Wireless Power Transmission (WPT) Application at 2.4 GHz in Common Network

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Doctor of Philosophy

RMIT University
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Wireless Power Transmission (WPT) Application at 2.4 GHz in Common Network

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the dissertation is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

________________________

Wai Siang, Yeoh
31st March 2010
To the world
ACKNOWLEDGEMENT

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ABBREVIATIONS

3G : 3rd Generation or IMT-2000 defined by International Telecommunication Union (ITU).

AC : Alternating Current

BPF : Band Pass Filter

C : Capacity (mAh) of Battery

CPS : Coplanar Stripline

Data-COM : Data Communication

DRP : Decoupled Rectenna Pair

EDTA : Electric Drive Transportation Association

EHF : Extremely High Frequency

EIRP : Equivalent Isotropic Radiated Power

EM : Electromagnetic

EV : Electric Vehicle

DRP : DRP Pairs

f : Frequency

FCC : Federal Communications Commission

GPS : Global Positioning System

GSM : Global System for Mobile communications

HF : High Frequency

I : Electric current, unit is Ampere (A)

IC : Integrated Circuit

IDF : Intel Developer Forum

IEEE : Institute of Electrical and Electronics Engineers

iPhone : Smart phone from Apple Inc.

iPod : Portable media player from Apple Inc.

IPT : Inductive Power Transfer

LAN : Local Area Network

LDO : Low Drop Out

LF : Low Frequency

Li-Po : Lithium-ion Polymer

MP3 : Digital audio encoding format

MPT : Microwave Power Transmission, WPT at IEEE's microwave range.

NASA : National Aeronautics and Space Administration

NIMH : Nickel Metal-Hydride

ODM : Original Design Manufacturer

PCB : Printed Circuit Board

PDA : Personal Digital Assistant

PDA : Printed Dipole Antenna

PSU : Power Supply Unit

PTMP : Point to Multi Point

PTP : Point to Point

R : Resistance, unit is ohm (Ω)

R&D : Research and Development, a common term in the technological industry.

RF : Radio Frequency

RFID : Radio Frequency Identification

SBS : Smart Battery System

SHF : Super High Frequency

SMBus : System Management Bus (SBS Protocol)

SPSS : Solar Power Satellites System
UHF : Ultra High Frequency
V : Electric potential difference or voltage, measured in Volt (V)
VNA : Vector Network Analyser
Wi-Fi : Wireless Fidelity
WLAN : Wireless LAN
WPC : Wireless Power Consortium
WPT : Wireless Power Transmission
WREL : Wireless Resonant Energy Link
ORIGINAL CONTRIBUTIONS

The papers are attached in the appendix sections.

Chapter 4
A high efficiency rectifier (74%) is designed and matched to rectify AC at 2.4 GHz. The rectifier is suitable for rectenna applications. Its high DC conversion efficiency is mainly due to the compact layout with meandered matching network. Moreover, it is specifically designed to integrate as part of the rectenna layout without the requirement of extra board space.

Chapter 5
Section 5.1
- A novel printed antenna utilises half bowtie and integrated microstrip balun. The antenna has over 40% bandwidth with relatively small dimension as compared to similar PDA at 2.4 GHz.

Section 5.2
(Accepted at 9th July 2010 and to be published)
- A printed antenna utilises novel CPS-tuner on integrated balun. The antenna has 47% bandwidth with relatively small dimension as compared to similar PDA at 2.4 GHz. The CPS-tuner provides flexibility in impedance control and better average gain.

Section 5.5 and 6.3
(Submitting in progress)
- A pair of vertically polarised dipoles with horizontal decoupling characteristic. The novel microstrip decoupling network enables close proximity between two dipoles.
Moreover, it is designed to operate at 5 mm on top of a conducting surface. These characteristics are suitable for multiple antennas wireless applications and wireless power transmission as the receiving power per unit area has increased.

**Chapter 6**

**Section 6.1 & Section 6.3**

“Wireless Power Transfer”

Australia provisional patent 2009905921 filed 4th December 2009.

- The patent policy is the reason of delay in publication. This patent has included both rectenna devices which is able to power up microwatts devices and charge batteries at close distance from the 2.4 GHz WLAN transmitter in compliance with FCC regulations.

**Section 6.1 & Section 6.2**


(Submitted Manuscript: 10-0399-TIE)

- A wireless LAN energy harvesting system using rectenna at 2.4 GHz to extend battery life is presented. The rectenna used in the proposed system is a miniaturised half bowtie dipole rectenna and a collinear rectenna array. The single rectenna unit is able to power up microwatts electronics whilst the collinear rectenna unit is able to extend mobile phone battery life.
SUMMARY

Wireless Power Transmission (WPT) technology by electromagnetic propagation coupling has been under active research and development due to the emergence of wireless technology. This dissertation presents an analytical and experimental study to design rectenna prototypes and to investigate the feasibility of a WPT system which harvests energy at the 2.4 GHz ISM band. According to the FCC regulation, a WLAN transmitter is required to abide by the FCC’s guideline for Equivalent Isotropic Radiated Power (EIRP) output, which is stated as 36 dBm. The power available within several meters range from an FCC’s certified wireless transmitter is suitable for low power consumption electronics or battery trickle charging applications at close distance.

Part of this research work includes the design and development of rectenna, which consists of antenna and rectifier. Several novel techniques are presented in printed antenna development and efficient Radio Frequency (RF) rectifiers. These components are specifically designed to occupy the smallest form factor possible for consumer device integration. The rectifier used throughout the design and development of rectenna is the Villard’s Voltage Doubler (VVD), which has been optimised to provide over 70% DC conversion efficiency at 2.4 GHz ISM band within certain input power range. It is able to be integrated in to the rectenna designs without the need for any extra space on the PCB board.

The major innovation is in the area of the antenna miniaturisation. A Miniaturised Half Bowtie Printed Dipole Antenna (MHB PDA) with integrated balun is designed and proven to work successfully. The MHB PDA possesses omnidirectional radiation patterns and 47% bandwidth with only 0.36 \( \lambda \) size, centralised at 2.97 GHz. It covers ISM band at 2.4 GHz and suitable for multiple wireless communication standards and the wireless power transmission system. The low profile characteristic and simplicity of MHB PDA have enabled the possibility of consumer product integration.

Further enhancement is achieved by reducing the capacitive ground plane effect caused by nearby conducting surface. The three directional WLAN antennas on the conducting surface are designed. They are Half Bowtie Yagi-Uda (HBYU) antenna, HBYU collinear array and lastly the Decoupled Dual Dipole (DDD) antenna. The
HBYU (6.7 dBi) and HBYU collinear array (8.8 dBi) are printed WLAN antennas which are able to operate at 1 cm spacing from a conducting surface. On the other hand, the DDD is a pair of antennas (4.5 dBi) with a compact decoupling structure in between. The microstrip decoupling circuits enables integration of two identical antennas with narrow spacing (3 mm) in between. Furthermore, the DDD is intentionally designed to operate at 5 mm on top of the conducting surface.

The first rectenna is the MHB Printed Dipole Rectenna (PDR), which is designed by integrating the rectifier into the MHB PDA. The minimum power required to produce an open circuit voltage of more than 0.1 V is at -23 dBm. The range required by MHB PDR to harvest 1 V from the transmitter is 2.3 meter. The second rectenna is the HBYU Collinear Rectenna Array (HBYU CRA). On average, the voltage harvested by HBYU CRA is higher than 1 V within 4 meters range. Furthermore, it can fully charge NiMH batteries (4.8 V, 900 mAh) up to 5.3 V at 23 cm away from transmitter. For a Li-Po cell pack (3.7 V, 1100mAh), the HBYU CRA is able to charge it from 3.46 V to 3.62 V in 330 minutes. At 10 cm from the transmitter, it is capable to prolong Nokia Li-Po cell pack cycle life by 31 minutes when the cell pack is discharging heavily during video playback. The last rectenna is the DDD Rectenna (D^3R), which is designed by integrating the VVD at the centre of the DDD without a requirement for extra board space. Apart from its smaller physical dimensions than the HBYU CRA, the output of D^3R is configurable like the batteries. The rectenna pair in a D^3R can be connected in parallel or series configuration depending on the applications. It is also able to charge NiMH batteries and Li-Po. To increase the current, D^3R optimal array distribution is introduced to improve the overall performance by at least 56%.

This research study has clearly demonstrated the possibility of implementing the wireless power transmission technology in battery powered applications. The feasibility of the WLAN energy harvesting system is highly application-specific in terms of power requirement and physical dimension. The wireless power transmission technology using WLAN band is possible to be a successful energy harvesting technology for low-power applications.
CHAPTER 1: INTRODUCTION

In modern society, portable electronic devices and computers have become indispensable tools for people in their everyday life. These devices are mainly used for personal communication and entertainment. In the case of personal communication devices such as mobile phones, one of the biggest challenges faced by the manufacturers and producers are the limited battery cycle life. A typical mobile phone can be used for an average of 7 hours [1]. Depending on conditions, battery can last for days when device is kept in an idle mode. Once the battery power is exhausted, the battery in the device will need to be recharged. There are several ways to charge a battery. A straightforward method is by using an AC to DC charger. The main function of the charger is to convert the Alternating Current (AC) from the power outlet to a Direct Current (DC) to charge battery. Each type of battery has its own unique charging voltage, charging current and charge capacity measured in milli-Ampere-hour (mAh).

According to [2], there are three major types of battery, which are the primary, secondary and reverse battery. Primary battery is easy to use and convenient to be sized and shaped for portable devices. It is commonly termed as “dry cells”. Secondary battery is the rechargeable battery. It is usually used as an energy storage device and needs to be recharged by a primary energy source. The reverse battery is not popular. It uses highly active component materials to meet high energy requirement to withstand deterioration in storage or to prevent self discharge before use. The unique characteristic of reverse battery results in special applications such as weapon system. In this dissertation, the main interest is on the secondary battery where the battery is rechargeable.

Nowadays, many portable devices are packed with secondary or rechargeable batteries. Examples of portable electronics include calculators, cameras, mobile phones, handheld computer, remote controls, toys and watches. Each device may require single or multiple batteries for normal operation. A single rechargeable battery may consist of many cells. Generally, a battery which consists of many cells is known as cell pack. Popular rechargeable batteries for portable electronics are Nickel-Cadmium (NiCd), Nickel-Metal Hydrate (NiMH) and Lithium-ion (Li-ion) batteries. NiCd and NiMH are normally available off the shelf in separate cells or cell packs. They are frequently used in the digital electronics such as remote controls,
timer, LED torch or DC motor driven devices such as toys and low power mixer. Li-ion battery is always being manufactured into compact cell packs for mobile phone, camera and camcorder. The voltage requirement of consumer devices varies. Nevertheless, every type of battery follows standard reference parameters for more convenience understanding.

There are different references made to the voltage of a battery. The NiCd, NiMH and Li-ion cells are made of different electrochemical technology. Therefore, they have different voltage references. The nominal voltage of single cell NiCd, NiMH and Li-ion are usually 1.3 V, 1.2 V and 3.6 V [3]. When a cell is fully recharged, the upper voltage limit is usually approximately 1.15 times the nominal voltage provided by the manufacturer. For a better clarification, only the following definitions will be used in this dissertation [4]:-

1. Open circuit voltage ($V_{\text{open}}$): The voltage under no load condition.
2. Nominal voltage ($V_{\text{nominal}}$): The voltage that is generally accepted as the typical operating voltage of the battery.
3. Working voltage ($V_{\text{working}}$): The actual operating voltage of the battery under load and will be lower than open circuit voltage.
4. End or Cut-off voltage ($V_{\text{cut-off}}$): The end of discharge where most of the capacity of the battery has been delivered.

### 1.1 Secondary Batteries

The rechargeable NiCd, NiMH and Li-ion cells are still widely available in the consumer market. Nickel cells (NiCd and NiMH) are normally used for remote controls, LEDs and toys due to lower power specifications. The advantage of NiMH battery over NiCd battery is the new metal hydride electrode which offers higher energy density. This results in larger capacity and longer service life. This is also the reason it is replacing NiCd in computers and phones at early stage. Nevertheless, Li-ion cell packs are surpassing nickel batteries due to even higher specific energy (Wh/kg) and energy density (Wh/L). It employs lithium intercalation compounds as the positive and negative materials, which contributes to the high potential difference between electrodes and Li-ions exchange between electrodes during the cycling period. Besides, a single Li-ion cell can supply $V_{\text{working}}$ from 2.6 V up to 4.2 V
depending on the cell parameters, which is about 3 times higher than NiCd and NiMH cells [5]. According to [6], rechargeable Li-ion has undergone advance development and surpassed nickel batteries in terms of specific energy and energy density since 1999. This is the reason most of the latest portable electronics implement Li-ion technology as the energy storage device. Li-ion cell packs with large capacity are very suitable for 3G phone, camcorder and camera due to its higher nominal voltage, larger capacity and longer service life.

Battery technology has improved over the years in terms of its capacity, size and durability. However, one of the common limitations that yet to be overcome is the limitation in cell capacity. This is because the available charge capacity of Li-ion cell is still inadequate to the modern technology. In general, battery with larger size has larger capacity and so brings lasting benefit. Portable electronics are usually compact, hence limits the physical dimensions of a cell pack. For example, a new Lithium ion Polymer (Li-Po) battery in a 3G phone is a very thin rectangular cell pack. The general parameters of Li-Po [1, 5, 7, 8] are given in Table 1.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Li-Po cell packs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{nominal}}$</td>
<td>3.6 V to 3.7 V</td>
</tr>
<tr>
<td>$V_{\text{max_charged}}$</td>
<td>4.1 V to 4.2 V</td>
</tr>
<tr>
<td>$V_{\text{cut-off}}$</td>
<td>2.75 V to 3.0 V</td>
</tr>
<tr>
<td>$V_{\text{working}}$</td>
<td>3.6 V to 4.2 V</td>
</tr>
<tr>
<td>Average charging time</td>
<td>2.5 hours</td>
</tr>
<tr>
<td>Average talk time</td>
<td>6 to 8 hours, model dependent</td>
</tr>
<tr>
<td>Charge capacity</td>
<td>1100 mAh</td>
</tr>
<tr>
<td>Charge capacity loss</td>
<td>0.045% per cycle</td>
</tr>
</tbody>
</table>

Table 1.1: Parameters of Li-Po Cell Packs

Li-Po cell is nominally rated at 3.7 V, 1100 mAh. Normally, it requires 2.5 hours to fully charge to the $V_{\text{max\_charged}}$ at 4.1 V or 4.2 V. However, the practical $V_{\text{cut-off}}$ is depends on application. Usually, a mobile phone will switch off when discharging to 3.5 V. The difference between the $V_{\text{max\_charged}}$ and $V_{\text{cut-off}}$ is the $V_{\text{working}}$ which is equivalent to the talk time stated in the manual by the manufacturer. In average, a mobile phone with Li-Po cell packs will provide several hours of talk time. Depending
on the phone model and feature, normal talk time varies from 6 to 8 hours. Additionally, the extra power consumption is proportional to the size of LCD screen because the LCD colour screen of mobile phone is always active when a call is in progress. Consequently, the average capacity of 1100 mAh is still not lasting since the overall power consumption has increased. Furthermore, the \( V_{\text{working}} \) duration after each recharging cycle, i.e. cycle life will not be preserved forever. A typical Li-ion battery is facing a linear loss of charge capacity (mAh) at 0.045% per cycle or 22.5% over 500 cycles [9], which implies a year of heavy use. The loss is mainly due to the increase in internal resistance developed during recharging cycle. This internal resistance will shorten the actual charging duration and reduces the effective operating hours of the cell packs in the consumer devices. The loss is currently unavoidable and thus leads to more frequent recharging cycle. This is a very tedious process if the cycle life (i.e. operating hours) has deteriorated to the same amount of time required for charging. Therefore, it is important to investigate alternative method to prolong the battery life in a more convenient way.

1.2 Battery Charging Systems using Wireless Power Transmission (WPT) Technology

Among the innovative in battery charging technology, wireless battery charging system that uses non-contact approach to charge a battery has attracted strong interest in recent years. In fact, wireless charging systems are now found in many real world applications. Wireless Power Consortium (WPC) is formed by some of the largest consumer electronics manufacturers such as Philips, Duracell, Hosiden, Leggett & Platt and Nokia and Sanyo with the aim of setting an international standard for compatible wireless charging systems [10]. In January 2009, WPC has selected close-range magnetic induction technology as the first standard mean of transferring power wirelessly. The determination is owing to the maturity of Close-Range Magnetic Induction (CRMI) technology. Generally, every CRMI system consists of two circuit components, one consists of a transmitting inductive coil and another one has a receiving inductive coil. Both transmitting and receiving circuits are to be tuned to the same resonance frequency in order to cancel out the stray inductance in the receiver and magnetizing inductance in the transmitter. This inductance exists in the coupling coils during the operation. By eliminating this inductance, power can be coupled from transmitter to the receiver more effectively. Examples of consumer
products that are implementing CRMI technology are electronics charging dock, toothbrush charger, electronic warming shoes, game console charger, water treatment system and cochlear implants.

Nevertheless, CRMI is not the only system that able to transfer power wirelessly for battery charging. In this dissertation another wireless power system, which is a charging system by microwave radiation will be investigated.

1.2.1 WPT by Radio Frequency Electromagnetic Radiation

The concept of transmitting power wirelessly using EM radiation has long been researched in many countries. Brief description of two references is presented in this section. Solar Power Satellites System (SPSS) is a system involving Wireless Power Transmission (WPT) technology transferring microwave power from outer space back to earth surface [11-21]. In SPSS, giant space satellites orbiting around the Earth have vast arrays of solar cell panels to gather solar energy from the sun at all times in the outer space except the equinox period. Electricity is then converted to gigawatts of microwave energy by the massive transmitting antenna panels [16]. These transmitting antennas aim at the terrestrial receiving stations on the Earth where power is transferred to existing electric distribution grid network and then routed to consumer. The energy carrier of most of the references is at 2.4 GHz and some at 5.8 GHz. The reason of using these frequencies is because these bands are reserved internationally for Industrial, Scientific and Medical (ISM) purposes other than communications. By increasing the transmitting power, EM radiation at these frequencies is able to travel very long distance.

The SPSS is an ultra high wireless power transmission system. There is another WPT system for a shorter range application, which is introduced by Powercast™ Corporation [22]. The corporation has developed proprietary methods to enable wireless power system. Their system resembles a miniaturised SPSS system because it is theoretically identical, as depicted in Figure 1.1. The differences of Powercast™ from SPSS are lower transmitting power, smaller equipments and the requirement of AC to DC conversion. Their proposed system requires a special transmitter (Powercaster™) and receiver (Powerharvester™). The Powerharvester™ is a rectifier Integrated Circuit (IC). This IC is very low profile and is used to convert
Radio Frequency (RF) energy from the transmitter into DC efficiently. The Powerharvester™ have to be attached to an antenna of 915 MHz operating frequency. This harvesting technology is claimed to be able to recharge alkaline battery and Li-ion battery over 5 meters distance.

