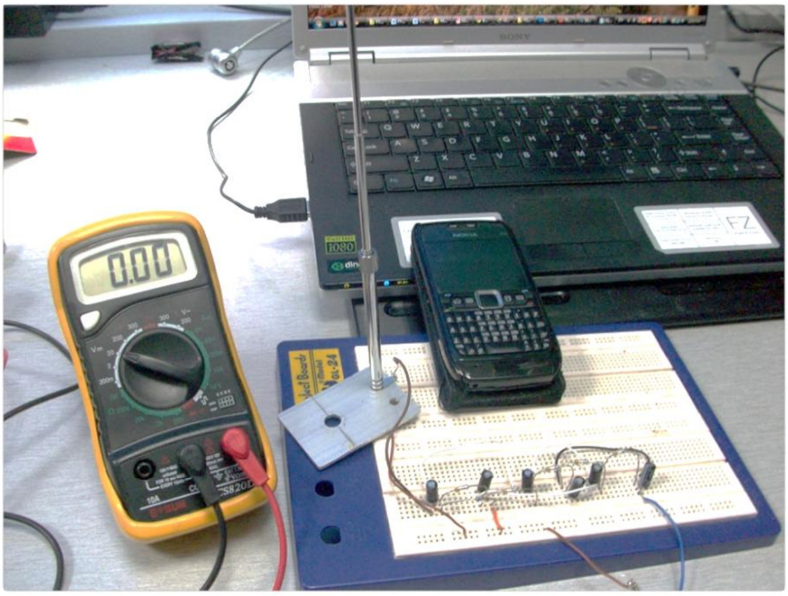


Figure 48: Bluetooth RF energy harvesting experiment setup

Another configuration involved placing the prototype near to a wireless router in the lab which is not depicted here. The result of the experiment is as follow:

Table 21: Output voltage of RF energy harvesting from WiFi & Bluetooth signal

Distance	DC Output Voltage	
	WiFi	Bluetooth
0 cm	0.1V	0 V

4.3 Discussion

4.3.1 Discussion on simulation results

Based on the various simulations above, it can be seen that there are various factors to be considered in the design of voltage multiplier circuit for RF energy harvesting. The factors include the types of voltage multiplier configuration, the number of stages needed as well as the types of diodes and capacitors used.

From the analysis of the results of the simulations, it is decided to carry out the design using Villard voltage multiplier using Schottky diode. It is known that the number of stages will increase the output voltage, as well as increasing the number of components needed, thus increasing the cost. Therefore, the number of stages to be implemented will be determined later during the prototype testing and analysis. Meanwhile the value of capacitors will be dependent on the frequency of RF energy source that would be harvested. The results of simulations show that capacitor value of 1 μF is a better choice compared to 1 mF and 1 nF.

4.3.2 Discussion on prototype build and tests

Several testing has been carried out in order to determine the RF energy harvesting capability of the prototype. As mentioned in the methodology section, there are two main phases for prototype build testing. The first phase focuses on getting to know that the prototype works as shown in simulation by using direct AC input power through a function generator. The second phase meanwhile tests the capability of the prototype to harvest the energy of radio frequency waves which are emitted through several sources.

The first test (Test #1) is to verify the performance of the 3-stage voltage multiplier circuit with germanium diodes and 1μF capacitors. Comparing the simulation results with the prototype results, it is confirmed that the voltage multiplier is able to yield the result as it should be.

Table 22: Comparing simulation and prototype results for 3-stage VM

AC Input Voltage (50 kHz)	**DC Output Voltage** (Simulation – using Schottky diode)	**DC Output Voltage** (Prototype – using Germanium diode)
5 V	27.517 V **refer to Table 12*	33.27 V **refer to Table 14*

The comparison also provides a hint that the germanium diodes used in the prototype may perform better than the Schottky diode used in the simulation circuit design. This has been confirmed through Test #3 whereby the same configuration of the prototype using different diodes is tested. By analyzing the performance and taking into account the cost of both Schottky diode and Germanium diode, it is found out that the Germanium diode would be more suitable as it has better performance and more cost-effective.