Long range and short range WPT technologies are not limited to SPSS and Powercast™ systems only. There are several WPT technologies, which will be covered thoroughly in Chapter 2.

1.2.2 Advantages of Wireless Power Transmission System

Owing to the increasing demand for stronger connectivity between computers and personal communication devices, WPT system such as one developed by Powercast™ Corporation will further prolong the battery life in consumer electronics application and provokes development of a truly wireless standalone system.

The development and implementation of WPT system provide several advantages to the community. First and foremost, the manufacturing cost of consumer devices can be reduced because the chargers will become integral parts due to the integrated WPT receivers. WPT enabled devices gives better mobility because the battery capacity will not be a critical issue to the manufacturer. Smaller and lighter cell packs are applicable and yields further reduction in product size and weight. Apart from that, WPT enabled devices have greater expandability than multi power outlet since a single transmitter can transmit power to multiple receivers within the coverage area without additional hardware. In short, WPT integrated device will provide ultimate

Figure 1.1: The SPSS and Powercast™ Functional Blocks
(a) SPSS System (b) Powercast™ System [22]
convenience to the community because charger will not be necessary and the use of cables and power cords will be reduced.

1.3 Proposed WPT System by Wireless Local Area Network at 2.4 GHz ISM Band

Since 2000s, the IEEE 802.11 standard, generally known as the Wireless Local Area Network (WLAN) is gaining popularity. Many portable electronics such as mobile phones, handheld gaming consoles and laptops are integrated with wireless network capability. The Original Design Manufacturers (ODMs) are competing to integrate this wireless network feature into their products as an attractive feature to consumers. The technology has allowed users to access the internet at any location within wireless network coverage. Examples of WLAN acceptance as the standard wireless communication include the Malaysia’s world first Wi-Fi centric mobile phone [23] and free WLAN access in fast food restaurants [24]. Besides, business and industrial offices are well equipped with WLAN facility as well. As a result, WLAN routers are in popular demand.

Majority of network routers in the market are built-in with WLAN transceiver, which enables wireless networking along with the conventional networking method, which is Local Area Network (LAN) connection. The rapid development of WLAN is mainly owing to the existence of internet. Generally, internet is indispensable to the general community, especially the computer-centric users since 2000s. For the younger generation, they prefer to stay online via WLAN whenever it is available. In fact, it has become a habit to be available online at anytime, anywhere. The industrial sector has been aware of this trend and they had long since exerted great effort to push the WLAN compatible electronic products to the consumer. The popularity of WLAN has soared because of its convenient, simplicity and flexibility to connect to private computer network or internet without any tedious cabling. This is the worldwide trend and it is reasonable to research on the feasibility to harvest the WLAN signal for wireless charging purpose.

In this dissertation, the main objective is to develop a low cost, compact WPT receiver to harvest ISM band at 2.4 GHz WLAN signal and convert the power for battery charging. The theory of operation can be summarised by the block diagram in
Figure 1.2. Several WPT receivers have been developed and tested. The receiver of a WPT system using electromagnetic radiation is commonly known as rectifying antenna, or technically termed as rectenna. Basically, a rectenna consists of a receiving antenna and a rectifying circuit. A transmitter is required to transmit WLAN signal towards the rectenna at desired frequency and power level. The travelling wave will be received by the receiving antenna and the rectifier will convert the AC current into constant DC current to charge the battery.

![Battery Charging by ISM Band at 2.4 GHz WPT](image)

This research covers the design of rectenna, which is made up of two major components, the antenna and rectifier. The efficiency of each component determines the overall performance of the rectenna. To charge a battery, a high efficiency rectifier and antenna are required. The rectifier is mainly consists of an impedance matching network and rectifying circuit. The impedance matching network is required to enable the rectifier to work at typical 50Ω RF platform at 2.4 GHz. At the same time, the rectifying circuit will rectify the AC before it reaches the load, which is the battery.

The research directions for the rectifier are mainly on two areas. Firstly, the efficiency analysis of single diode and dual diodes rectifiers is required to determine the most suitable rectifying circuitry. Schottky barrier diode is the key component in the rectifier design. A high efficiency rectifier should deliver more than 50% of DC power from the harvested Electromagnetic (EM) power. Otherwise, alternative rectifier should replace the inefficient one as more than 50% is wasted. Secondly, the efficiency analysis of rectifiers at different input power is necessary to determine the best performance power range. This is because the nonlinearity characteristic of Schottky barrier diode causes inconsistency in rectifier efficiency when the input power varies.

Similarly, an efficient antenna element is required in order to transfer the received EM power to the rectifier with minimum loss. This parameter is technically
characterised as antenna radiation efficiency. Several antennas with specific characteristics will be presented in this dissertation (in Chapter 5) to accomplish the following objectives. Among the characteristics, antenna miniaturisation is one of the important criteria for a WPT system in consumer products. It is critical to limit the physical dimension of an antenna so that more units can fit into a limited space to harvest more EM energy. The antennas should also possess the ability to integrate. Most of the antennas do not work ideally when being close to a conducting surface because most of the EM energy is trapped by the capacitance formed between the surfaces. In order to embed the rectenna into the portable electronics without performance degradation, this issue must be eliminated for more efficient WPT system. Lastly, it is an extra advantage to integrate the miniaturised antennas with decoupling characteristic. To increase the power harvesting capability, antenna array formation is essential. Mutual coupling occurs when distance between two antennas is less than half wavelength (½ λ) of the operating frequency. Decoupling techniques enable close distances between antennas by reducing the mutual coupling.

In this dissertation, the rectennas are used to charge batteries. Two types of commercial batteries will be tested with these rectennas. They are off the shelf AAA NiMH cylinder batteries and Li-Po cell pack from a commercial 3G phone. The scope of rectenna study will include the experiments on battery charging concerning the ability to prolong the cycle life and the ability to charge up the batteries.

1.4 Research Hypotheses

The research design focuses on the development of a low cost, compact and efficient wireless battery charging system. Based on the Section 1.3, several research hypotheses can be made in accordance to each component in a rectenna as shown in Figure 3.1.

The size of receiving antenna is critical for consumer products as they are shrinking in size. Microstrip antennas such as traditional patch and Printed Dipole Antenna (PDA) may not be suitable for small devices. However, wideband microstrip antenna has the potential to be miniaturised by scarifying unwanted impedance band in order to achieve smaller dimension. This could be achieved by shrinking the antenna layout without removing the desired frequency channel. When multiple antennas are
required to increase the harvesting capability, antenna array configuration could be applied to achieve higher gain. However, large spacing between antenna modules is essential to prevent unnecessary mutual coupling loss. However, mutual coupling issue have to be resolved to achieve smaller spacing and size reduction of the entire rectenna array. Research in microstrip decoupling technique would be useful to discover possible solution for this issue.

Selection of suitable rectifier is also critical in this research. The power requirement of the target battery-powered device and the distance of the device from the power source are taken into design consideration to select the best fitted rectifier for this research. Similar to the antenna miniaturisation, the rectifier shall be designed to occupy least possible board area in order to achieve low profile characteristic in overall. The impedance matching (i.e. balun) between the receiving antenna and rectifier is indispensable to provide low loss electric path for UHF energy. It is possible to create a low profile impedance matching balun with minimum space required on the antenna board. Possible techniques rely on the microstrip technique that forms the balun circuit.

Batteries are used as the DC load in this research. The input impedance of these loads is different. Therefore, the effect of battery to the input impedance of the rectifier has to be investigated and further impedance tuning will be suggested to resolve the question. After the rectenna design, actual implementation of the rectenna prototype to several target devices will be examined. This may help to understand the reality performance of the rectenna. With these analyses, further extrapolation can be made to study the larger dimension rectenna integration.

1.5 Dissertation Organization

This dissertation presents the novel design of high efficiency rectenna that receives and converts ISM band 2.4GHz electromagnetic radiation into useful DC power for battery charging application. Results from extensive studies based on computer simulation using Ansoft HFSS, ADS Momentum and experimental study of a hardware prototype are presented. The outcomes of this research work contribute towards the development of a low cost, compact and efficient wireless battery
charging system. The main body of this work has been included in a provisional patent filed by RMIT University in 2009.

This dissertation divides into six chapters. Chapter 1 describes the importance of this research study and scopes of the work. Chapter 2 elaborates the literature review in accordance with the history background and modern development of WPT technology. Next, the proposed WPT system by WLAN and an in depth analysis of WLAN power characteristic in compliance with FCC regulations are presented in Chapter 3. Chapter 4 describes the analysis and design of high efficiency rectifier. This includes the rectifier performance comparison by simulations and measurements. After that, several miniaturised antenna designs suitable for integratable rectenna applications are presented in Chapter 5. Following the antenna designs, the overall performance of the complete rectenna for battery applications is compiled in Chapter 6. In addition to rectenna experiments, the proposed possible implementation, optimised rectenna array distribution and examples of integration are demonstrated at the second half of Chapter 6. Lastly, contribution, key findings and conclusion of this research will be drawn in Chapter 7.
CHAPTER 2: LITERATURE REVIEW

The literature review of WPT technologies will include the theoretical background and system concept. There are three basic methodologies to achieve wireless power transmission. They are longitudinal acoustic compression wave, inductive resonance coupling and electromagnetic propagation coupling. WPT by longitudinal acoustic compression wave was discontinued, therefore only a brief description is available as follows. The inductive resonance coupling and electromagnetic propagation coupling are modern methodology to achieve wireless power transmission. Both technologies will be described in detail later.

2.1 WPT by Longitudinal Acoustic Compression Wave

The first WPT system in the world was proposed by Nikola Tesla. The system was predicted to provide free electricity globally by longitudinal acoustic compression wave. The Tesla’s system, which is also known as the World System, consists of a Tesla Transformer or Tesla Coil and a Magnifying Transmitter [25]. According to [25], the principle of Tesla’s WPT system was fundamentally different from the transverse electromagnetic (TEM) wave, which is radiating electromagnetic wave, realised by Hertz [26]. Tesla’s WPT system was to generate a broad resonating high voltage pulse evenly to the globe. The proposed generator was the Tesla coil with a conducting sphere of three feet in diameter. The idea of World System was originated from an experiment in 1899 during the test of 1.5 megawatts system in Colorado Springs. During that particular experiment, a spherical conductive ball was charged by ultra high voltage facility and being discharged as an electrical pulse. The pulses had passed across the globe and returned without significant loss. These pulses were then being named as “longitudinal acoustic type of compression wave”. The apparatus that create these pulses was modified and patented to build a 187 feet tall Tesla Tower in 1903 for actual field test.

Tesla’s complete WPT concept can also be visualised by using a balloon coated with a conductive layer, which represents the ionosphere layer and Earth surface including the seawater. This idea was to transmit low frequency longitudinal wave between atmosphere and ground to the other end of the Earth and echo back to the origin like a standing wave with very little loss. With this, a special receiver could tap
the energy with a load at anytime and anywhere. However, this project failed as the practical field test was not completed. The second installation was incomplete due to funding shortage and the only tower was demolished in 1917 by government during world war.

Figure 2.1 illustrates the wireless power transmission concept from Tesla’s World System. The giant Tesla Tower between the ionosphere and the Earth was planned to be used as the main transmitter to deliver lossless and low frequency wireless power to the world. It is analogous to a monopole antenna inside a huge waveguide tunnel with both ends being joined to form a circle. Although Tesla’s World System was unsuccessful, it has been the fundamental methodology and inspiration to the current WPT technology such as the inductive resonance coupling.
2.2 WPT by Inductive Resonance Coupling

Other than the Tesla’s World System, an alternative method to achieve contactless power transmission is by inductive resonance coupling. Inductive resonance coupling can be subdivided into very close proximity and short range system. The distance between transmitter and receiver of close proximity system is typically less than 25 millimetres whilst short range system will provide an effective range of tens to hundreds of centimetres. The existing inductive resonance coupling technologies are tabulated in Table 2.1.

<table>
<thead>
<tr>
<th>Inductive Resonance Coupling Systems</th>
<th>Research Organisation</th>
<th>Transmission Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Resonance Coupling (MRC) [27-31]</td>
<td>Massachusetts Institute of Technology (MIT)</td>
<td>300 mm to 1500 mm</td>
</tr>
</tbody>
</table>

Table 2.1: List of Current Inductive Resonance Coupling Systems

Generally, these technologies share the same concept by having the receiving and transmitting devices both tuned to a certain resonance frequency. The energy from the transmitting coil will be coupled to the receiving coil through magnetic induction. The effective distance of the coils has to be maintained within several inches unless larger coils are used to create a stronger magnetic field. Depending on the transmitting power, the inductive resonance coupling for WPT system within several inches can be divided into low power and high power applications. The following sections will describe CRMI and MRC in more details.
2.2.1 Close-Range Magnetic Induction (CRMI)

The CRMI system is the first matured technology being recognised by Wireless Power Consortium (WPC) as the standard for transferring power wirelessly in battery charging system [10]. Generally, every CRMI system consists of two integrated circuit components with coils. As illustrated in Figure 2.2, the charging circuitry consists of a miniaturised primary inductive coil and the portable device will integrated with secondary inductive coil. This configuration can be considered as a transformer. When the coils are active, the unwanted inductance in the coils will degrade the coupling efficiency. Therefore, both transmitting and receiving circuits require an adjustable capacitive component to achieve the same resonance frequency in order to cancel out the stray inductance in the receiver and magnetizing inductance in the transmitter. By eliminating this inductance, power can be coupled from transmitter to the receiver more effectively. Practically, the coils can be realised by using spiral microstrip traces on multilayered PCB whilst the capacitive tuning component is achievable at semiconductor level. Examples of consumer products with integrated CRMI technology are electronics charging dock, toothbrush charger, electronic warming shoes, game console charger, water treatment system and cochlear implants.

![Figure 2.2: Typical CRMI System for Low Power Consumer Electronics](image)

Apart from low power consumer electronics, CRMI technique is also useful in the industrial sectors for higher power applications. In high power application, CRMI is better known as Inductive Power Transfer (IPT) system. It was developed and was patented by Auckland Uniservices Limited in 1988 [32]. Similarly to the low power system, it requires a primary system to transfer electric energy to the secondary
system through magnetic induction. It can be considered as the modified CRMI system because the primary coupler may be in coil form. In the manufacturing floor, IPT technology is well known for material handling, lighting and can be integrated with data handling capability. The objective is to supply power to the receiver by magnetic induction from the metallic track hidden underneath the target receiver in the devices.

In the electric automotive industry, IPT can be developed into electric vehicle (EV) charging system. An example is illustrated in Figure 2.3 in accordance to [33, 34]. The power supply unit is secured underground with a primary track conductor. When EV parks above the track conductor, magnetic induction will induce electric energy to the pickup coil in the EV. The DC power will be available after rectification and regulation processing units. In 2009, Bombardier had presented the Primove system to achieve catenaries free environment for trams and light rail vehicle [35]. The demonstration of the first catenaries free and contactless operating tram is presented at Bautzen, Germany. Primove system is similar to the fuel cell system as in Figure 2.3 but with slight variation. The bottom part of the tram compartment contains the special coupling apparatus whilst unique inductive conductors are embedded underground along the railway and supplying constant electrical energy to the special coupler [36]. Each compartment can fit single coupler or several pairs of couplers in order to charge the battery storage system located on top of the compartment.

![Typical IPT Technology for High Power Automobiles](image_url)
2.2.2 Magnetic Resonance Coupling (MRC)

The magnetic resonance coupling system was proposed by a MIT team led by Prof. Soljačić in 2007. The system is depicted in Figure 2.4. They had implemented the IPT theory to achieve WPT by utilising a pair of large magnetic coils. The coils are made of laminated copper wires for high power application. The loops is designed and tuned to resonate at about 10 MHz. The primary coil is connected to an AC power source that is modulated at megahertz whilst the secondary coil is connected to the AC load at about 2 meters away. The low frequency resonating coil forms a strong magnetic tunnel to which the receiving coil within the near field region being induced efficiently with the AC energy. According to the team, this invention is non-radiative due to the low frequency and is safer to human health. Besides, the functionality is unaffected to any obstacle between the coils such as life being and metallic objects. Therefore, it has the potential to be commercialised for application within 2 meters. The prototype has successfully illuminated a 60 watts light bulb with more than 2 meters distance away with 40% efficiency [27-31].

![Figure 2.4: Typical IPT Technology for Distance of Several Feet](image-url)
2.3 WPT by Electromagnetic Propagation Coupling

The WPT system by EM propagation coupling was begun after the electric and magnetic discoveries during the classical era prior to 19th century. This includes electric and magnetic theories, formulas and laws from Faraday’s, Henry’s, Gauss’s etc, especially Maxwell’s equations that explained electromagnetism before 1880’s [26].

The realisation of electromagnetic propagation occurred when a tuned spark gap radio transmitting and receiving system was built by physicist Heinrich Hertz in 1887, which was the first real hardware that realising the propagation of radio wave based on the theoretical concept from Maxwell [37-39]. Hertz’s spark gap radio was in fact later known as a modified end loaded dipole aerial that proved the propagation of wave through space. This aerial, or antenna, is part of the rectenna component today. The making of the first EM signal transmitter was a very significant milestone and has led to the evolution of many wireless technologies nowadays and wireless power scavenging is only one of them.

According to Brown [40], the technological advancement was progressed at a slow pace prior to 1950s because high frequency, high power directional radiators had not been made available. Besides, knowledgeable researchers at that time believe that the only practical way to achieve efficient WPT was to utilise a reflector to focus the electromagnetic beam at the receiving direction. Since very large lenses were impractical before 1950s, a shorter wavelength from a high frequency generator was proposed. However, high frequency generator was unrealisable at that time due to technology limitations.

Technically, the WPT system by EM propagation coupling can be divided in accordance to the specific service range. There are long range and short range systems. Electromagnetic radiation suffers great loss when travelling in the space as described by Friis Equation as follows:-

\[ P_r = P_t \times G_r \times G_t \times \left( \frac{\lambda}{4\pi R} \right)^2 \]  

(2.1)

Where,

\( P_r \) = receiving power (watt)
\[ P_t = \text{transmitting power (watt)} \]
\[ G_r = \text{receiver's linear gain (dimensionless)} \]
\[ G_t = \text{transmitter's linear gain (dimensionless)} \]
\[ R = \text{range (meter)} \]
\[ \lambda = \text{wavelength (meter)} \]

Therefore, short range system can only transmit useful EM energy within several feet whilst the long range system is in kilometres.

### 2.3.1 Long Range Propagation Coupling

The world had begun to seek for alternative energy source due to energy crisis after World War 2. This time represents the beginnings of research interest in modern WPT by long range propagation coupling [40]. Companies and research centres such as National Aeronautics and Space Administration (NASA, USA) and Raytheon (the world largest defence contractor) sponsored a major study in SPSS, an EM propagation coupling application for long range WPT system, leading to various contributions in free space microwave power transmission. The proposed SPSS is an advance energy harvesting system in future that attracts attention from U.S. government. Department of Energy and NASA in U.S. had aggressively researched the practical use of SPSS since then. SPSS was initially predicted to be realised in 2030s [40]. The central frequency of the EM radiation used in SPSS is 2.4 GHz ISM band. The merits of gigahertz range EM radiation are easy access and better efficiency than other frequency bands.

Figure 2.5 demonstrates the overview of the proposed SPSS. The giant satellites for SPSS have vast arrays of solar cell panel in geosynchronous orbit, roughly 22300 miles above the Earth’s equator. Solar panels on the satellites are playing the major role to gather solar energy from the sun all the time in the outer space. The solar panels convert the sunlight into gigawatts of electricity and then it will be transformed into microwave energy beam by massive transmitting antennas, which are aiming at the terrestrial rectenna stations (i.e. Earth stations) on the Earth. The existing electric distribution grid network will route the electric energy from the rectennas to every neighbourhood.
However, SPSS study was discontinued due to many factors. Firstly, the solar cell technology was still immature because the solar energy conversion was still inefficient and unpopular during 1970s. Besides, the assembly process of solar powered satellites was initially suggested to be completed by using remote robotic arms in the space, which was unavailable at that time. Furthermore, space travelling was very costly.

![Figure 2.5: The SPSS: WPT System by Long Range Propagation Coupling](image)

In 1990s, SPSS regained attention due to oil crisis and the advancement of modern engineering [40]. Continuous evolution and maturity of several industries have contributed to the feasibility of SPSS. Firstly, very large-scale integration (VLSI) revolution in semiconductor sector had also lead to faster processing and better performance in computer engineering. Additionally, new solar cells from the industry are smaller, more efficient and affordable for household usage since 90s. The robotic automated assembly system was also a practical reality in automobile industry for repetitive tasks to replace work force and to increase productivity. Furthermore, the growth of modelling tools in engineering fields has resulted in more efficient rectenna design cycle with higher accuracy. As a result, high performance rectenna prototypes
can be realised and tested. Lastly, reusable space transportation has reduced the cost of space travelling and satellite manufacturing.

Owing to these factors, SPSS had to undergo strict evaluation and demonstration of a few key features such as beam control from satellite, overall system stability, development and maintenance cost and safety. Such assessment was essential in order to provide the utilities confidence in every aspect stated previously. Several revised concepts based on original SPSS were studied. As described by Nansen in 1996, the wireless power transmission is the key to SPSS but the plan might require a long time frame to accomplish because the entire SPSS modal will include several huge satellites, large dimension solar panels, huge antenna panels, many of terrestrial rectenna stations and a fully compatible power distribution grids [20]. Nansen has published a development plan together with the cost analysis and forecast for coal power and SPSS from 2000 to 2040. He has concluded that by comparing the solar energy from the sun to the coal energy, the charges for SPSS power will be much lower than conventional coal power after 40 years.

In 2002, Parise has proposed an annexure system to utilise the energy for fuel cell or electric vehicle via transmitting and receiving units [15]. A year later, Ahmed concluded that the terrestrial WPT system is still more costly than physical extension of grid system unless it was to be crossing the river or ocean where overhead and submarine lines are not feasible, or between protected landscapes such as preserved mountain and forest [14].

2.3.2 Short Range Propagation Coupling

Wireless energy transmission is not limited to high power and long range SPSS only. One of the popular short range WPT applications is the RFID system. Recently, another short range WPT system was introduced by Powercast™ Corporation for remote sensor and battery charging applications. Owing to safety and health issues of the public, WPT systems by propagation coupling are always abided by regulations to limit the exposure of EM radiation, typically put in place by a governing body such as the Federal Communications Commission (FCC).
a) Radio Frequency Identification (RFID)

The implementation of RFID system started during the World War 2 when radar was the common infrastructure of war machines. Germans was the first discovered the RFID concept during the flight, which was used to differentiate between allied from the others in the sky [41]. Later, British developed an active and passive system for radar station and the aircraft, which was the Identify Friend or Foe (IFF) system.

According to [41], the RFID was officially introduced to the public in 1973 when Cardullo claimed the first U.S. patent for his active RFID tag with built-in memory and Walton received a patent for his passive RFID in door lock system. Since the 1970s, the U.S. government has urged for intensive research and development in RFID systems such as the tracking system of nuclear material developed by Los Alamos National Laboratory. The scientist from the same development team was then commercializing the RFID system to a toll payment system during 1980s.

Generally, the power transmission in RFID systems is relatively similar to the SPSS system. The components in the receiving tag include a transponder, microchip and antenna whilst the reader contains a processing unit and single or multiple antennas. The tag reader may be standalone or connected to a computer database. Depending on application, RFID tags can be designed to operate within several meters or inches by changing the power level of the reader and antennas. The antenna in the tag can also be used to harvest energy from the reader to charge the battery. Due to the design flexibility, RFID industries have standardised the operation of RFID into 3 categories.

There are passive, semi passive and active tags in the market. The typical read range of active tags is about 20 to 100 meters. These tags have to consume solar cell or rechargeable battery to broadcast memory data such as transponder and beacon system. Generally, active transponders are implemented in toll payment system and beacons are used in the large manufacturing facility as Real Time Locating System (RTLS).

Conversely, passive tags can only reflect energy back to the reader since it has no internal power source or transmitter. Therefore, passive tags are cheaper. The frequency of operation is application specific and is critical to determine the readable
range. Low frequency passive tag is only readable within inches. As a result, companies and warehouses usually implement a higher frequency passive tag system which also helps to prevent interference from other equipments. There has been a lot of advancement since RFID was introduced to the market and modern passive RFID usually harvest energy either by inductive or propagation coupling. Inductive coupling requires resonating wire coils at each side to obtain sufficient power whilst propagation coupling is the WPT technology by EM radiation [42].

Semi passive tags are battery-aided tags. It requires a battery to run the microchip circuitry whilst communicates by harvesting power from the reader. Similar to active tags, the passive tags are suitable in tracking system to track valued goods over long range such as railways cars. RFID tags operate at many different frequencies across the radio spectrum, from low frequency (LF) to ultra high frequency (UHF) band. Modern RFID tags in 1990s uses ISM bands such as 915 MHz and 2.45 GHz. UHF band is preferred due to its high frequency characteristics that lead to longer effective read range, higher data rate and less interference from other operating equipment near to the target. In 1999, research and development performed by Brock and Sarma from MIT brought RFID technology to the internet [42]. This enabled the global tracking system and became the most well known tracking technology today. These experts gained support from several end user companies and constructed research labs in many countries such as Australia, United Kingdom, China, Japan and Switzerland.

b) **Powercast™ Wireless Power Technology**

There is another short range WPT system for application within several meters, which was introduced by Powercast™ Corporation [22]. The theory of operation was already depicted in Figure 1.1. The wireless power distribution is similar to other wireless communication infrastructure. General, this technology is applicable for building automation such as indoor sensors behind walls or above ceiling. Besides this, it is also suitable for location tracking and to be used as longer range RFID, battery-free Real Time Location Systems (RTLS) and beacons. Similarly, it can be used for industrial monitoring at hazardous regions and battery trickle charging

The differences of Powercast™ from SPSS are lower transmitting power, smaller equipments and the requirement of AC to DC conversion circuitry. Technically,
Powercast™ Corporation has developed a unique transmitter (Powercaster™) and receiver (Powerharvester™). The Powercaster™ has a total fixed power of 3 watts effective isotropic radiated power (EIRP). They have created two types of Powercaster™, which are the removable antenna module and fixed antenna module. Both modules are able to radiate constant EM energy in compliance to the regulation from FCC part 18. The physical dimension of the fixed antenna module is 261 mm × 60 mm × 46 mm whilst the dimension of removable antenna module will depend on the antenna used.

The Powerharvester™ modules (i.e. P1100, P1200 and P2100) are specially designed integrated circuits (IC), which is less than 0.25 square inches and is used to convert RF energy into DC efficiently. The Powerharvester™ have to be attached to an antenna that operates at 915 MHz. The common applications of this IC are battery recharging, low power wireless sensors, battery free sensors and low wattage lighting.

c) Ubiquitous Power Source (UPS)
Recently, Shinohara from Kyoto University has shown the latest research activity in WPT technology by EM propagation coupling. A detail progress and achievement of their recent WPT research studies are being compiled by Shinohara in [12]. In 2009, they have developed Ubiquitous Power Source (UPS) that is able to charge mobile phone [11]. This concept is demonstrated in Figure 2.6. Conclusion has been drawn by the team that EM energy at safety level of 1 mW/cm² is sufficient to charge mobile phone using several rectennas. In this report, this team has also proposed a WPT application similar to Parise’s EV model, which is to implement WPT system in household or office area.

![Ubiquitous Power Source System](image)
2.4 Review of Current Rectenna Technology

The research and development of rectenna is growing because the rectenna is a key component of any WPT system by propagation coupling of EM radiation. The rectenna consists of a rectifier and an antenna and is used to convert high frequency EM energy into DC. The development of rectenna technology started since the introduction of WPT theory and along with the application development such as SPSS, RFID and Powercast™ system. In short, many of these rectennas are designed based on similar architecture which consists of five main components.

Figure 2.7 describes the fives components of typical rectenna architecture. The first component is the receiving antenna. The antenna of a rectenna is commonly a high efficiency RF radiator used to receive incident EM energy. Secondly, an input filter such as LC network is required for impedance matching and frequency filtering. The third component is the high efficiency single diode or dual diode rectifier. The fourth component is the DC filter, which is basically a decoupling capacitor to remove unwanted voltage transient or spikes after the rectification. The final component is the load. The load can be a battery or electrically resistive object that consumes the converted DC power.

Generally, there is no restriction on the types of radiator and rectifying components being used in the design of rectenna because rectenna is an application dependent device. However, the rectenna can be divided into four main groups. They are rectenna with mechanical parts, rectenna with solid-state components, solid-state printed rectenna on microwave substrate and lastly the rectenna with silicon-based rectifier.

![Figure 2.7: Typical Rectenna Architecture](image-url)
2.4.1 Rectenna with Mechanical Parts

When SPSS was discontinued due to technological constraints, Raytheon’s group continued in the development until a practical realization of the first complete WPT system in May 1963 [40]. The first system is able to deliver 100 W successfully with 13% of Direct Current (DC) conversion efficiency at Raytheon Spencer Laboratory for Raytheon Airborne Microwave Platform (RAMP) system. This system utilized a super power Amplitron source with horn-illuminated ellipsoidal reflector that focused the beam to a trapezoidal horn connected to a waveguide and then attached to a close-spaced thermionic rectifier at 20 feet away.

Followed by the success of the first full WPT system, the first rectenna with semiconductor diodes is created to replace the close-spaced thermionic full wave rectifier that attached to 28 half-wave dipoles. The DC conversion efficiency of this design was 40-50%. Efficiency of semiconductor diodes has led to the creation of a large rectenna with 4,480 1N82G diodes, which is equivalent to 1120 sets of classical bridge rectifier. This rectenna was capable to fly a helicopter (i.e. without main body) at an altitude of 50 feet for 10 hours continuously. The amount of power required for the experiment is approximately 270 W. The performance of the same design was optimised further by using silicon Schottky Barrier Diode, which is HPA2900 by Hewlett Packard (HP).

2.4.2 Rectenna with Solid-state Components

Along with the Raytheon’s achievement, Brown had pursued WPT system development with better signal generator, better analysing equipments and better Schottky diodes [40]. In 1975, evolution of rectenna has succeeded at Goldstone Deep Space Facility where the rectenna is capable to produce 30 kilowatts at 1 mile away. The DC conversion efficiency is about 84% [21, 43]. This rectenna can be graded as the first successful high efficiency rectenna. This achievement was suitable for the SPSS integration and led to the thin film design consideration, which is the new form of fabrication very similar to the modern PCB technology [44]. The power collecting bus of the rectenna had moved to the fore plane for simplicity, less weight and further cost reduction. The simplification has enabled the integration of rectenna to an airplane wing for further experiment. In 1991, Brown modified the rectenna array with less diode in order to supply power for solid state device at 5 V
DC. The prototype was experimented under low power density and the DC conversion efficiency is about 55% [45].

2.4.3 Solid-state Printed Rectenna on Microwave Substrate

Apart from rectennas from Raytheon and Brown, there were significant contributions from Chang’s team in modern rectenna development after 1990s, according to [46]. Their active involvement in microstrip rectenna designs had led to significant contribution in WPT system due to the creation of many high efficiency microstrip rectennas. The majority of the designs were based on a similar architecture. Therefore, information of the rectenna designs from Chang’s group is tabulated in Table 2.2 and design layouts are illustrated in Figure 2.7.

In 1992, McSpadden, Yoo and Chang had provided a comprehensive theoretical and experimental investigation of rectenna elements for WPT [46]. They had developed a microstrip measurement system to analyse packaged GaAs Schottky barrier diode. The result from this analysis was a good foundation and design reference for the group. McSpadden proved that the measured efficiency of the Schottky barrier diode could reach 85% of DC conversion efficiency at 2.45 GHz ISM band. Then, a rectangular patch rectenna was designed at 35 GHz and achieved 29% of DC conversion efficiency with 100 $\Omega$ of load resistance. This design is shown in Figure 2.7(a). At the same time, Yoo had created a dipole rectenna at 35 GHz which can achieve 39% DC conversion efficiency with 400 $\Omega$ of load resistance [47]. The rectenna architecture consisted of an antenna, input low pass filter, rectifier and an output low pass filter. The layout is depicted in Figure 2.7(b). The major difference between their rectennas is the diode and the radiator. The diode used by McSpadden was from Jet Propulsion Laboratory and Texas A&M whilst the diode used by Yoo was DMK 6606 GaAs Schottky diode from Alpha Industries.

In 1998, McSpadden and Fan designed a dipole rectenna for the 5.8GHz band using a full wave simulator [48]. The rectenna is shown in Figure 2.7(c). This rectenna had achieved 82% of DC conversion efficiency with 327 $\Omega$ of load resistance. The architecture of the rectenna is identical to Yoo’s design except the Schottky barrier diode was changed to M/A COM Si Schottky diode (MA40150-119). They also provided a closed form equation to calculate the “RF to DC efficiency” of this particular diode and the numerical data matched well to the measuring test. The
equation given is also able to provide approximated input impedance of the diode. Additionally, they had identified a few critical parameters required to achieve high efficiency rectification. These parameters are zero biased junction capacitance ($C_{jo}$), diode’s built-in voltage in the forward biased region ($V_{bi}$), series resistance ($R_s$) and the DC load resistance ($R_L$).

In 2002, Suh and Chang created another new rectenna, which was a dual frequency rectenna for ISM bands at 2.45 GHz and 5.8 GHz [49, 50]. The rectenna geometry is shown in Figure 2.7(d). As illustrated in the diagram, the dual frequency property is owing to two pairs of closely coupled dipoles. The longer arms are designed to resonate at 2.45 GHz and shorter arms are resonating at 5.8 GHz. Two new CPS filters are connected in series between the dipoles and the rectifier. The first filter has three tiny digital filters act as a low pass filter that cut off at 7 GHz and passes 2.45 GHz and 5.8 GHz signal. However, this in turn passing the second and third harmonics of 2.45 GHz, which are 4.9 GHz and 7.35 GHz. This is the reason two pairs of T-strips are added to block 4.9 GHz and 7.35 GHz. This design had achieved 84.4% and 82.7% of DC conversion efficiency with 310Ω of load resistance at 2.45 GHz and 5.8 GHz respectively.

The ultimate goal of their research is to realise the high efficient rectenna for use in the SPSS. In 2002, McSpadden published a manuscript about the modern SPSS and comparison between new rectenna designs from recent publications and also included the latest diode analysis [16]. A high efficiency circularly polarised rectenna is designed for 5.8 GHz frequency band in 2003 [51]. The designer, Strassner utilised dual rhombic loop travelling wave antenna as the receiver as depicted in Figure 2.7(e) [51, 52]. Similar to Suh’s design, CPS filter is implemented in the rectenna system as well. Eight pairs of rhombic loops are used in Strassner’s design to obtain 14.6 dB of circularly polarised array. The overall DC conversion efficiency of this design is 82% and the measured output voltage is 3.8 V.

In 2006, Ren and Chang released several new rectenna systems. The first design in February was a retrodirective bowtie rectenna as presented in Figure 2.7(f). This rectenna consists of two pairs of balanced bowtie antennas, a band pass filter, a Schottky diode and a load resistor [53]. Retrodirective rectenna is unique because the main lobe can steer automatically towards the microwave power transmitter. It is
reported that 100% of DC voltage can be provided within ±10° and 90% of DC voltage within ±30°. Hence, it is less sensitive to the alignment from power source. The DC conversion efficiency of this array is about 84%.

The second rectenna from Ren was retrodirective rectenna array. This array consists of circularly polarised proximity-coupled microstrip rings [54] as illustrated in Figure 2.7(g). This antenna is characterised with an intrinsic harmonic rejection up to the third component. It possessed all the advantages of the retrodirective bowtie with wider angle than the previous, with ±45° required for 90% of DC voltage. In a 2 by 2 array mode, this rectenna is capable to demonstrate 73.3% of DC conversion efficiency.

Apart from these designs, Tu, Hsu and Chang focused on the size reduction in 2007 [55]. A stepped impedance dipole rectenna at 5.8 GHz was designed at that time and successfully reduce the length of the arms by 23%. The DC conversion efficiency is about 76% with 250 Ω of load resistance. The layout is depicted in Figure 2.7(h). The end of each arm has a capacitive patch structure used to replace traditional long dipole arms. This is similar to the concept of flare angle implemented by bowtie-like radiating structure by reducing the length and widening the arm.

Apart from the inventions from western first world nations, recent years have also seen Japan taking significant steps in rectenna technology. For instance, Shinohara from Kyoto University had completed a huge rectenna array (3.2 m × 3.6 m) that operates at 2.45 GHz ISM band in 1998 [56]. The proximity-coupled circular microstrip antennas are used in the rectenna system as illustrated in Figure 2.8 and the effective DC conversion efficiency was 64%. Later, a huge rectenna array panel was constructed with over 2000 elements.