The second part of the test (Test #2) was carried out to find out the optimum number of stages of voltage multiplier to be implemented on the prototype design. AC input voltages at 1V, 2V and 3V are tested respectively and the same behavior can be seen as the graph below. Shown in the graph is the power loss at different stages when the prototype is tested at 1V AC input voltage:

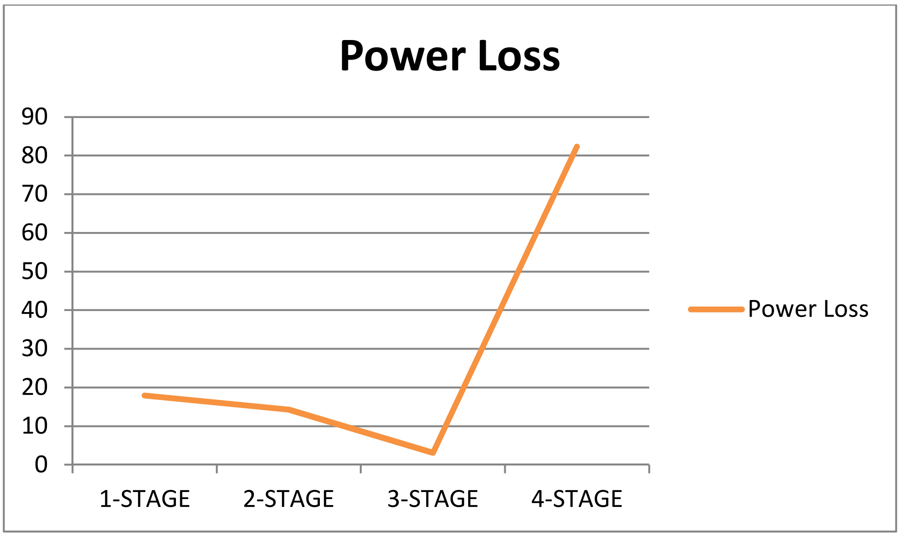


Figure 49: Power loss exhibited by prototype using different stages of VM

From the graph, it can be seen that the power loss reduces gradually from stage-1 through stage-3 but when stage-4 voltage multiplier is used, the power loss increases drastically. The same behaviour is seen on experiments using 2V and 3V AC input voltage. A valid explanation for this is that the output voltage increases linearly with the increment of number of stage. However, the output current decreases much drastically than the voltage increment (do note that when voltage increases, current must decrease). This resulted in a much lower output power at a higher stage. At stage-4 and beyond, the output current drop is so high that it is not sufficient to complement the power loss across the increasing components. From these behaviours, it can be concluded that stage-3 would be the optimum stage to be implemented.

The forth part of the test (Test #4) focused on RF energy harvesting capability of the prototype by using a 300MHz RF transmitter. Based on the results, it can be seen that the prototype has successfully captured some of the energy that exists within the RF signal produced by the transmitter. The maximum achievable real power captured is roughly around 540μW, which is enough to power an RFID tag. A low power active RFID tag can operate within the region of 1V to 3V at 15 μW to 250 μW.

Meanwhile, the fifth part of the test (Test #3 and Test #4) involved RF energy harvesting of GSM waves (aka mobile phone waves). GSM signals have a frequency of 900MHz. The main purpose of this test is to find out how much energy the prototype can harvest from one of the most common waves that exist in our surrounding.

From the results analysis, it can be seen that the prototype successfully harvested RF energy of GSM signal. The maximum dc output voltage captured is around 8.98V with a 135μA dc output current. This is much higher than the RF energy harvested from the 300MHz transmitter. Even though the mobile phones are placed 10 cm away from the antenna, it still manage to capture around 1.47V with 24μA current.

The next round of test involves RF energy harvesting from TV transmission signal. The signal is simulated using an adjustable RF transmitter set at 180 MHz. The result shows some energy are able to be harvested, measured at around 1.87V and 10 μA. The result may be even higher if tested using real TV transmitting/receiving antenna.

The Bluetooth/WiFi RF energy harvesting test on the other hand produce only very small output voltage due to the fact that the power in these waves itself is very weak. Improvements need to be implemented in order to hike up the energy harvested from these waves.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The project's main objective is to design and construct a mechanism to harvest energy from the surrounding radio frequency in order to charge the on-board battery of active RFID tag or to provide direct wireless energy to power the active RFID tag. One of the most important components in the design is the voltage multiplier circuit. Various simulations have been carried out to determine the optimum parameters in designing the voltage multiplier circuit for RF energy harvesting purpose as described in the results and discussion section.

Applying the results obtained through the simulations, a prototype is built in order to test out its capability. From the obtained results, it can be seen that RF energy harvesting from an RF transmitter and using GSM waves are very promising to the active RFID tag as well as the charge the on-board battery of the tag. The applications of the harvested energy are not only limited to active RFID tags, but also to low power devices which can operate at a very small amount of power.