Besides this, Youn and Park from Korea had also contributed in this area by focusing in the analysis of rectenna efficiency in 1999 [57, 58]. A square patch as shown in Figure 2.9 was used and able to achieve an average of more than 70% DC conversion efficiency. However, the efficiency was observed being slightly lower in array formation.
Most of the rectenna designs have similarities regardless of geometrical layout. Rectennas from Heikkinen, Chen, Yo, Theeuwes, Ungan were implementing similar architecture to other designs [59-63]. The group used Schottky barrier diodes fabricated by Avago and the only difference is the type of receiving antenna. This trend implies that more researchers are using market readied diodes which are widely available rather than unique component.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Year</th>
<th>Reference</th>
<th>Frequency (GHz)</th>
<th>Type of Radiator</th>
<th>Polarisation</th>
<th>Tested Power</th>
<th>Load Resistance (Ω)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7(a)</td>
<td>1992</td>
<td>[46]</td>
<td>35</td>
<td>Rectangular Patch</td>
<td>Linear</td>
<td>120 mW</td>
<td>100</td>
<td>29</td>
</tr>
<tr>
<td>2.7(b)</td>
<td>1992</td>
<td>[47]</td>
<td>35</td>
<td>Dipole</td>
<td>Linear</td>
<td>135 mW</td>
<td>400</td>
<td>39</td>
</tr>
<tr>
<td>2.7(c)</td>
<td>1998</td>
<td>[48]</td>
<td>5.8</td>
<td>Dipole</td>
<td>Linear</td>
<td>50 mW</td>
<td>327</td>
<td>82</td>
</tr>
<tr>
<td>2.7(d)</td>
<td>2002</td>
<td>[50]</td>
<td>2.45 &amp; 5.8</td>
<td>Dipoles</td>
<td>Linear</td>
<td>2.48 &amp; 8.77 mW/cm²</td>
<td>310</td>
<td>84.4 &amp; 82.7</td>
</tr>
<tr>
<td>2.7(e)</td>
<td>2003</td>
<td>[51]</td>
<td>5.8</td>
<td>Dual Rhombic Loops</td>
<td>Circular</td>
<td>2 mW/cm²</td>
<td>150</td>
<td>82</td>
</tr>
<tr>
<td>2.7(f)</td>
<td>2006</td>
<td>[53]</td>
<td>5.8</td>
<td>Bowtie Retrodirective</td>
<td>Linear</td>
<td>10 mW/cm²</td>
<td>150</td>
<td>84</td>
</tr>
<tr>
<td>2.7(g)</td>
<td>2006</td>
<td>[54]</td>
<td>5.8</td>
<td>Proximity-Coupled Microstrip Rings</td>
<td>Circular</td>
<td>10 mW/cm²</td>
<td>150</td>
<td>73.3</td>
</tr>
<tr>
<td>2.7(h)</td>
<td>2007</td>
<td>[55]</td>
<td>5.8</td>
<td>Step Impedance Dipole</td>
<td>Linear</td>
<td>100 mW/cm²</td>
<td>250</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 2.2: List of Specification of Rectennas from Chang’s Group (1992 to 2007)
Figure 2.8: Layouts of Printed Rectenna from Chang’s Group (1992 to 2007) [46-51, 53-55]
2.4.4 Rectenna with Silicon-based Rectifier

The performance of the rectenna is critical in any WPT system. The use of solid-state components is able to reduce the loss and increase the efficiency. Nevertheless, the introduction of all in one silicon based rectifier could achieve the best performance. The modules (i.e. P1100, P1200 and P2100) from Powercast™ Corp. are the silicon-based rectifiers of their rectenna. The antennas designed by Powercast™ Corp. for transmitting and receiving modules include dipole (1.76 dBi), sleeve dipole (1.76 dBi), patch arrays (2.44 dBi and 8.57 dBi) and Yagi-Uda (7.85 dBi). The Powerharvester™ is claimed to be high efficiency over a broad range of load resistance, input power and recharging current in order to recharge alkaline battery and Li-ion battery. According to the technical data from Powercast™ database, the functionality is listed in Table 2.3 and the efficiency is summarised in Table 2.4.
<table>
<thead>
<tr>
<th>Application</th>
<th>P1100</th>
<th>P1200</th>
<th>P2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline rechargeable battery</td>
<td>Lithium ion rechargeable battery</td>
<td>Non-battery energy storage</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>902 - 928 MHz</td>
<td>902 - 928 MHz</td>
<td>902 - 928 MHz</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>0 to 20 dBm</td>
<td>0 to 20 dBm</td>
<td>-10 to 10 dBm</td>
</tr>
<tr>
<td>$V_{out}$ Loaded Max</td>
<td>3.3 V</td>
<td>4.2 V</td>
<td>5.25 V (configurable)</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>$\leq 100$ mW continuous</td>
<td>$\leq 100$ mW continuous</td>
<td>262.5 mW peak output</td>
</tr>
</tbody>
</table>

Table 2.3: Technical Specification of Powerharvester™

<table>
<thead>
<tr>
<th>Frequency</th>
<th>915 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power</td>
<td>1 W</td>
</tr>
<tr>
<td>Transmitter Linear Gain</td>
<td>4.0</td>
</tr>
<tr>
<td>Receiver Linear Gain</td>
<td>6.0</td>
</tr>
<tr>
<td>Distance</td>
<td>5 meters</td>
</tr>
<tr>
<td>Efficiency</td>
<td>60%</td>
</tr>
<tr>
<td>DC Power</td>
<td>392 $\mu$W</td>
</tr>
</tbody>
</table>

Table 2.4: Efficiency of Powerharvester™

### 2.5 Conclusion

This chapter presents the literature review of WPT technologies. The review covers the technologies created in accordance with the historical time line from the earliest approach by Tesla to the most recent discovery by coupling. These include the Inductive Resonance Coupling (IRC) and electromagnetic propagation coupling. The IRC can be divided into Close-Range Magnetic Induction (CRMI) and Magnetic Resonance Coupling (MRC) developed by different parties using coil to achieve wireless energy induction. Basic concepts of these technologies are presented. WPT by propagation coupling includes long range and short range applications. Long range application requires high transmitting power whereas the short range application is not. The rectenna is the essential component used to rectify the induced current. This chapter has also introduced the fundamental component of rectenna and comparison of several recent reported designs.
CHAPTER 3: SYSTEM ARCHITECTURE OF PROPOSED WPT SYSTEM

Wireless power transmission system is said to become one of the major advancements in modern power supply for electronic and electrical devices [11, 14, 15, 20]. However, before the technology could be accepted into mainstream product, factors such as health concern, integration capability, hardware size and cost must be thoroughly investigated. The rectennas presented in the literature review are usually larger than consumer’s handheld devices such as remote control, mobile phone and wireless house phone. Larger WPT receivers are usually costly and designed to handle long range and higher power transmission. Hence, it may not be suitable for low profile integration in the proposed system using WLAN energy. Moreover, the electrical strength of the WLAN signal is very low as compared to the system proposed by [11, 30, 34, 64]. Additionally, implementation of WLAN related applications has to be in compliance with a standard regulation, which is defined by FCC. The main discussions in this chapter include the following topics:

a) Proposed WLAN Energy Harvesting System
b) Limitation of EM Energy Propagation
c) Analysis of Propagation Loss with FCC Compliance
d) Health Concern

Generally, a complete WPT system by EM propagation coupling consists of a wireless power transmitter, WPT receiver and a load. The WPT system architecture of this research is shown in Figure 3.1. It has three functional blocks, which are the energy source, energy harvester and energy storage. The energy source consists of a microwave signal generator and a transmitting antenna. These are the essential component to radiate the EM energy through the space to the receiving side. The receiving side is where the energy being harvested. The EM energy harvester is the rectenna. The rectenna has a receiving antenna to absorb the EM energy and rectify the AC from microwave frequency into the constant DC. The converted DC will be stored by energy storage device. As referred to Figure 3.1, the main focus of this study is the development of rectenna to harvest ISM band at 2.4 GHz WLAN signal for battery charging. Therefore, the proposed rectenna design will be presented in this chapter.
3.1 Proposed WLAN Energy Harvesting System

As referred to [44, 47-49, 51, 65, 66], a typical rectenna has five subsystems, as illustrated in Figure 3.2 (a). An antenna is used to receive EM energy at the desired operating frequency. The input filter (i.e. band pass filter) is used to block the successive harmonics reflection from the rectifier back to the antenna. Elimination of harmonics reflections from nonlinear devices (i.e. Schottky barrier diodes) is important to achieve higher efficiency because energy loss occurs during the reflections, as discussed in [50]. Impedance matching network is typically designed to match impedance of rectifier to the impedance of input filters. This is to ensure the transmission line is effective. After rectification, the output filter is required to remove the spikes and ripples, thus a smooth and constant DC level can be retained for the resistive load.

The proposed WLAN energy harvesting system is depicted in Figure 3.2 (b). The proposed rectenna is technically a simpler model as it has only three subsystems, which are miniaturised PDA, impedance matching network and voltage doublers. The transmitting antenna used in this research will be a compatible radiator for 2.4 GHz.
ISM band. The advantages of smaller architecture model include low profile integration, low cost and low conductor and radiative losses at UHF band. As a result, it has the potential for better performance.

![Figure 3.2: Proposed WLAN Energy Harvesting System](image)

(a) Common System Architecture  (b) Proposed System Architecture

### 3.1.1 The Miniaturised PDA

The proposed miniaturised PDAs have several critical characteristics which are different from other low profile printed antenna [67, 68]. As suggested in Section 1.4, the antenna should be geometrically small in size. In general, the receiving antenna is the largest component in a rectenna device. The radiating elements of an antenna have a total length of $\lambda/2$ for the selected operating frequency. The elementary wavelength is described by Equation 3.1.

$$\lambda = \frac{v}{f} \quad (3.1)$$

Where,

- $\lambda$ = free space wavelength (throughout the dissertation)
- $v$ = speed of light
- $f$ = operating frequency

The proposed miniaturised printed antennas will have the length of radiator much shorter than $\lambda/2$, which is 62.5 cm. Methodology of miniaturisation will focused on shrinking the dimension of a wideband microstrip antenna (e.g. microstrip bowtie antenna) with the use of integrated microstrip balun. Changing the dimension could narrow the original impedance bandwidth. However, a fine tuned microstrip balun can be implemented to preserve certain band from the original performance. When this
antenna is printed on low loss microwave substrate, it will be a very efficient and low profile radiator for consumer electronics integration.

The second property is the expandability. Printed dipole is vertically polarised antenna and it can be expanded into array form by joining the collecting traces in order to harvest more energy per unit area. An example can be found in [44] where the interconnections between dipoles are achieved by joining the collecting buses in parallel to form a series dipole array.

A series dipole array requires λ/2 spacing between the adjacent antennas to prevent mutual coupling. If the spacing is less than λ/2, the performance will be affected (e.g. gain, antenna efficiency) and the receiving energy will be lost exponentially [69, 70]. The spacing distance of λ/2 is impractical in consumer electronics due to product size constraint. Hence, the novel solution to decouple two dipole antennas will be introduced in Chapter 5.

Most consumer electronics contain conductive material or inner metallic shielding. A capacitive gap will be formed to trap the energy when the printed antenna is placed at close proximity to the metallic shielding. This will affect the radiating efficiency of the antenna and causing low performance. Therefore, the proposed miniaturised PDA will include a conducting surface into design consideration. Several designs that are able to operate at 5 mm or 10 mm from a conducting surface without severe interference and performance degradation will be introduced in Chapter 5.

3.1.2 The Rectifier Circuitry
The rectifier circuitry of the rectenna consists of the impedance matching network and voltage doublers for rectification. It is built on the same substrate as the receiving antenna in order to achieve smaller form factor and to share the electrical grounding. The entire circuitry is intended to be designed on the limited ground plane between the radiating elements of the printed antenna. Therefore, an analysis will be shown in Chapter 4 in selecting the circuit topology that provides the highest efficiency while remains miniature in size.
The equivalent linear circuit model is presented in Figure 3.3 [71]. In the Schottky diode, there are three components. These are series resistance, junction resistance and junction capacitance. The junction resistance is subject to the changes in room temperature, variation in bias current and saturation current during the operation. As a result, they contribute to the non-linearity characteristic of Schottky diodes. The impedance of the diodes in the rectifier can be computed with these parameters in the equivalent circuit. In short, the diode is internally a capacitive and low resistance circuit. To match its impedance to real 50 Ω, inductive L-network can be introduced at the diode input.

![Figure 3.3: Equivalent Linear Circuit Model of Diode]

The impedance matching network is responsible for a lossless transmission between the receiving antenna and the rectifier. Without impedance matching, the UHF energy will be reflected to the source and not delivered to the rectifier efficiently. This results in less DC output. In short, impedance matching is designed to prevent reflection loss at desired band, which will be shown in Chapter 4. Typically, the antenna is designed and terminated at 50Ω load. However, the impedance of a generic RF circuit module (e.g. transceiver modules, detector circuit) is not always at 50 Ω due to the reactance of the circuit components such as Schottky barrier diode, inductor and capacitor. The inductive and capacitive reactance of the circuits can be described by Equation 3.2 ad 3.3. To prevent energy reflection loss, a conjugate matching network is required to eliminate the reactance and match the impedance of the rectifier to 50 Ω.

\[
X_L = 2\pi f L \quad (3.2)
\]

\[
X_C = -\frac{1}{2\pi f C} \quad (3.3)
\]

The rectifier implemented in the proposed system architecture is a voltage doubler. Basically, the rectifier consists of Schottky barrier diodes and capacitors. It is
designed to operate at 2.4GHz ISM band to amplify the amplitude of the output voltage during rectification. The amplification is important because the signal strength of the WLAN energy is very low, which is predictably less than 100 mV$_{rms}$ when the receiver is further than 1 meter away from the transmitter. If a normal rectifier is used, the output DC level is inadequate to charge a commercial battery. Therefore, amplification is required to boost the voltage level to the battery requirement.

The output of rectifier is connected to the energy storage devices of this system, which are the commercial batteries. The interconnection between the rectifier and batteries is a pair of jumper wire. The Li-Po cell pack (3.7 V, 1100 mAh) from mobile phone and off the shelf rechargeable NiMH (1.2 V, 900 mAh) will be used in the prototype experiments.

### 3.2 Limitation of WLAN Energy Propagation

Generally, the EM energy radiated from WLAN is categorised as a low power energy radiation and the available receiving energy is very low in power, i.e. nanowatts or microwatts at several meters away from a transmitter. Monopole and dipole rod antennas are typically used as the radiators on the wireless networking devices. The lengths of these WLAN antennas are usually between 7 cm and 11 cm, which are about $\lambda/4$ or $\lambda/2$ long with 2 to 3 dBi gain. The radiated EM energy is omnidirectional unless special focusing apparatus is attached. The omnidirectional characteristic results in even energy spreading across its horizon and become very low in power when it reaches the receiver. This is the reason for networking hardware to boost the signal by using an amplifier integrated near to the microwave transceiver.

Theoretically, WPT is based on several parameters described by Equation 3.4, which is the Friis Transmission Equation [72]. The equation can calculate the available receiving power from the transmitting system. The parameters are transmitting antenna gain, receiving antenna gain, transmitting power, wavelength (operating frequency) and the distance between the antennas. The Friis equation is shown as follows.
\[ P_r = P_t \times G_r \times G_t \times \left(\frac{\lambda}{4\pi R}\right)^2 \]  \hspace{1cm} (3.4)

Where,

- \( P_r \) = received power (watt)
- \( P_t \) = transmitted power (watt)
- \( G_r \) = receiver gain (dimensionless)
- \( G_t \) = transmitter gain (dimensionless)
- \( R \) = Range (meter)
- \( \lambda \) = wavelength (meter)

The higher the transmitting power the higher the EM energy is at the receiver for a given distance and frequency. Referring to Equation 3.4, energy wave of higher frequency (i.e. shorter wavelength) will have a shorter propagating distance. The gain and radiation pattern of both sides will also affect the effective range and available DC power for the load. A larger antenna array will usually emit more directional radiation and the radiation will be more concentrated at elevation or azimuthal planes depending on the array structure. Directional beam can provide more energy to the rectennas at a given direction with best alignment. In other words, larger receiving WPT system has better reception from radiating source but the trade-off is narrower coverage. Equation 3.4 will be used throughout the numerical analysis in Section 3.3.
3.3 Analysis of Propagation Loss with FCC Compliance

Apart from the natural constraints in energy propagation, there are regulations that specify the limitation of WLAN energy. These regulations are defined by FCC in the USA [73]. In general, FCC provides two regulations to govern Point to Point (PTP) and Point to Multipoint (PTMP) operations. The advantage of PTP system is the greater transmitting power as compared to PTMP system. PTP operation allows the use of directional radiator whilst PTMP system only allows the use of omnidirectional radiator. Hence, both operation modes will be analysed and compared in this session. The objective of the analysis is to compute the distance where 10 mW of EM energy can be harvested by the receiver (i.e. rectifier input). In order to achieve effective commercial battery charging at a significant distance, it is necessary to push the distance where 10 mW of power can be harvested, to a distance further than 1 m from transmitter. The 10 mW requirement for battery charging will be explained in Chapter 4.2.4.

Generally, PTMP transmitter and power level is abided by FCC’s 36 dBm EIRP (4 W EIRP) and PTP transmitting power has to be reduced by 1 dB for every 3 dB increase in gain of the transmitter [73]. EIRP describes the amount of transmitting power required by an isotropic radiator to produce the maximum power observed at the direction of maximum gain of the referenced antenna. The formula is shown in Equation 3.5.

\[ \text{EIRP (dBm)} = P_t \text{ (dBm)} + G_t \text{ (dBi)} - L_c \text{ (dB)} \]  

(3.5)

Where,

- \( P_t \) = Transmitting Power
- \( G_t \) = Transmitter Gain
- \( L_c \) = Cable Loss

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver gain</td>
<td>( G_r )</td>
<td>Receiving power = ( P_r )</td>
</tr>
<tr>
<td>Transmitter gain</td>
<td>( G_t )</td>
<td>Transmitting power = ( P_t )</td>
</tr>
<tr>
<td>Distance</td>
<td>( R )</td>
<td>WLAN Frequency = 2.4 GHz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>125 mm</td>
<td></td>
</tr>
<tr>
<td>Power in FCC’s EIRP</td>
<td>( P_{\text{EIRP}} )</td>
<td></td>
</tr>
</tbody>
</table>
3.3.1 FCC’s PTMP Rules with Standard Dipoles as Transmitter and Receiver (36 dBm EIRP)

The first analysis is to analyse the lowest power available across 1 meter range from maximum allowable power. This distance is set because the typical distance between Personal Computer (PC) and wireless router (i.e. WLAN adapter) is less than 3 meters. Higher power is required for batteries in the consumer products whereas less for ordinary wireless data communication. Therefore, 1 meter is selected in this analysis for the proposed system. For any radiator with lower gain than a standard dipole, it will not be capable to deliver sufficient power for embedded electronics in milliwatts range unless the transmitting power is increased. Therefore, the transmitting and receiving antennas in this case are assumed to possess the standard gain of a dipole, i.e. approximately 2.2 dBi. The maximum permitted $P_t$ is 1 W (i.e. 30 dBm) and the maximum EIRP is limited at 4 W (i.e. 36 dBm). Hence, a standard transmitting dipole under this regulation will result in 32.2 dBm of EIRP. In this condition, the receiving power versus distance is shown in and Figure 3.4.