In conclusion, this project has proven that it is possible to harvest energy from the radio frequency waves for the application of active RFID tags.

5.2 Recommendation

There are several measures that can be implemented in order to achieve a higher output and to potentially increase the distance of RF wave captured while maintaining a stable and desirable yield. Such measures include implementation of the following:

1. Resonant inductive coupling
2. EM-absorbing antenna

5.2.1 Resonant inductive coupling

Resonant inductive coupling or electrodynamic induction is a common technology employed in wireless electricity. The main goal of using resonant inductive coupling is to greatly improve the distance of wireless energy transfer, i.e. to solve the "short range" problem. The idea behind this is to utilize the properties of resonance phenomena, which states that two same frequency resonant objects tend to couple, while interacting weakly with other off-resonant objects in the surrounding.

Resonant inductive coupling is achieved using LC resonant circuit, also known as resonant tank circuit. LC resonant circuit, as it name implies, consist of inductor and capacitor. The resonant frequency of an LC circuit is shown as follow:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

f = frequency in Hertz (Hz)
L = inductance in Henry (H)
C = capacitance in Farad (F)

This method can be employed to improve RF energy harvesting. For example, GSM waves oscillate at 900 MHz. Configuring the RF energy harvesting circuit to oscillate at the same frequency, resonance phenomena can be achieved.

5.2.2 EM-absorbing antenna

The current antenna implemented in the prototype design is a normal radio antenna. Replacing the antenna with an electromagnetic wave absorbing antenna can improve the input power into the RF energy harvesting circuit. Electromagnetic wave absorbing antenna is constructed using EM-absorbing material, such as ferrite (ferromagnetic metal oxide) absorber. Ferrite is formed by a mixture of various iron oxide and carbonate. An example is an antenna made of MnZn-ferrite and carbon.

CHAPTER 6

AWARDS AND RECOGNITION

6.1 ELECTREX

The project is presented in Electrical and Electronics Engineering Department Exhibition (ELECTREX) on 6th of April 2011 in Universiti Teknologi Petronas. This project was listed as one of the top 10 projects out of the total 114 competing exhibits on that day. As such, the project is eligible to participate in the 27th edition of Engineering Design Exhibition (EDX 27) on the 13th and 14th April 2011 at the Chancellor Complex Foyer of Universiti Teknologi Petronas.

Figure 50: ELECTREX for January 2011 semester

6.2 EDX 27th Edition

EDX consists of two days of judging and exhibition attended by both students and academicians of UTP as well as external visitors mainly from PETRONAS. This project competes under the Final Year Project (FYP) category, representing the Electrical and Electronics Engineering Department.

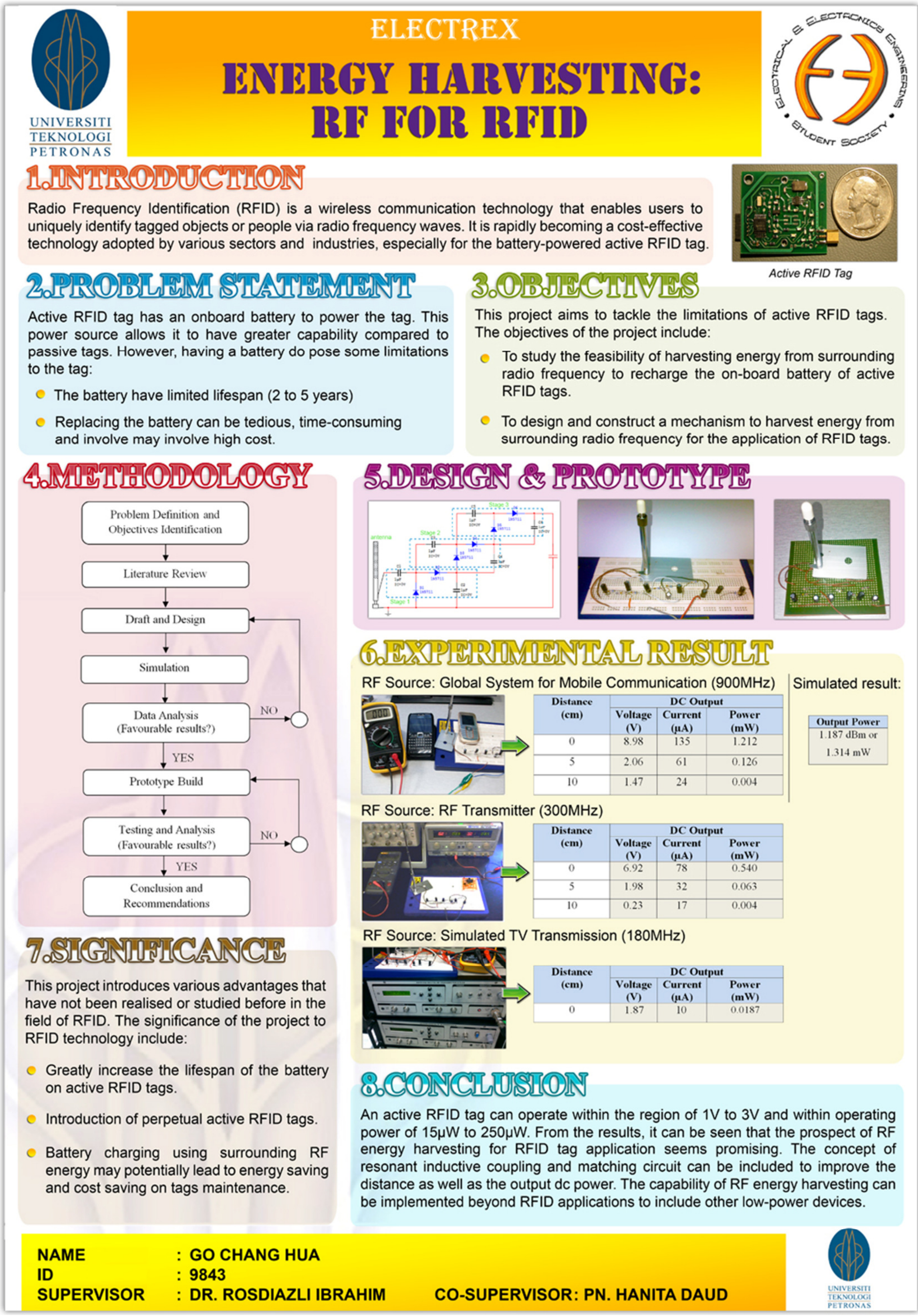
Figure 51: Exhibition and judging session during EDX 27

Award ceremony for EDX 27 was in the evening of 14th April 2011 after the second day of exhibition. This project was awarded a gold medal as well as overall champion for the Final Year Project category.

Figure 52: EDX 27 Gold Medal Award

Figure 53: EDX 27 Best Final Year Project Award

6.3 Poster for Exhibition



6.4 EDX 27 Gold Medal Award Certification

UNIVERSITI TEKNOLOGI PETRONAS

Certificate of Appreciation

EDX 27

This certificate is awarded to

GO CHANG HUA

in recognition of his/her contribution as
Participant of
Final Year Project

"Gold"
in the Twenty-Seventh edition of

ENGINEERING DESIGN EXHIBITION
UNIVERSITI TEKNOLOGI PETRONAS

held on
13 – 14 April 2011

Mr Mohd Zamri B Abdullah
Chairman
27th Engineering Design Exhibition

Assoc. Prof. Dr. Hilmi B Mukhtar
Director of Undergraduate Studies
Universiti Teknologi Petronas

ENGINEERING DESIGN EXHIBITION
EDX
PORTAL TO THE FUTURE
UNIVERSITI TEKNOLOGI PETRONAS

6.5 EDX 27 Best Final Year Project Award Certification

UNIVERSITI TEKNOLOGI PETRONAS

EDX 27

Certificate of Appreciation

This certificate is awarded to

GO CHANG HUA

in recognition of his/her contribution as
Participant of
Final Year Project

"Best Research Award Project"
in the Twenty-Seventh edition of

ENGINEERING DESIGN EXHIBITION
UNIVERSITI TEKNOLOGI PETRONAS

held on
13 – 14 April 2011

Mr Mohd Zamri B Abdullah
Chairman
27th Engineering Design Exhibition

Assoc. Prof. Dr. Hilmi B Mukhtar
Director of Undergraduate Studies
Universiti Teknologi Petronas

ENGINEERING DESIGN EXHIBITION • UNIVERSITI TEKNOLOGI PETRONAS
EDX
PORTAL TO THE FUTURE

REFERENCES

[1] V. Daniel Hunt, Albert Puglia & Mike Puglia (2007), *RFID: A Guide to Radio Frequency Identification*, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

[2] Harvey Lehpamer (2008), *RFID Design Principles*, Artech House, Inc., Norwood, Massachusetts, USA.