![Receiving Power Analysis by using Standard Dipoles as Transmitter and Receiver](image)

Figure 3.4: Receiving Power Analysis by using Standard Dipoles as Transmitter and Receiver

(FCC’s PTMP 1 W $P_t$ Standard)

As referred to Figure 3.4, 10 mW ($P_r$) is available at 16 cm away from transmitter. This range is too close to implement WPT system and fairly inconvenient in practical. There is no useful power beyond 50 cm because the predicted receiving power is effectively less than 1 mW. This amount of power is insufficient to perform efficient battery charging for most commercial batteries which has large capacity and 5 V
requirement unless special rechargeable battery that is compatible with very low charging current is used. As conclusion, low gain omnidirectional antennas are not suitable to be used for WPT applications. The next section will show the analysis of using higher gain transmitting dipole.

3.3.2 FCC’s PTMP Rules with Higher Gain Transmitting Dipole (36 dBm EIRP)

Since the maximum EIRP is 4 W (36 dBm) and $P_t$ cannot be higher than 1 W (30 dBm), $G_t$ can be set to 6 dBi to reach the maximum EIRP, i.e. $(30 + 6)$ dBm. The FCC’s PTMP rules stated that the $P_t$ has to be reduced by 3 dB for every 3 dB increment in $G_t$ to maintain a $P_t$ of 36 dBm EIRP [74]. With this rule, the $P_r$ will always be the same at one point because the reduction and increment in $P_t$ and $G_t$ by 3 dB produces a constant EIRP. In this case, another variable is added into the analysis of this rule, which is the distance. The standard $G_r$ of dipole (2.2 dBi) is reused throughout the analysis and $P_r$ versus $R$ is plotted in Figure 3.5. The analysis starts by setting $P_t$ and $G_t$ to 30 dBm and 6 dBi respectively on the first data point and then applies the rule on the subsequent points. The graph shows a similar trend as the previous section.

![Figure 3.5: Receiving Power Analysis by using Higher Gain Transmitting Dipole (FCC’s PTMP 36 dBm EIRP Regulation)](image)

In this case, 10 mW of WLAN power can be obtained at about 25 cm away on the 4th data point. At that point, the $G_t$ is 15 dBi and $P_t$ is 21 dBm. There is no effective
electric power for effective battery charging at further than 80 cm because the $P_r$ is lower than 1 mW. Moreover, an omnidirectional WLAN transmitter with gain higher than 15 dBi might be too bulky as compared to the size of consumer portable devices. For instance, 15 dBi Wi-Fi dipoles manufactured by OEM is about 100 cm long [75]. As a result, high gain omnidirectional transmitter is also unsuitable for the proposed WPT system in this case. Using high gain receiving dipole will be an option to overcome this problem.

### 3.3.3 FCC’s PTMP Rules with Higher Gain Transmitting and Receiving Dipoles

Since 36 dBm EIRP from omnidirectional transmitter is insufficient, increasing the gain of receiving dipole may be an option. Here, calculation from Section 3.3.2 is repeated by starting $G_r$ at 2.2 dBi and increment by 3 dB for each computation. The $G_t$ and $P_t$ are set to 6 dBi and 30 dBm respectively (i.e. 36 dBm EIRP) throughout the numerical iteration. The distance of receiver is fixed at 1 meter and the results are shown in Figure 3.6.

![Graph](image)

**Figure 3.6:** Receiving Power Analysis by using Higher Gain Transmitting and Receiving Dipoles

(FCC’s PTMP Rule at 36 EIRP Regulation)

As presented in Figure 3.6, the $G_r$ of omnidirectional receiver has to be higher than 14 dBi, in order to harvest 10 mW at 1 m distance. Theoretically, the overall gain will increase by 3 dB when the amount of radiator in an array is doubled [76] (i.e.
collinear stack array). Thus, a typical receiving collinear dipole array that provides 14.2 dBi will require more than 10 elements. Using standard printed dipole (i.e. \( \lambda/2 \) in size) as example, this is equivalent to a well-tuned rod dipole that is longer than 1 m [75] or a 642 cm\(^2\) patch antenna [77]. In conclusion, it is difficult to fit an antenna of 14.2 dBi gain into consumer product. This is possible only if each element in the array is well decoupled to reduce overall board size of the array. A prototype with decoupling characteristic will be shown in Chapter 6. In short, this case is also not recommended for WLAN WPT application due to the size limitation on receiving antenna. The PTP operation could be a better consideration because higher EIRP is permitted.

### 3.3.4 FCC’s PTP Rules with Standard Dipole and Directional Transmitter

FCC has stated that the PTP transmitting power has to be reduced by 1 dB for every 3 dB increase in directional gain [73]. This is an advantage because longer range of transmission has become possible with the use of directional radiator such as horn, patch and other linear arrays. By applying this rule and analyse with standard receiving dipole (\( G_r = 2.2 \) dBi), the \( P_r \) versus \( G_t \) at 1 meter distance is presented in Figure 3.7. The \( P_r \) is higher than 1 mW if \( G_t \) is about 9 dBi and above. This power range is sufficient for micropower electronic applications only. Nevertheless, the \( P_r \) did not reach 10 mW even with a 20 dBi transmitter. Undoubtedly, directional receiver with higher \( G_r \) is necessary.

![Figure 3.7: Receiving Power Analysis by using Standard Dipole and Directional Transmitter (FCC’s PTP Regulation)](image)
3.3.5  **FCC’s PTP Rules with Directional Receiver and Transmitter**

Similar to the previous section, this section analyses the effect of using high gain directional receiver and transmitter. Results are presented in Figure 3.8. Both $G_r$ and $G_t$ must be roughly 11.2 dBi and 15 dBi respectively in order to harvest 10 mW over 1 m. For lower power consumer electronics such as remote controls that require far below 10 mW a 5 dBi receiver can be used to harvest a few milliwatts for direct powering up.

![Figure 3.8: Receiving Power Analysis by using Directional Receiver and Transmitter (FCC’s PTP regulation)](image)

In conclusion, FCC’s PTMP regulation is feasible only if larger radiator size is not an issue. In comparison, the FCC’s PTP regulation has higher potential to be applied in WPT system since higher EIRP is allowed. However, WLAN system is a PTMP system. High gain receiver can be used to increase the harvested power from a PTMP system. As a result, the maximum transmitting EIRP of 36 dBm under FCC’s PTMP regulation is implemented for every rectenna experiment. The transmitting setup consists of a 9 dBi directional antenna with 27 dBm transmitting power.
3.3.6 The Common Radiator in Australia

In Australia, the gain provided by commercial omnidirectional WLAN transmitter is commonly found between 2.2dBi and 15 dBi. Transmitters with higher gain than 7 dBi are intended to be used on vehicle or specifically for inter-building applications. Radiators with over 15 dBi are used for inter-region (neighbourhood) communication. Generally, the extended Wi-Fi antenna for PCs and laptops is about 5 dBi. Referring to Section 3.3.3, an antenna of 14 dBi is recommended if the WLAN transmitter is an omnidirectional antenna for FCC’s PTMP system. However, such omnidirectional antenna is bulky and inconvenient to be used together with consumer products.

There is also a wide range of directional radiators in Australia. The gain of these antennas is usually between 8 dBi and 20 dBi. The antenna with gain higher than 10 dBi are comparatively bulky (i.e. >30 cm in length or width) and only used for outdoor long range applications. However, if a WPT system is intended to be implemented, high gain directional radiator is the better choice at 2.4 GHz ISM band, given that the location of receivers are known. This is because multiple rectenna can be used to harvest the recommended level of $P_r$ for battery trickle charging.

3.4 Health Concern

The EM energy harvesting system utilises EM radiation at 2.4 GHz (UHF band) as the energy carriage. The EM radiation at UHF is considered as thermal radiation, which is used in microwave oven to heat food. The common concern of the public is the long term health effect of irradiation from base stations and wireless communication hotspots. Since the strength of RF is strongest at its transmitting source, access to the transmitting station and area near to the transmitter is restricted. Considering low exposure levels, there is no convincing scientific evidence that the weak RF radiation from WLAN can cause severe health effect [78].

There is another issue that have been reported to be the cause of various health problems related to the EM exposure. It is termed as EM Hypersensitivity (EHS) and is able to afflict individuals attribute to exposure to EM radiation [79]. According to World Health Organisation (WHO), EHS can be characterised by a variety of symptoms. However, there is no firm scientific proof to link EHS symptoms to EM exposure.
The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has given result of 7 exposed subjects. Averagely, the subjects were exposed for 45 minutes and they can accommodate whole body 2.45 GHz RF heat loads up to several watts per kilogram (i.e. unit of Specific Absorption Rate - SAR) with minimal changes in core temperature [80]. Under high SAR (i.e. \( \sim 6 \text{ W/kg}^{-1} \)) dorsal exposure, the skin blood flow is increased and profuse sweating is observed. Moreover, it has also stated that exposure to RF pulses will increase skin temperature more than that of the continuous wave. A SAR threshold of 4 W/kg for adverse effect [81] is derived in the guideline. In [81], the whole body SAR for controlled and uncontrolled environment must be less than 0.4 W/kg and 0.08 W/kg respectively. For partial body exposure, the SAR level can be 20 times larger than the whole body standard. Moreover, the FCC limits for Maximum Permissible Exposure (MPE) under controlled and uncontrolled scenarios are 5 mW/cm\(^2\) (< 6 minutes) and 1 mW/cm\(^2\) (< 30 minutes) respectively. The power density of a non-isotropic transmitter is given by Equation 3.6.

\[
P_{\text{density}} = \frac{P_t \times G_t}{4\pi R^2} \tag{3.6}
\]

Where,
Transmitter linear gain = \( G_t \)
Transmitting power (mW) = \( P_t \)
Distance (cm) = \( R \)

In short, a WPT system is considered safe if the power density and SAR level are much lower than FCC’s regulations. For example, wireless communication systems abide by FCC’s PTMP rule is already in compliance with these safety standards. Under FCC’s PTP rule, the power density at 20 cm away from a transmitter with 36 dBm EIRP is about 0.8 mW/cm\(^2\). Although the power density is below the restriction, it is recommended to keep further clearance distance after leaving the portable devices for wireless battery charging.
3.5 Conclusion

This chapter presents the system architecture of the proposed WPT system. The system consists of an energy source, harvester and an energy storage component, which is proposed specifically to meet the research goals. The harvester is known as the rectenna, which is proposed to have three components rather than five components in a conventional approach. The three components include miniaturised printed dipole antenna, impedance matching network and Villard’s Voltage Doubler (VVD). The load of the proposed design is the commercial batteries rather than resistor in traditional design. Miniaturised antenna is essential to achieve low profile requirement for comparatively small consumer devices. The VVD rectifier is required to meet the voltage requirement of consumer electronics. The equivalent circuit of such rectifier is capacitive in UHF band. As a result, impedance matching network is the critical component to ensure the least transmission loss between the antenna and rectifier circuit.

Additionally, this chapter has also included the limitation of WLAN energy propagation due to the propagation loss as defined by Friis’ Transmission Equation. Several numerical computations have been presented in accordance with the different antenna gain and travel distance to understand the relationship between the equation parameters. Lastly, a summary on health concern regarding the radiation exposure is given at the end of this chapter.
CHAPTER 4: RECTIFIER FOR 2.4 GHz ENERGY HARVESTING SYSTEM

This chapter presents several rectifier designs for the proposed WLAN energy harvesting system. An appropriate rectifier will be selected based on the conversion efficiency from AC voltage to DC voltage. This includes the detailed analysis of various rectifier designs using computer simulation as well as experimental study. A typical rectifier consists of a circuit with either one or two Schottky barrier diodes to perform high frequency rectification.

One of the original contribution of this chapter is the performance comparison of different rectifier circuits using the same Schottky barrier diode (HSMS 286C). Different model of Schottky diodes has different characteristics. When they are used in the system with different input parameters, the DC conversion efficiency varies, as in [60, 62, 63, 82]. As a result, Section 4.1 presents a comprehensive performance comparison of four typical rectifier circuits using the same Schottky diode. The rectifier circuit with highest DC conversion efficiency from the specific input parameters will be used in the rectenna design in Chapter 6. Another contribution is the design of highly efficient rectifier with simple architecture. The rectifier is capable to provide highest DC conversion efficiency among the similar designs [60, 62, 63, 82] tested under limitation of uncontrolled environment [81]. It has only three components. The impedance matching is achieved by microstrip meander network, which has the advantage of low profile integration into rectenna modules in Chapter 6. The final contribution of this chapter is the experimental results of commercial battery charging using the selected highly efficient rectifier. The design technique and experimental results from this chapter will be useful in WPT technology.

In the following sub-chapters, a general introduction of rectifier will first be presented and follow by the detailed description of each rectifier circuit. All the prototypes are etched on RT/duroid 5880 microwave substrate with a thickness of 0.787 mm. The circuit simulations are analysed by using the Agilent's Advance Design System (ADS). The ADS is chosen because of its excellence features such as flexibility in schematic and layout editing and time efficient simulation. The detail parameters of Avago’s diodes that are used in all rectifier circuits can be obtained directly from the component library in ADS.
Direct impedance matching of rectifier to off-the-shelf NiMH batteries and Li-Po cell packs will also be presented. This is necessary to determine the applicability and performance of battery charging with microwave rectifier at low input power. Comparison and measurement results will be presented at the end of this chapter. In short, the rectifier selection process that was used in this study is depicted in Figure 4.1. The power source, DC load are kept constant throughout the process. Different rectifier designs will be investigated in order to identify the rectifier with highest output.

![Flowchart of Rectifier Selection Cycle]

**4.1 Analysis of Rectifier Designs for 2.4 GHz Microwave Application**

The rectifier in a rectenna circuit is theoretically identical to any existing rectifier except that the system is operating at microwave frequency and the bulky parts are replaced by surface mount components (SMC) for microwave applications. Therefore, these rectifiers are also commonly known as microwave rectifiers. Four microwave rectifiers which are listed in Table 4.1 will be presented. These rectifiers are the most frequently used as described in Chapter 2. Therefore, this is the reason of analysing the performance of these four microwave rectifiers altogether. Simple
optimisation with microstrip technology will be presented later to identify the rectifier with better performance for the proposed 2.4 GHz WPT system.

<table>
<thead>
<tr>
<th>Rectifier Design</th>
<th>Typical Application</th>
<th>Number of Capacitor</th>
<th>Number of Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series diode half-wave rectifier</td>
<td>Microwave Detector Diode [83]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Shunt diode half-wave rectifier</td>
<td>Differential-mode Half-wave Rectifier [44, 46, 49]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Single capacitor voltage doubler</td>
<td>Voltage doubler [84]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dual capacitor voltage doubler</td>
<td>Voltage doubler [62]</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.1: Four Typical Microwave Rectifiers

The series diode half-wave rectifier is a generic circuit commonly found in wireless communication devices. It is usually used as the detecting diode connected to the receiving antenna to recover modulated signal. The shunt diode half-wave rectifier is usually used in the low cost printed rectenna designs to rectify the incident microwave energy. The receiving antenna for such rectifier is usually a balance mode radiator that utilises differential mode coplanar striplines (CPS).

Besides, two voltage doubling rectifiers are also included in the analysis. Voltage doubler is an amplitude amplifying circuit that uses dual diodes. The first voltage doubler is a rectifier with dual diodes chip and single capacitor. The second voltage doubler with dual diodes chips and capacitors is Villard’s voltage doubler, or also known as Cockcroft-Walton voltage multiplier. Villard voltage doubler is a well defined single stage voltage doubler that doubling the amplitude of input signals.

Most of the microwave rectifiers use Schottky barrier diode for rectification because it has a low forward voltage (e.g. $V_f \sim 0.2$ V) and high frequency switching capability.
The input power ($P_{\text{in}}$) to the rectifier is measured in dBm or milliwatts and is typically terminated at 50 $\Omega$ line. The power received ($P_{r}$) by the rectenna can be calculated by using Friis’ Transmission Equation and Ohm’s law to estimate the adequacy of the input voltage for rectification.

The four microwave rectifier circuits are shown in the Figure 4.2. Rectifier in Figure 4.2 (a) is a common microwave detector circuit found in many microwave applications such as RFID and wireless receiver [82, 85, 86]. Rectifier in Figure 4.2(b) can be found in most of the rectenna designs at earlier time due to simplicity [44, 46, 49]. Figure 4.2(c) [84] and (d) are voltage doublers [62].

Design simulations with Agilent’s ADS will be performed to estimate the conversion efficiency of each rectifier. The substrate used is the Roger/duroid 5880 ($\varepsilon_r = 2.2$, Thickness = 31 mils) and results are presented in the following sections.

### 4.1.1 Series Diode Half-Wave Rectifier

Series diode half-wave rectifier made up of a diode and a capacitor. The rectifier blocks the negative half cycle. Without optimisation on the microstrip in the circuit,
this rectifier can only supply a maximum of 0.779 V to the load. In order to improve the efficiency of the rectifier, optimisation can be performed to the circuit as depicted in Figure 4.3. As referred to Figure 4.3(a), a microstrip of 17 mm (0.1856 λ) can be added to improve the $V_{DC}$ from 0.779 V to 1.076 V. This equals to 48.24% of DC conversion efficiency, which is given by

$$P_{eff} = \frac{P_{DC}}{P_{in}} \times 100\%$$  \hspace{1cm} (4.6)

$$P_{DC} = \frac{V_{DC}^2}{R_{load}}$$  \hspace{1cm} (4.7)

*eff = efficiency

---

**Figure 4.3:** Simulated $V_{DC}$ of Series Diode Half Wave Rectifier

(a) Microstrip before diode (b) Microstrip after diode
(c) Microstrip before and after diode
The microstrip is inductive and it matches the capacitive rectifier circuit towards the real part of impedance. This reduces the reflection loss in the transmission line of the rectifier circuit and helps to improve the AC to DC conversion efficiency. Alternative improvement can be performed by adding a microstrip of 12 mm long between diode and capacitor as shown in Figure 4.3 (b). This results in 1.031 V at the load. Combination of Figure 4.3 (a) and Figure 4.3(b) will give better output and yields 1.166 V at the load in Figure 4.3 (c). Besides, it is found that when microstrip delay is created between the capacitor and the load, the $V_{DC}$ drops and the ripples increase. Hence, the $R_{load}$ must be as close as possible to the capacitor.