[3] LabAutopedia (2009), *Automatic Identification and Data Capture*, Retrieved from http://www.labautopedia.org/mw/index.php/Automatic_identification_and_data_capture

[4] Dipankar Sen, Prosenjit Sen & Anand M. Das (2009), *RFID For Energy and Utility Industries*, Penwell Corporation, Tulsa, Oklahoma, USA.

[5] NobelPrize.org (2009), *The Nobel Prize in Physics 1909 Guglielmo Marconi, Ferdinand Braun*, Retrieved from http://nobelprize.org/nobel_prizes/physics/laureates/1909/marconi-bio.html

[6] Jerry Banks, David Hanny, Manuel A.Pachano et al. (2007), *RFID Applied*, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

[7] William Oliver Hedgepeth (2007), *RFID Applied*, Taylor and Francis Group, LLC, Boca Raton, Florida, USA.

[8] Parul Oswal & Michelle Foong of Frost & Sullivan Asia Pacific (2006), *RFID Vs Contactless Smart cards – An unending debate*, Retrieved from http://www.frost.com/prod/servlet/market-insight-top.pag?docid=83467478

[9] Intermec Technologies Corporation (2007), *Supply Chain RFID: How it Works and Why it Pays*, Retrieved from http://epsfiles.intermec.com/eps_files/eps_wp/SupplyChainRFID_wp_web.pdf

[10] Philips Semiconductor, TAGSYS & Texas Instruments Inc. (2004), *Item-Level Visibility in the Pharmaceutical Supply Chain: A comparison of HF and UHF RFID Technologies*, Retrieved from www.electrocom.com.au/pdfs/jointPharma_RFID_TIRFID.pdf

[11] Accenture (2004), *Radio Frequency Identification (RFID)*, Retrieved from https://www.accenture.com/NR/rdonlyres/D27DDAE9-CAB2-43B5-B6F2-27BD4F22EC1C/0/rfidwhitepapernov01.pdf

[12] Stephen B. Miles, Sanjay E. Sarma, & John R. Williams (2008), *RFID Technology and Applications*, Cambridge University Press, New York, USA.

[13] Alice Wang, Benton H. Calhoun & Anantha P. Chandrakasan (2006), *Sub-threshold Design for Ultra Low-power Systems*, Springer Science+Business Media, New York, USA.

[14] Murugavel Raju, Texas Instruments Inc. (2008), *ULP meets energy harvesting: A game-changing combination for design engineers*, Retrieved from http://www.ti.com/corp/docs/landing/cc430/graphics/slyy018_20081031.pdf

[15] Shashank Priya, D.J. Inman (2009), *Energy Harvesting Technologies*, Springer Science+Business Media, New York, USA.

[16] Hamid Jaabar, Young. S. Song, Taikyeong Ted. Jeong (2010), *RF Energy Harvesting System and Circuits for Charging Mobile Devices*, Department of Electronics Engineering, Myongji University, Korea and Department of Material Science, Dankook University, Korea.

[17] Harry Ostaffe & Charlie Greene, Powercast Corporation, and Bharat Rawal, AVX Corporation (2010), *Power Module and Double Layer Capacitor Harvest Energy from Radio Signals,* Retrieved from http://powerelectronics.com/power_systems/power-module-double-layer-201007/index.html & http://powerelectronics.com/power_systems/power-module-double-layer-201007/index1.html

[18] TutorialWeb.com (2009), *RFID: A Tutorial*, Retrieved from http://www.tutorialsweb.com/rfid/operation-of-rfid-systems.htm

[19] *RFID Forecasts, Players & Opportunities 2011-2021* (2010), Retrieved from http://www.idtechex.com/research/reports/rfid_forecasts_players_and_opportunities_2011_2021_000250.asp

APPENDIX I: ADDITIONAL CITATIONS

1) IDTechEx (2010), *RFID in 2010: The New Dawn*, Retrieved from http://www.idtechex.com/research/articles/rfid_in_2010_the_new_dawn_00002437.asp

2) Lisa Grossman, Science News (2010), *New RFID Tag Could Mean the End of Bar Codes*, Retrieved from http://www.wired.com/wiredscience/2010/03/rfid/

3) Transition Products, Inc (2010), *RFID Overview*, Retrieved from http://www.tpi1.com/rfid_63.html

4) RFID Weblog (2004), *Active vs. Passive RFID tags*, Retrieved from http://www.rfid-weblog.com/50226711/active_vs_passive_rfid_tags.php