4.1.2 Shunt Diode Half Wave Rectifier

Shunt diode half wave rectifier is popular since the introduction of the SPSS concept as described in Chapter 2. This rectifier implements the theory of travelling wave in order to perform AC to DC rectification. A thorough analysis for this type of rectifier with Schottky barrier diode from different manufacturer can be found in [46, 48]. In Figure 4.2 (b), the Schottky diode is located adjacent to the feed point and followed by a charging capacitor. Similarly, the circuit can be realised as illustrated in Figure 4.4. Assuming the input voltage is the sine wave as described in Figure 4.4 (a), the voltage level in the capacitor is indicated in Figure 4.4(b) to Figure 4.4(f) for both effective and ineffective rectification implementing shunt diode configuration.

Effective rectification using shunt diode is described in Figure 4.4(b) to Figure 4.4(e). After first cycle in Figure 4.4 (e), the rectification output repeats from Figure 4.4(b) again. The optimising solution is to keep a distance between the charging capacitor and the diode in order to create a 90° electrical delay in between. This can prevent the charges in the capacitor from neutralisation during the AC cycling. Apart from that, the inductance of the microstrip can counteract the capacitor reactance and yields higher efficiency. An appropriate schematic for this rectifier is depicted in Figure 4.5. As referred to Figure 4.5 (a), it is found that 0.2222 λ (20 mm) of distance will provide highest $V_{DC}$ (0.386 V) to the load.

Ineffective rectification using shunt diode is illustrated in Figure (f) where the distance between diode and capacitor is much less than 90° apart. In this case, the $V_{C}$ is approximately zero because the negative half cycle (same amplitude as positive half
cycle but with inverse polarity) is unable to forward-bias the diode in time before it neutralises the charges in capacitor that is accumulated during the positive half cycle.

Besides, an equivalent differential-model can be found in [52] where the shunt diode and the capacitor are separated by a differential pair or coplanar stripline (CPS) of 9.5 mm in length. The circuit model is presented in Figure 4.5 (b). In [52], the length of 9.5 mm is equivalent to 92°-93° of electrical length at 5.8 GHz on the selected substrate. By comparison, 9.5 mm is about 0.2581 λ on the substrate used in [52], which is close to result in Figure 4.5 (a). In short, a microstrip with 0.20 λ to 0.26 λ in length is able to optimise the performance of shunt diode rectifier. Besides, this rectifier is convertible between common mode and balance mode circuit depends on the characteristic of antenna input port. For example, a differential-mode will work well with a balance dipole whilst the common-mode configuration is suitable for patch antenna, which has a microstrip feed on the ground plane.
Figure 4.4: Operation of Shunt Diode Rectifier

(a) Input sine wave (b to e) Effective rectification (f) Ineffective rectification
4.1.3 Voltage Doubler: Dual Diode with a Capacitor

A dual diodes voltage doubler with only single capacitor is unpopular. However, [84] has implemented this rectifier with a spiral monopole attached to it. Another similar implementation is found in [60]. Hence, an investigation on the performance of this rectifier is required to compare its performance with the Villard’s voltage doubler in next section. The schematic looks like a combination of Figure 4.5 (a) and 4.3 (b). However, the performance is not the summation of both. The first diode does not contribute in rectifying the P_in whilst the second diode operates exactly like Figure 4.3 (b). This is because the negative half cycle will not charge the capacitor efficiently but returns to the source when the shunt diode is forward biased. Improvements are shown in Figure 4.6 (a), (b) and (c).

Microstrip can be added before and after the dual diode chip. The highest simulated V_DC is 0.930 V as indicated in Figure 4.6 (b). This configuration is very suitable for low profile integration since it can be fed with shortest possible microstrip at the input and only 12 mm of microstrip inductance is required for impedance transformation. If the input microstrip line is not maintained shortest possible, the performance deteriorates and the next peak V_DC will require a microstrip of 40 mm, as shown in Figure 4.6 (c).
Figure 4.6: Simulated $V_{DC}$ of Voltage Doubler

(a) Microstrip before diode
(b) Microstrip after diode
(c) Microstrip before and after diode
4.1.4 Villard’s Voltage Doubler: Dual Diode and Capacitors

Schematic in Figure 4.2(d) depicts a single stage Villard’s voltage multiplier or often known as the Villard’s Voltage Doubler (VVD) [87]. It is formed by combining two sets of half wave rectifiers in a cascading structure and the VDC can be charge-pumped by the D-C (Diode-Capacitor) pair. In this structure, each pair rectifies half cycle. The capacitor nearest to the R_load will hold the total charges accumulated by each D-C pair. However, the rise of VDC will not be significant if there are too many D-C stages. This is due to the component loss and low amplitude at Pin from UHF signal. Hence, only single multiplying stage is considerable for this WLAN energy harvesting application.

The schematics are shown in Figure 4.7(a) and Figure 4.7(b), where microstrips are included between components. The best configuration is depicted in Figure 4.7(b), which is able to achieve highest VDC at 1.151 V. The microstrip lines required for efficient charging and impedance transformation are shorter as compared to the other configurations. As a result, this configuration has the potential to allocate smaller footprint. The merit of smaller form factor is significant because multiple rectifiers are essential in rectenna array design later.

![Schematic of Villard’s Voltage Doubler](image_url)

**Figure 4.7:** Simulated VDC of Villard’s Voltage Doubler
(a) Microstrip before diode (b) Microstrip before and after diode
### 4.1.5 Comparison of Simulation Results of Four Rectifiers

Four rectifier configurations have been analysed with ADS and the results are tabulated in Table 4.2. Evidently, single diode configurations are subjected to board space constraint. It requires larger board space for efficient rectification. Although majority of papers from Chang’s group are proposing the shunt diode rectifier in differential-mode rectenna design [47-51, 53-55, 88], these microstrip networks occupy larger board space as compared to the rectifying circuit. Replacement by using discrete SMC may resolve this issue but the cost will be increased. In contrary, dual diode chip does not require very long microstrip. Although this results in higher diode cost, the board size is small.

<table>
<thead>
<tr>
<th>Single Diode</th>
<th>Max $V_{DC}$</th>
<th>Required Microstrip Dimension</th>
<th>$V_f$ per cycle</th>
<th>$I_{leak}$ per cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series diode half wave rectifier</td>
<td>1.166V</td>
<td>&gt;29mm × 1 mm</td>
<td>Once</td>
<td>Once</td>
</tr>
<tr>
<td>Shunt diode half wave rectifier</td>
<td>0.386V</td>
<td>&gt;20mm × 1 mm</td>
<td>None</td>
<td>Once</td>
</tr>
<tr>
<td><strong>Dual Diode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single capacitor voltage doubler</td>
<td>0.930V</td>
<td>12mm × 1 mm</td>
<td>Once</td>
<td>Once</td>
</tr>
<tr>
<td>Dual capacitor voltage doubler</td>
<td>1.151V</td>
<td>12mm × 1 mm</td>
<td>Twice</td>
<td>Once</td>
</tr>
</tbody>
</table>

Table 4.2: Comparison of Four Typical Rectifiers

* $V_f$ = forward voltage consumed during DC charging, $I_{leak}$ = leakage current

According to Table 4.2, the maximum $V_{DC}$ of the best single diode and dual diode rectifiers are reasonably close. This is due to the RF signal characteristic and diode switching loss. In household power line, the AC is at low frequency (LF), which is 50 Hz. The power transformation circuit in the power supply unit (PSU) usually contains bulky solid-capacitors to store large amount of charges. However, the AC current at gigahertz band (UHF) is alternating much faster than the regular AC. When the incident UHF sinusoidal waveform is rectified and the half-cycle pulses reach the capacitor, it appears as constant amplitude (e.g. ultra high frequency DC pulses) to the capacitor. The capacitor will charge up to the level contributed by these small pulses. However, portion of the energy has been dissipated as $V_f$ and $I_{leak}$ (leakage current during reverse bias) in the switching mechanism. The $I_{leak}$ will neutralise the charges during the reverse bias of the diode. Evidently, the loss of $V_f$ and $I_{leak}$ across
dual diodes model are higher than single diode model during high frequency rectification. The \( V_f \) per cycle does not exist in shunt diode configuration because the capacitor is charged up by the input current without passing through the diode. Additionally, diodes from different IC manufacturer have different performance. As a result, the conversion efficiency between single and dual diodes rectifiers is seen similar in this case when \( P_{in} \) is very low. However, the \( V_{DC} \) of dual diodes rectifier will increase exponentially and surpasses single diode model when the \( P_{in} \) is higher than 1 mW. This is because the loss will become insignificant as compared to the larger \( P_{in} \). Besides, Strassner's has provided information regarding the rectifying output across a wide range of \( P_{in} \) [51]. The rectification efficiency can always reach higher than 80% easily at input power higher than 100 mW.

Another issue from the single diode rectifier is regarding the output ripple. This phenomenon can be easily overcome by using larger capacitor for a smoother DC. This increases the cost and results in several milliseconds of delay to reach the peak \( V_{DC} \). However, a split second of delay is realistically insensible. Another solution to remove the output ripples is by reducing the distance between the load and the charging capacitor e.g. less than 5 mm beside the capacitor. Otherwise, an extra filter and regulator will be required in consumer products to remove the ripples.

As conclusion, the section explains the characteristics and reveals the performance of four typical microwave rectifiers by using the same diode. Among single and dual diode rectifiers, the shunt diode rectifier and VVD are selected for further experimental analysis. Shunt diode is selected because it is the most commonly used rectifier since SPSS is introduced and suitable to be the reference design to the VVD. They are prototyped and examined in the next section.

4.1.6 Experimental Analysis of Shunt Diode Rectifier and Villard’s Voltage Doubler

The shunt diode rectifier and Villard’s voltage doubler are selected for prototyping and measurements. Layouts are presented in Figure 4.8 whilst Table 4.3 indicates the detail dimension of the prototypes. In the experiment, the single shunt diode rectifier is fabricated as the reference design. In order to investigate the potential to be smaller form factor, three Villard’s voltage doublers prototypes with different
length of ‘b’ are fabricated for performance comparison. Table 4.4 shows the measured $V_{DC}$ when $P_n$ is 10 dBm.

Figure 4.8: Prototypes of Shunt Diode Rectifier and Villard Voltage Doubler

(a) Villard’s Voltage Doubler (b) Shunt Diode Rectifier

<table>
<thead>
<tr>
<th>Villard’s Voltage Doubler</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>d</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shunt Diode Rectifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
</tr>
<tr>
<td>f</td>
</tr>
<tr>
<td>g</td>
</tr>
</tbody>
</table>

Table 4.3: Detailed Dimension of the Prototypes in Figure 4.8

*0 $\lambda$ indicates the shortest possible distance

<table>
<thead>
<tr>
<th>Villard’s Voltage Doubler</th>
<th>DC Conversion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>b = 0.5 $\lambda$</td>
<td>0.75 V</td>
</tr>
<tr>
<td>b = 0.25 $\lambda$</td>
<td>1.01 V</td>
</tr>
<tr>
<td>b = 0 $\lambda$</td>
<td>1.07 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shunt Diode Rectifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>f = 20 mm</td>
</tr>
</tbody>
</table>

Table 4.4: Measured $V_{DC}$ when $P_n$ = 10 dBm

*0 $\lambda$ indicates the shortest possible distance
Experiment measurements in Table 4.4 shows that VVD have outperformed shunt diode rectifier with much smaller board size. The measured $V_{DC}$ (i.e. 1.07 V) is close to the simulated result of 1.151 V. Besides, the discrete components of Villard’s voltage doubler can be very compact whereas this is impossible to shunt diode rectifier because an approximately $0.2 \lambda$ of delay microstrip is essential between charging capacitor and Schottky diode. Therefore, VVD can provide the smallest form factor and highest efficiency among four rectifiers.

Apart from that, the experimental measurements in Figure 4.9 reveal the changes in $V_{DC}$ from $P_{in}$ variation. Apparently, voltage doubler can produce higher voltage than shunt diode rectifier when $P_{in}$ increases. The different in $V_{DC}$ is getting obvious when $P_{in}$ is larger than 13 dBm (20 mW). In conclusion, Villard’s cascade voltage doubler has higher $V_{DC}$ with comparatively smaller board size. Although dual diode chip cost higher, it produces higher the voltage level occupies smaller board size. Therefore, this is suitable for WLAN energy harvesting application and it will be used as the rectifier throughout this research and rectenna development. The next section will introduce the actual prototype this rectifier to be examined with various type of loads.

![Figure 4.9: Measured $V_{DC}$ with Increasing $P_{in}$](image)
4.2 Villard’s Voltage Doubler with Various Loads

The fundamental experiment of VVD reflects higher performance than other configurations. As a result, it is selected as the core rectifier of all the rectenna design in this research. However, the optimum performance of VVD with realistic load remains unknown. Therefore, design and experiment of VVD with various typical loads are presented here. These loads include regular resistor, low dropout (LDO) voltage regulator, off the shelf NiMH rechargeable battery and Li-Po cell packs. A summary of peak efficiency achieved by VVD with different loads and input power ranged from 0 dBm to 10 dBm is shown in Table 4.5.

<table>
<thead>
<tr>
<th>Loads</th>
<th>$P_{\text{eff}}$ Achieved (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive load</td>
<td>68.7</td>
</tr>
<tr>
<td>LDO Regulator</td>
<td>35</td>
</tr>
<tr>
<td>NiMH Batteries</td>
<td>74</td>
</tr>
<tr>
<td>Li-Po Cell Packs</td>
<td>74</td>
</tr>
</tbody>
</table>

Table 4.5: Peak efficiency of VVD with Various Loads and $P_{\text{in}}$ ranged from 0 dBm to 10 dBm

The input impedance of Villard’s voltage doubler ($Z_{\text{rec}}$) varies when the load changes. However, the input impedance of an antenna ($Z_{\text{ant}}$) at microwave frequency band is usually terminated at 50 $\Omega$. Therefore, the $Z_{\text{rec}}$ has to be transformed to 50 $\Omega$ in order to match $Z_{\text{ant}}$ to prevent energy reflection loss. In this section, the impedance matching design and performance of Villard’s voltage doubler with four different loads are presented in detail. Common matching techniques include discrete LC network such as L-network, $\pi$-network, or T-network. Owing to the advancement in microstrip technology, high frequency matching networks can be designed with microstrips. In this section, a microstrip L-network is implemented to match the rectifier with different loads to 50 $\Omega$. 
4.2.1 Villard’s Voltage Doubler with Resistive Load

The circuit layout and experimental setup of the first VVD (known henceforth as Rectifier-A) are presented in Figure 4.10. The $Z_{\text{rec}}$ can be obtained by simulation verify by direct measurement, and then matched to 50Ω by using shorted stub and meander line. The meandered microstrip is 0.2 mm in width only. The compact layout is preferred ad emphasised because all the rectifier is aimed to integrate into the antenna without the requirement of extra board space. The capacitors are commercial SMC chip capacitor sized at 0402, which represents (40 × 20) mils. The component pads are in smallest possible size in order to reduce unnecessary reactance from the solder joins.

![Diagram of Villard’s Voltage Doubler with Resistive Load](image)

Figure 4.10: Experiment Setup for Rectifier-A with Potentiometer (Pin <0 dBm)

a = b = 0.35 mm diameter via, c = 1.54 mm, capacitor size = 0402,

Meander line width = 0.2 mm, meander line spacing = 0.3 mm,

VIA patch = 1.4 mm × 1.4 mm, SMA pin pad = 0.85 mm × 1 mm,

SMD capacitor pad = 0.5 mm × 1 mm

The rectifier output is connected to a 10 kΩ potentiometer and the entire circuit is analysed by Agilent’s ‘E5071B 300 kHz - 8.5 GHz’ Vector Network Analyser (VNA). In this experiment, the $P_{\text{in}}$ is set to three values, which are 0 dBm, 5 dBm and 10 dBm. These values are selected as the reference $P_{\text{in}}$ because it is the amount of EM energy (2.4 GHz ISM band) available within 1 meter according to the analysis in Chapter 3. The Schottky diode is a non-linear device. Hence, the $Z_{\text{rec}}$ changes when the $P_{\text{in}}$ varies. Therefore, the potentiometer is used to tune the impedance locus of these three cases ($P_{\text{in}} = 0, 5, 10$ dBm) to the prime centre of the Smith Chart. With this method, a perfect match point can be obtained. By setting the perfect match
point as the single output, a constant $V_{\text{DC}}$ can be obtained across the resistor to compute $P_{\text{eff}}$. The overall $P_{\text{eff}}$ of Rectifier-A are summarised in Table 4.6. The central frequency is not at 2.45 GHz due to simulation and fabrication error. Minor tuning in the microstrip L-network is performed to correct the central frequency later in the design of Rectifier-B.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$P_{\text{in}}$ (dBm)</th>
<th>$P_{\text{in}}$ (mW)</th>
<th>$V_{\text{DC}}$ (V)</th>
<th>$R_{\text{Load}}$ ($\Omega$)</th>
<th>$P_{\text{eff}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6325</td>
<td>0</td>
<td>1</td>
<td>2.154</td>
<td>7.88k</td>
<td>58.9</td>
</tr>
<tr>
<td>2.6568</td>
<td>5</td>
<td>3.162</td>
<td>4.54</td>
<td>9.47k</td>
<td>68.7</td>
</tr>
<tr>
<td>2.671</td>
<td>10</td>
<td>10</td>
<td>7.7</td>
<td>9.74k</td>
<td>60.9</td>
</tr>
</tbody>
</table>

Table 4.6: DC Conversion Efficiency of Rectifier-A with Resistive Load

4.2.2 Villard’s Voltage Doubler with LDO Regulator

Most of the consumer electronics are built in with input voltage regulator. Therefore, the performance of microwave rectifier with voltage regulator has to be investigated. In this section, the Rectifier-A is connected with a low dropout (LDO) adjustable micropower voltage regulator manufactured by Linear Technology. The LDO regulator is commonly implemented inside the low power handhelds and its function is to regulate the input $V_{\text{DC}}$ of the device. The schematic and layout of the LDO regulator are included in Appendix A.

The measured $Z_{\text{rec}}$ of Rectifier-A with LDO regulator is depicted in Figure 4.11 and the measured $S_{11}$ magnitude is presented in Figure 4.12. Due to the use of different load, the LDO regulator has changed the $Z_{\text{rec}}$ by a minor degree, which leads to impedance mismatch. However, the rectifier can be rematched to 50 $\Omega$ (typical input impedance of RF system) without difficulty by manipulating the $P_{\text{in}}$. According to Figure 4.11, the perfect matching occurred when $P_{\text{in}} = -7$ dBm (200 $\mu$W). The $P_{\text{in}}$ is adjusted to obtain the range of $P_{\text{in}}$ which falls within the circle of SWR = 2 (i.e. $S_{11} \approx -10$ dB). The maximum and minimum $P_{\text{in}}$ that match 2.4 GHz ISM band on the boarder of SWR = 2 are -12 dBm and -2 dBm respectively. Therefore, the effective $P_{\text{in}}$ for this rectifier with this specific load is from -12 dBm to -2 dBm. During the tuning process, it is observed that the adjustable resistor connected at the output of the LDO regulator is isolated from the rectifier and its variation did not affect $Z_{\text{rec,LDO}}$. 

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This implies that an arbitrary load can be used at the output of LDO regulator without affecting the impedance of this rectifier.

Figure 4.11: Measured $Z_{\text{rec,LDO}}$ of Rectifier-A with Regulator from 1 GHz to 8 GHz when $P_{in} = -12$ dBm, -7 dBm and -2 dBm

$m1 = m2 = m3 = 2.40$ GHz

Figure 4.12: Measured $S_{11}$ of Rectifier-A with Regulator from 1 GHz to 8 GHz when $P_{in} = -12$ dBm, -7 dBm and -2 dBm
Although the $Z_{\text{rec-LDO}}$ is matched closely to 50Ω, the rectifier with LDO regulator did not achieve good DC conversion efficiency. The $P_{\text{eff}}$ of the rectification is shown in Table 4.7. The main reason of $P_{\text{eff}}$ below 50% as compared to the reference results in Table 4.6 is mainly due to low $P_{\text{in}}$ and internal consumption of LDO regulator. In short, the power is not adequate to saturate the circuits. Additionally, the $V_{\text{DC}}$ is too low when $P_{\text{in}} = -12$ dBm, thus insufficient to drive the LDO regulator effectively and results in 2.5% efficiency. Since $P_{\text{in}}$ at microwatts range is unable to provide adequate $V_{\text{DC}}$ to meet the industrial standard of 3.3 V, charging battery with Rectifier-A through a regulator can be concluded as infeasible. An alternative is by replacing the regulator with battery, to enable direct energy storage through trickle charging without energy dissipation losses in electronic components e.g. transistors.

<table>
<thead>
<tr>
<th>Best Matched Frequency (GHz)</th>
<th>$P_{\text{in}}$ (dBm)</th>
<th>$P_{\text{in}}$ (mW)</th>
<th>$V_{\text{DC}}$ (V)</th>
<th>$R_{\text{Load}}$ (kΩ)</th>
<th>$P_{\text{eff}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.488</td>
<td>-2</td>
<td>0.631</td>
<td>1.353</td>
<td>11</td>
<td>26%</td>
</tr>
<tr>
<td>2.454</td>
<td>-7</td>
<td>0.2</td>
<td>0.882</td>
<td>11</td>
<td>35%</td>
</tr>
<tr>
<td>2.445</td>
<td>-12</td>
<td>0.0631</td>
<td>0.133</td>
<td>11</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Table 4.7: DC Conversion Efficiency of Rectifier-A with LDO Regulator

4.2.3 Requirement of Batteries Trickle Charging

Although direct powering by RF energy from WLAN is impractical to devices that require a few hundred milliwatts, it is still feasible to trickle charge battery. Trickle charging is a method implemented in battery charging mechanism to compensate for self discharge, if the batteries are not removed from the charger for a period of time [89, 90]. Usually, a constant flow of electrical current is applied at a very low rate during the trickle charging period. The current ($I$) required for charging can be expressed as:

$$I (\text{A}) = M \times C_n (\text{Ah})$$  \hspace{1cm} (4.8)

Where,

$I$ = current in Ampere

$M$ = multiple or fraction of $C_n$

$C_n$ = rated capacity declared by manufacturer in Ah

$n$ = time base in hours for which the $C_n$ is declared
Table 4.8 shows the minimum constant current required for trickle charging various consumer batteries. The results are computed using Equation 4.8. Different brands of batteries in the market are selected for comparison. Trickle charging is achievable when harvested energy is sufficient to provide 0.01C or higher at 0.05C. Besides, the numerical analysis from Figure 3.8 has stated that it is possible to receive 10 mW of EM energy at 1 m away when $G_r = 11.2$ dBi and $G_t = 15$ dBi. The amount of energy within 1 meter range is adequate for battery trickle charging. Therefore, experimental analysis of rectifier with battery is presented next to verify the feasibility of trickle charging the battery by 10 mW $P_{in}$.

<table>
<thead>
<tr>
<th>Consumer Battery</th>
<th>Minimum mAh</th>
<th>Brand</th>
<th>0.01C</th>
<th>0.05C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handphone</td>
<td>600</td>
<td>Motorola</td>
<td>6.0mA</td>
<td>30.0mA</td>
</tr>
<tr>
<td>MP3 Player</td>
<td>550</td>
<td>Apple</td>
<td>5.5mA</td>
<td>17.5mA</td>
</tr>
<tr>
<td>PDA</td>
<td>950</td>
<td>Dell</td>
<td>9.5mA</td>
<td>47.5mA</td>
</tr>
<tr>
<td>Camera</td>
<td>220</td>
<td>Canon</td>
<td>2.2mA</td>
<td>11.0mA</td>
</tr>
<tr>
<td>Laptop</td>
<td>2200</td>
<td>Dell</td>
<td>22.0mA</td>
<td>110.0mA</td>
</tr>
</tbody>
</table>

Table 4.8: Minimum Constant Current required for Trickle Charging Portable Devices

4.2.4 Matching Villard’s Voltage Doubler to Batteries

In this section, the regular NiMH AAA rechargeable batteries are included in the rectifier design. The aim of this experiment is to match the rectifier to the NiMH battery at the input power level close to 10 dBm. The new input impedance of rectifier with NiMH ($Z_{rec_{NiMH}}$) is measured by connecting NiMH battery terminals to the Rectifier-A with jumper wires and the VNA output is set to 10 dBm (10 mW). It is observed that the locus is shifted to the open circuit direction on the Smith chart. This is due to the electrodes separation in the battery that acts as an open circuit. Therefore, modification in Rectifier-A is required to rematch the circuit impedance back to 50 $\Omega$.

The impedance matching can be done by tuning the existing microstrip L-network. As a result, Rectifier-B is designed and is presented in Figure 4.13. In the impedance matching network, the shorted stub is lengthened to eliminate higher degree of imaginary part originated from the battery. Besides, the component pad for diode is shifted slightly aside from the pad of capacitor. This is performed to reduce the layout dimension in order to fit on the antenna ground plane, which will be shown in Chapter 6.
Figure 4.13: Experiment Setup for Rectifier-B with NiMH Battery (P_{in} \sim 10 \text{ dBm})

- $a = 1.85 \text{ mm, } b=1.65 \text{ mm, } c= 1.7 \text{ mm,}$
- Meander line width = 0.2 mm, meander line spacing = 0.2 mm,
- VIA patch = 1.4 mm $\times$ 1.4 mm, SMA pin pad = 0.85 mm $\times$ 1 mm,
- SMD capacitor pad = 0.5 mm $\times$ 1 mm

Prior to the experiment on NiMH, the overall $P_{eff}$ of Rectifier-B is verified with a potentiometer similar to Figure 4.10. The measurement and $P_{eff}$ are tabulated in Table 4.9. The central frequency for each $P_{in}$ is shifted because potentiometer is used to verify the $P_{eff}$. Apparently, Rectifier-B is capable to achieve good $P_{eff}$ above 70%. This is the highest DC conversion efficiency among [60, 62, 63, 82] which also uses HSMS diode models for their rectifier circuit under FCC’s power limitation of uncontrolled human exposure standard [81]. Rectifiers in [82] and [62] are using conventional microstrip stubs matching technique. Rectifier in [63] is using discrete components for impedance matching whilst rectifier from [62] matched the rectifier directly on the edge of patch antenna. Table 4.10 shows the comparison of DC conversion efficiency of rectifier using HSMS series diodes from recent designs. The result of high conversion efficiency is mainly due to the compact component layout with a low profile and meandered matching network. With smaller layout, the transmission loss of ultra high frequency AC along the microstrip is minimal.
<table>
<thead>
<tr>
<th>Best Matched Frequency (GHz)</th>
<th>$P_{in}$ (dBm)</th>
<th>$P_{in}$ (mW)</th>
<th>$V_{DC}$ (V)</th>
<th>$R_{Load}$ (kΩ)</th>
<th>$P_{eff}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.58</td>
<td>0</td>
<td>1</td>
<td>1.913</td>
<td>6.06</td>
<td>60%</td>
</tr>
<tr>
<td>2.60</td>
<td>5</td>
<td>3.162</td>
<td>3.89</td>
<td>6.86</td>
<td>70%</td>
</tr>
<tr>
<td>2.565</td>
<td>10</td>
<td>10</td>
<td>7.15</td>
<td>6.89</td>
<td>74%</td>
</tr>
</tbody>
</table>

Table 4.9: DC Conversion Efficiency of Rectifier-B with 3.6 V NiMH Batteries

<table>
<thead>
<tr>
<th>Refs</th>
<th>Year</th>
<th>Operating Frequency (GHz)</th>
<th>$*P_t$ (dBm)</th>
<th>$P_{in}$ at rectifier (mW)</th>
<th>DC Conversion Efficiency (%)</th>
<th>Size (mm$^2$)</th>
<th>$R_{Load}$ (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[82]</td>
<td>2004</td>
<td>2.45</td>
<td>27</td>
<td>3.75</td>
<td>40.3</td>
<td>~ 19 x 5</td>
<td>3.2</td>
</tr>
<tr>
<td>[63]</td>
<td>2009</td>
<td>0.3</td>
<td>20</td>
<td>0.338</td>
<td>63</td>
<td>~ 20 x 8</td>
<td>3</td>
</tr>
<tr>
<td>[60]</td>
<td>2007</td>
<td>2.45</td>
<td>0</td>
<td>1</td>
<td>52</td>
<td>~ 4 x 3</td>
<td>0.9</td>
</tr>
<tr>
<td>[62]</td>
<td>2008</td>
<td>2.45</td>
<td>--</td>
<td>100</td>
<td>53</td>
<td>~ 19 x 8</td>
<td>1</td>
</tr>
<tr>
<td>Rectifier B</td>
<td>2008</td>
<td>2.56</td>
<td>27</td>
<td>10</td>
<td>74</td>
<td>~ 9.5 x 5.5</td>
<td>6.89</td>
</tr>
</tbody>
</table>

Table 4.10: Comparison of DC Conversion Efficiency with References

*Transmitting power in the rectenna experiment in Chapter 6

The measured $Z_{rec,NiMH}$ is depicted in Figure 4.14 and the $S_{11}$ magnitude is shown in Figure 4.15. Referring to the Smith chart measurement, the maximum and minimum $P_{in}$ that matches 2.40 GHz on the border of SWR = 2 (i.e. $S_{11}$ ~ -10 dB) are 6 dBm (~4 mW) and 12 dBm (~16 mW) respectively. The locus of 10 dBm $P_{in}$ is shown instead of 12 dBm because the VNA has a threshold limit at 10 dBm, therefore the upper margin is estimated to be 12 dBm. In Figure 4.15, the $S_{11}$ plots are similar to that of Rectifier-A except wider impedance bandwidth. Hence, it can be concluded that the effective bandwidth of the rectifier will be wider when the bias current of the Schottky barrier diode increases.
A short experiment with battery is carried out by replacing the potentiometer with three NiMH (1.2 V, 900 mAh) batteries. According to Table 4.9, Rectifier-B is able to achieve ~70% DC conversion efficiency and the NiMH batteries are charged from a constantly microwave power at 10 dBm. Therefore, the actual charging power is only about 7 mW (~70% of 10 mW). It is observed that the battery reaches 3.95 V after an hour of charging and reaches 4.04 V after six hours. The voltage level maintains in
between 3.9 V and 4.0 V after disconnected from the source. As compared to a commercial Li-Po battery that reaches 4.15 V, 1100 mAh when fully charged, Rectifier-B has achieved a minimum charge ratio of 0.8. As conclusion, Rectifier-B is suitable to be implemented in the miniaturised rectenna design later. In Chapter 6, this rectifier is used in the rectenna which is designed to charge batteries. More comprehensive charging characteristic will be provided in Chapter 6.

4.2.5 Power Requirement of Li-Po Mobile Phone Battery

Different from NiMH rechargeable battery, the Li-Po smart battery has an embedded microcontroller module hidden in the cell pack for safety control [91]. The embedded monitoring system governs a few extra features such as the thermal throttling, charge level etc to ensure safe operation and to prevent overcharging and overheating. The Smart Batter System (SBS) utilise internal SMBus management protocol to handle the handshake of these interfaces. It is drawing power from the Li-Po battery constantly at anytime cut off the battery output when the working voltage ($V_{working}$) of Li-Po cell packs is below pre-programmed level. Therefore, higher charging power is required to maintain an effective constant charging current for the smart battery.

The BlackBerry’s Li-Po battery used in this experiment is rated at 3.7 V with a charge capacity at 1100 mAh and the electrical specifications of the compatible charging adapter is 5.1 V, 900 mA. When the mobile phone is in sleep or idle mode, the measured discharging current is between 20 mA and 50 mA, which is equivalent to 0.02C and 0.05C. To trickle charge the phone, the same amount of current is required. Assume the charging voltage is 5 V, the minimum trickle charging power of 100 mW (0.02C) for BlackBerry seems much higher than the 50 mW target suggested in [92, 93]. This is because 50 mW is suggested to trickle charge simple mobile phone whereas BlackBerry is a complex 3G mobile phone. Moreover, the new smart battery in BlackBerry has an embedded safety circuit, the trickle charging requirement could be higher and assumed to be 0.05C, which is 55 mA. The reason of higher rate requirement is to compensate the power consumption by the internal SMBus circuitry. In order to disclose the real power required to charge the BlackBerry’s battery, the experiment is performed as illustrated in Figure 4.16.
Charging Li-Po cell packs is different from NiMH because its electrochemical architecture is different. When BlackBerry’s Li-Po cell packs is charging with genuine charge, the green LED charging indicator on the phone will turn on and off in a slow pace, which represents an efficient and steady charging process. The aim of the following experiment is to determine the minimum voltage ($V_{out}$) and current ($I_{out}$) level required from the PSU to activate the charging circuit of the cell packs, which is useful reference to the rectenna experiment in latter chapters. A summary of results is presented in Table 4.11.

<table>
<thead>
<tr>
<th>PSU</th>
<th>Unloaded $V_{out}$</th>
<th>Loaded $V_{out}$</th>
<th>Constant $I_{out}$ required to hold the specific loaded $V_{out}$</th>
<th>Phone Status</th>
<th>Steady LED Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.75</td>
<td>90 mA</td>
<td></td>
<td>OFF</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>4.2</td>
<td>540 mA</td>
<td></td>
<td>OFF</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>890 mA</td>
<td></td>
<td>OFF</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>3.7</td>
<td>180 mA</td>
<td></td>
<td>ON</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>15 mA (minimum)</td>
<td>ON or OFF</td>
<td></td>
<td>Unstable</td>
</tr>
</tbody>
</table>

Table 4.11: Summary of Charging Power Requirement for BlackBerry’s Li-Po Cell Packs

During the experiment, the cell pack is in the phone and the device is switched on. The Li-Po battery in the phone has been pre-charged to 4.15 V, which is the typical peak voltage of Li-Po cell packs. At the PSU, the $V_{out}$ is fixed at 5 V and the $I_{out}$ is tuned to a minimum of 10 mA. The $I_{out}$ is increased to identify the minimum constant current that can activate the LED charging indication. It is observed the indication is activated when $I_{out}$ is about 15 mA and above. However, the LED charging indication is unstable and flickering. This implies that the charging current is too low although
the $V_{out}$ of the PSU is already set to 5 V at the beginning. Additionally, the LCD screen is seen toggling between active and sleep mode at random pace. It is also observed that the voltage of the cell packs is decreasing in a faster rate than observed during the sleep mode. This is because the toggling of LCD screen between active and sleep modes has increased the power consumption. Additionally, an active full colour LCD display consumes much more DC power than the sleep mode and thus the $I_{out}$ is inadequate to saturate the charging circuitry. As a result, the LED charging indicator flickers. As referred to Table 4.11, the mobile phone requires $I_{out}$ more than 180 mA to achieve a stable charging stage where LCD display is able to enter sleep mode forever and the charging indication is steady.

The same experiment is performed when Blackberry mobile phone is switched off. The open circuit $V_{out}$ from PSU is again fixed at 5 V and the current is started from 1 mA. When the charging cable is connected to the PSU, the battery voltage (i.e. loaded $V_{out}$) is dropping below 3.7 V. At the same time, the $I_{out}$ is adjusted to increase in a slow pace. It is noticed that the current must be at least 15 mA to activate the LED charging indication on the casing. Current is increasing until 90 mA where it preserves a stable $V_{out}$ in between 3.7 V and 3.8 V. Then the battery can be charged to the nominal voltage level at 3.7 V. However, it is observed that more than 540 mA is required from PSU to hold the $V_{out}$ at 4.2 V, which is the peak voltage level for Li-Po cell pack. At this stage, the cell pack is seen continues to charge towards 4.2 V. Lastly, it is observed that the cell packs requires about 890 mA from PSU to hold the loaded $V_{out}$ at 5 V, which is almost equivalent to the maximum output power (5.1 V, 900 mAh) from the genuine battery charger for this mobile phone model.

By comparing the experiment results to the genuine charger of the mobile phone, it can be concluded that the charger is precisely designed to suit the power requirement of Li-Po cell packs. In short, the 10 dBm (10 mW) is not effective to charge the portable devices with Li-Po SBS albeit it is capable to fully charge up the NiMH batteries. The recommended trickle charging rate of 0.05C is difficult to fulfil when the cell pack is inside the mobile phone. This is possibly due to the background software routines and monitoring circuits which keep the certain features active at all time. Multiple rectenna arrays maybe used to overcome this issue because the electric current can be accumulated in parallel to meet 0.05C requirement to trickle charge Li-Po. Alternatively, the cell pack could be trickle charged separately. In
Chapter 6, an experiment will be presented by charging a Li-Po cell pack outside the device, i.e. not in the phone socket. It is seen that the battery voltage can be increased by 2% to 3% when it is charging at very low rate, i.e. 0.0044C.