5) Cisco Systems, Inc (2010), *RFID Tags Considerations*, Retrieved from http://www.cisco.com/en/US/docs/solutions/Enterprise/Mobility/wifich6.html

6) IDTechEx (2010), *RFID Forecasts, Players & Opportunities 2011-2012*, Retrieved from http://www.IDTechEx.com/forecasts

7) IDTechEx (2010), *Printed Electronics, RFID & Energy Harvesting Research*, Retrieved from http://www.idtechex.com

8) *RFID Journal*, Retrieved from *http://www.rfidjournal.com*

9) *RFID Update: The RFID Industry Daily*, Retrieved from http://www.rfidupdate.com

10) *RFID News: Radio Frequency Identification Technology for Logistics, Tagging and EPC*, Retrieved from http://www.rfidnews.org

11) *Voltage Multiplier*, Retrieved from http://en.wikipedia.org/wiki/Voltage_multiplier

12) *Voltage Doubler,* Retrieved from http://en.wikipedia.org/wiki/Voltage_doubler

13) IDTechEx (2009), *RF harvesting from ambient sources,* Retrieved from http://www.energyharvestingjournal.com/articles/rf-harvesting-from-ambient-sources-00001395.asp?sessionid=1

14) *RF-Powered Wireless Sensor,* Retrieved from http://www.rfwirelesssensors.com/

15) Daniel M. Dobkin (2007), *RFID Basics: Backscatter Radio Links and Links Budget,* Retrieved from http://www.eetimes.com/design/industrial-control/4018929/RFID-Basics-Backscatter-Radio-Links-and-Link-Budgets

16) T. Sogorb, J.V. Llario, J. Plegri, R. Lajara, J. Alberola (2008), *Studying the Feasibility of Energy Harvesting from Broadcast RF Station for WSN*, Department of Electronic Engineering, Universidad Politecnica of Valencia, Gandia (Valencia), Spain.

17) A.P. Sample, D.J. Yeager, J.R. Smith, P.S. Powledge, A.V. Mamishev (2006), *Energy Harvesting in RFID Systems*, Intel Research Seattle, University of Washington, Seattle, Washington, USA.

18) Y.K. Tan, K.Y. Hoe, S.K. Panda (2006), *Energy Harvesting using Piezoelectric Igniter for Self-Powered Radio Frequency (RF) Wireless Sensors*, Department of Electrical and Computer Engineering, National University of Singapore, Singapore.

19) Thurien Paing, Erez Falkenstein, Regan Zane & Zoya Popovic (2009), *Custom IC for Ultra-low Power RF Energy Harvesting*, Department of Electrical and Computer Engineering, University of Colorado, Boulder, Colorado, USA.

20) Fabio Iannello, Osvaldo Simeone & Umberto Spagnolini (2010), *Energy Management Policies for Passive RFID Sensors with RF Energy Harvesting*, New Jersey Institute of Technology, University Heights, Newark, New Jersey, USA.

21) Tolgay Ungan, Xavier Le Polozec, William Walker & Leonhard Reindl (2009), *RF Energy Harvesting Design Using High Q Resonators*, Lab. For Electrical Instrumentation, Department of Microsystem Engineering (IMTEK), University of Freiburg, Germany and Ericsson France, Massy, France.

22) Myunghwan Park, Kwangsik Choi & Martin Peckerar (2009), *Ultra-Low Power Series Pass Element Voltage Regulator for RF-DC Energy Harvesting*, Department of Electrical and Computer Engineering, University of Maryland, College Park, USA.

23) Minghong Mi, Marlin H. Mickle, Chris Capelli & Harold Swift (2005), *RF Energy Harvesting with Multiple Antennas in the Same Space*, Department of Electrical Engineering and Office of Technology Management, University of Pittsburgh, Pittsburgh, Pennsylvania, USA.

APPENDIX II: GANTT CHART

SEMESTER I

MILESTONES / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project title selection														
Problem statement and objectives identification														
Background study & Literature review														
Further research and study														
Identify and purchase required equipments and materials, cost estimation.														
Circuit drafting and design														
Design simulation and data analysis														
Report compilation and project presentation														

SEMESTER II

WEEK / MILESTONES	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Literature review (for prototype build)														
Prototype build														
Testing and data acquisition														
Data analysis and comparison														
Recommendation and modification														
Conference paper preparation														
Pre-EDX														
Engineering Design Exhibition 27														
Final report compilation and presentation														