4.3 Conclusion

This chapter presents the rectifiers for the proposed energy harvesting system at 2.4 GHz ISM band. Four types of common rectifiers are taken under consideration, which are the series diode half wave rectifier, shunt diode half wave rectifier, voltage doubler and Villard’s Voltage Doubler (VVD). Numerical simulations have been performed using ADS to optimise and compare the performance of these rectifiers. The VVD and shunt diode rectifier are selected for experimental analysis due to its higher performance among the group. The VVD is proven to be better when the input power is higher than 10 mW. It is then experimented with different load such as potential meter, regulator and commercial battery. Impedance matching circuit by meander line and shorted stub are implemented match the impedance to 50Ω. Meandered L network is desired as it provides impedance matching with ability to be integrated onto the antenna board layout without occupying extra board space. Experimental result has shown that the VVD efficiency is lower than 40% when loaded with a regulator whilst it is over 70% when loaded with high resistance load such as resistor and commercial battery such as NiMH and Li-Po cell pack. Apart from that, trickle charging test has been carried out to ensure the DC power acquired is capable to increase the voltage of the commercial batteries.
CHAPTER 5: PRINTED ANTENNAS FOR WPT SYSTEM

This chapter will introduce various miniaturised printed antennas including novel techniques to achieve small form factor with comparatively better performance. As compared to other types of antenna, printed planar antenna has the potential for hardware integration due to the flat and thin radiating surface.

The first design is a miniaturized half-bowtie PDA with an integrated balun. It is presented in Section 5.1. It has also been presented in Asia-Pacific Microwave Conference (APMC) 2008 [94]. The novelty of this design includes the implementation of half bowtie shape to achieve wideband characteristic with simple integrated balun. This design possesses several merits, which is low profile, wideband, simple fabrication and high efficiency.

The second antenna is the enhanced edition of the first, with a novel CPS-tuner on balun. The details are described in Section 5.2. The novel CPS-tuner on balun is able to preserve all the characteristics of the first with better overall gain and slight reduction in size. Besides, the CPS-tuner is able to provide extra tuning flexibility to dipole antenna as compared to the conventional tuning parameters on dimension of the arms.

Section 5.3 introduces a Half Bowtie Yagi Uda (HBYU) on a conducting surface by a separation of 10 mm. This antenna is a Yagi-Uda edition of half bowtie antenna. It is specifically designed to work closely to conducting surface. This is a critical characteristic in consumer product integration because the antenna performance can be degraded by conducting surface close to it, such as impedance bandwidth mismatch, pattern degradation etc. To prevent performance degradation after rectenna is integrated into the consumer product, HBYU is designed and able to work close to conducting surface. Section 5.4 presents four elements collinear HBYU on the conducting surface. It has limited novelty since it is an array version of HBYU. Collinear HBYU possesses high gain and capable to harvest more EM energy at longer range. It is used to demonstrate long range WLAN energy harvesting in Chapter 6.
A compact Decoupled Dual Dipole (DDD) will be introduced in Section 5.5. DDD requires only an air gap of 5 mm from conducting surface. Besides, it has overcome the array spacing constraint by integrating a novel microstrip decoupling network between two antennas. This novel design has enabled compact integration for wireless application without performance degradation.

5.1 Miniaturised Half Bowtie (MHB) Printed Dipole Antenna (PDA) with Integrated Balun

A dipole antenna with an integrated balun is reported to have better bandwidth than the conventional balanced dipole [95]. The previously reported designs of similar PDAs can be found in [96-99]. All of these reference designs are designed to operate between 2 GHz and 3 GHz. The configuration of these antennas is very similar, in which the balun is integrated into the PDA. This balun consists of a microstrip feed line grounded to one arm of the dipole antenna located on the other side of the substrate, with via hole that shorts the line to the opposing arm.

Herein, a miniaturized half bowtie PDA (MHB PDA) is presented. It is a two layered printed antenna with the feed line on the top surface of a dielectric substrate, while the radiating arms are on the bottom surface. Agilent Momentum is used to simulate the performance of this design. It is proven to have better performance than the previously reported miniaturized printed dipole [96] in terms of its size and percentage bandwidth.

5.1.1 Design Methodology

The main objectives of the miniaturization of a printed antenna are shrinking and optimizing the overall dimensions of an antenna in order to achieve a smaller board size while preserving its performance. The design presented in this section is different from an ordinary dipole in that the dipole arms are replaced by half-bowtie shapes. In principle, a bowtie antenna requires shorter arm length than a normal dipole antenna that operates at the same resonance frequency. This can be observed by comparing a bowtie antenna with a normal dipole antenna that operates at same frequency. The wider the flare angle of the bowtie, the shorter the length of the arms is required for the particular frequency of choice [100].
In this work, the half bowtie shape is shown to closely resemble the characteristics of a full bowtie antenna, in that it achieves a wide impedance bandwidth with a short dipole arm length. The half bowtie dipole design consists of merely two geometries, which are the balun feed line and radiating arms. No additional structure is required to achieve this performance such as external impedance matching elements, as were used in [96].

A schematic diagram of the proposed half bowtie dipole antenna with integrated balun is presented in Figure 5.1. The overall dimensions of the antenna are 37.5 mm × 19 mm which is 11% smaller in size than previously reported miniaturized dipoles [96]. The design resides on a Rogers RT/Duroid 5880 (\( \varepsilon_r = 2.2 \)) substrate with 0.787 mm thickness.

![Figure 5.1: Schematic Layout of MHB PDA](image)

Feed line width = 1.15mm, VIA diameter = 0.6mm, gap = 0.5mm, \( \theta = 127.67^\circ \)

Tuning parameters such as the width and length of the balun feed line, position of the via hole, and the gap between the arms allows many degrees of freedom to improve the overall antenna performance. The input impedance of the balun feed line can be adjusted to match that of the bowtie and yield a wide bandwidth characteristic. Moreover, the simulated efficiency can be increased when feed length is close to \( \lambda/4 \)
at the desired central frequency. The depth and width of the gap between the dipole arms also affects the antenna response.

5.1.2 Simulation and Measurement Results

Figure 5.2 depicts the simulated and measured $S_{11}$ magnitude of the miniaturized half bowtie dipole antenna. The half bowtie dipole antenna provides a 10 dB return loss bandwidth of 1.17 GHz and centralized at 2.845 GHz (41%) whilst the measured bandwidth is about 47% and centralised at 3.1 GHz.

The measured radiation patterns of the antenna are shown in Figure 5.3. The simulated efficiency of the half bowtie dipole antenna is between 93% and 94%. This is due to the use of low loss substrate. Figure 5.4 shows the simulated realised gain and measured gain on the same plot. The simulated gain present good gain at lower frequency band and it declines at higher frequency band. However, the measured peak gain at 3.5 GHz is very low and approaching 0 dBi although the $S_{11}$ magnitude at 3.5 GHz is below -10 dB. The cause and solution to this issue will be discussed further in Section 5.1.4.
Figure 5.3: Measured Radiation Patterns of MHB PDA
(a) E-plane (YZ plane)  (b) H-plane (XZ plane)  (c) Isometric View
5.1.3 Comparison between Other Printed Dipole Designs

The centre frequency, substrate dielectric constants, antenna size and bandwidth of the referenced dipole designs are listed in Table 5.1 for comparison. The proposed half bowtie dipole occupies the smallest physical board size on the lowest permittivity material, while supplying the highest bandwidth.

<table>
<thead>
<tr>
<th>Refs</th>
<th>Central Frequency (GHz)</th>
<th>Substrate $\varepsilon_r$</th>
<th>Antenna Size</th>
<th>Bandwidth (SWR&lt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[97]</td>
<td>2.55</td>
<td>4.6</td>
<td>41mm × 40mm</td>
<td>1640</td>
</tr>
<tr>
<td>[99]</td>
<td>2.95</td>
<td>10.2</td>
<td>40mm × 18mm</td>
<td>720</td>
</tr>
<tr>
<td>[98]</td>
<td>2.52</td>
<td>4.4</td>
<td>44mm × 20mm</td>
<td>880</td>
</tr>
<tr>
<td>[96]</td>
<td>2.57</td>
<td>3.48</td>
<td>41mm × 19.6mm</td>
<td>803.6</td>
</tr>
<tr>
<td>This Design</td>
<td>2.85</td>
<td>2.2</td>
<td>37.5mm × 19mm</td>
<td>712.5</td>
</tr>
</tbody>
</table>

*This is also a miniaturised antenna

Table 5.1: Comparison of MHB PDA with References

In short, this section presents a miniaturisation method for a PDA. Compare to [96], simpler and more effective miniaturisation have been achieved by replacing the radiating element with half bowtie geometry. This yields a measured 47% bandwidth centralized at 3.1 GHz. The overall dimensions of this design are 37.5 mm × 19 mm. As a result, this miniaturised dipole will be useful in compact wireless electronic applications. Next section will discuss the gain issue of this antenna and introduce further development including new technique to resolve this issue and to enhance its performance.
5.1.4 Discussion on Low Gain Performance

One critical issue of this antenna is very low gain at 3.5 GHz band. The reason of low gain is believed due to the microstrip balun and the SMA connector which skew the radiation pattern. The microstrip balun is designed to introduce 180° phase shift between the arms of the half bowtie dipole element. The balun is actually a microstrip feed line on a truncated ground plane (formed by the dipole arm itself). The feed line of this design is located right on the edge of the balun ground plane, giving it non-ideal electrical characteristics for a microstrip transmission line. The asymmetry of the structure has caused the E-field become unevenly referenced to the ground plane beneath. Moreover, slight misalignment during fabrication could drastically impact the antenna performance because it can easily overlap to the edge of the radiating arm, which skews the radiation. To illustrate this, the electric field formation of this feed line misalignment phenomenon is simulated using HFSS and shown in Figure 5.5. The magnified E-field of the feed line from previous edition antenna is shown in Figure 5.5(a). The E-field is seen to reach around to the underside of the ground plane on the side which it has been truncated. When fabrication misalignment occurs, the situation is amplified as seen in Figure 5.5(b). This line overlapping past the edge of the left arm of the dipole can impact on the antenna’s bandwidth performance as the characteristic impedance of the feed line has been altered, and cause radiation skewing because of the unbounded fields leading to maximum gain direction variation. Additionally, the existence of SMA connector amplifies the variation further.

To combat this issue, the half bowtie antenna with new balun in the Section 5.2 has an “L” shaped microstrip line that has been shortened and shifted towards the centre of the antenna. This results in less skewing effect to the overall radiation pattern because the feeding microstrip and the SMA connector are now further from the left arm. There are pros and cons to this shortening and moving the line towards the centre of the antenna. Firstly, the inductive component of the antenna feed has been reduced, which leads to input impedance mismatch. Secondly, the microstrip balun no longer provides a path of half a wavelength since it has been shortened. However, the E-field of the microstrip feed line has been more evenly distributed as shown in Figure 5.5(c). This has solved the gain and pattern skewing problems of current design. Further detail will be presented in Section 5.2.2 together with the introduction of novel CPS-tuner technique (i.e. Coplanar Striplines).
Figure 5.5: Simulated E-Field in the Vicinity of the Feed Line
(a) Feed line and E-field of the Current Design
(b) Feed line and E-field when misalignment occurs
(c) Novel Balun and E-field of the Next Design

5.2 MHB PDA with CPS-tuner on Integrated Balun

PDAs with integrated baluns are able to provide omnidirectional coverage while also having the potential to be miniaturised. Miniaturisation is important trend for wireless embedded design integration in the consumer market. A plethora of research has been aimed at creating an antenna with a smaller form factor, such as producing a smaller radiating arm, shorter feed line etc. The performance of the finely tuned radiating arms can be enhanced by a balun which has been designed as part of the body of the radiator. Many recent articles have reported dipole-like antenna geometries with an integrated balun. A conventional 2.4 GHz PDA was introduced by Chuang and Kuo [97] in 2003 which incorporated an integrated balun. Wen et al. [99] designed an arrow shaped dipole at 3 GHz by using similar balun to that in [97]. This antenna design concept is also very similar to the 2.4 GHz radiator from the rectenna design of [97]. In 2005, Chu and Popovic [96] introduced some
improvement techniques for PDAs, with the integrated balun being one such technique. A similar antenna with wider bandwidth can also be found in [67]. Suh et al. presented a miniaturised balanced dipole using a meander line on the dipole arms [68], designed for use on a laptop. These and other references typically focus on tuning the dimensions of dipole arms and/or the balun feed lines to either obtain enhanced performance or smaller lateral dimensions.

In this section, a MHB PDA with a novel integrated balun is presented for wireless applications. An extremely wide impedance bandwidth of 47% is achieved with very small form factor, which incorporates the popular 2.4 GHz ISM band. The half bowtie dipole antenna has previously been proven to have a much wider bandwidth than conventional PDA in the previous section. However, a novel tuning technique to control the integrated balun performance is introduced here, which enhances the gain without changing the overall dimensions of the antenna. Sections 5.2.1 and 5.2.2 discuss the design of the half bowtie dipole antenna, and the details of the tuning technique applied to the modified balun. Simulated and measured validation of the concepts is provided in Section 5.2.3. A comparison is made to similar antenna configurations in Section 5.2.4 to highlight the exceptional performance of this antenna, and conclusions are drawn in the end.

5.2.1 Design Methodology
The antenna presented in this section is a variant of the antenna in Section 5.1. It has a novel integrated balun which resolves the gain issue and provides better tuning characteristic without changing the overall dimension. An integrated balun can be implemented as a microstrip feed line on a truncated ground plane (formed by the dipole arm itself). The smaller the dimensions of the radiator, the shorter the integrated balun structure needs to be if it is to remain within the extents of the antenna footprint. Excessive modification to conventional printed baluns may incur changes in radiator shape or overall lateral dimension of the antenna. Chip baluns like those employed in [68] are extremely small, but may not suffice if broadband performance and assembly costs are key considerations.

In the design presented in this section, the general half bowtie shape of previous section has been preserved. Modification has been made to the balun structure to enable the wide impedance bandwidth to be maintained whilst providing a more
useful level of gain. It was desirable that these changes to the balun structure would not create any major change to the dimensions of the half-bowtie shape. The proposed technique of shifting the microstrip feed line, and adding inductive tuning components between the dipole arms is depicted in Figure 5.6. Detailed dimensions for this layout are listed in the caption of Figure 5.6. The antenna is fabricated on a 31mil Rogers RT/duroid 5880 substrate.

Figure 5.6: Schematic Layout of the MHB PDA with CPS-tuner on Integrated Balun

a = 18.1 mm, b = 0.3 mm (gap between arms), c = 19 mm, d = 4 mm, 
e = 10.5 mm, f = 11.5 mm, g = 0.5 mm (inductive meander line width and gap),

h = 1.75 mm, i = 3.2 mm, j = 5.3874 mm, k = 17.1 mm,
l = 1.05 mm (feed line width), via hole diameter = 0.6 mm, θ = 126.67°
5.2.2 Miniaturisation of Integrated Balun

To achieve miniaturisation of the lateral antenna dimensions, a complex balun essential. Reducing the feed line length of a printed microstrip balun has two major consequences. Firstly, the inductive component of the antenna feed has been reduced, which leads to input impedance mismatch. Secondly, the traditional microstrip balun no longer provides a path of half a wavelength since it has been shortened. This section describes the methodology to achieve small form factor and wide impedance bandwidth half bowtie printed dipole by using inductive meander line in balun ground plane.

Traditionally, printed dipole arms have a capacitive gap between the arms. Usually, this is countered by the inductance from the feed line structure. Without sufficient feed length the feed structure has become more capacitive. Inductive meander lines are introduced at balun ground to repair the function of the balun by introducing a propagation delay with small amount of inductance. It is well known in Coplanar Stripline (CPS) design techniques that a meander line of folded shorted or open stubs between a balanced high frequency parallel transmission line possesses certain amount of inductance and capacitance [101]. They are similar to parallel LC pi-networks in CPS filter theory.

The design of the inductive transitions (known henceforth as the ‘CPS-tuner’) is as follows: First, a safe region of the radiator has to be determined, where minimal radiation activity is occurring. Second, a clear area is created between the two conductors of the dipole arms within the safe region. A rule of thumb for the maximum size of this clear area is half the length and width of the balun ground region, i.e. \( W = d/2 \) and \( L = e/2 \). Third, the inductive meander lines can be added into this clear area. The equivalent circuit of the CPS-tuner is depicted in Figure 5.7. Each line in the CPS-tuner contributes certain amount of inductance (dominant) and capacitance while serving as additional current path. Its operation is similar to a common LC tuner or pi-network in RF circuit design. The line/gap widths are fixed at 0.5 mm in width (~ 94 \( \Omega \)), which is about half the width of the 50 \( \Omega \) feed line.
The CPS tuner provides three effective tuning parameters for optimising performance, which are the length, width and gaps of the lines. Generally, the length is proportional to delay added and the line width can control impedance and bandwidth performance. The position of the CPS-tuner can also be changed to provide impedance matching. When CPS-tuner transitions are moved towards the half bowtie arms (decreasing the value of the distance f), the impedance locus circulates anticlockwise. When the gap width of CPS-tuner is increased (the value of g is larger), the locus shifted towards inductive region. Additional tuning can be performed by adjusting the feed line near the via hole, which can translate the impedance locus along the real axis. Optimizing these parameters can attain a good match across wide range of frequencies. Apart from impedance control, the CPS-tuner also allows the microstrip feed line to be shortened to almost any length providing that there is enough space to create a sufficient current path with the inductive lines. This can provide significant miniaturisation to this antenna architecture. Additionally, having two parallel inductive transitions will form a less volatile RF tuner, with minimal performance impact arising from fabrication error. This is because small geometric changes the inductive transitions in parallel produce less variation to overall inductance than a single transition. Last but not least, the CPS-tuner is able to resolve the low gain issue found in Section 5.1.
5.2.3 Simulation and Measurement Results

The MHB PDA with integrated balun design was simulated using Agilent Momentum. The simulated and measured $S_{11}$ magnitudes are shown in Figure 5.8. Excellent agreement is observed between simulation and measurement, and the simulated and measured bandwidths (VSWR < 2) of 46% and 47% respectively.

![Simulated and Measured S11 Magnitude of MHB PDA with CPS-Tuner](image)

Figure 5.8: Simulated and Measured $S_{11}$ Magnitude of MHB PDA with CPS-Tuner

The measured far field radiation patterns of this antenna are presented as Figure 5.9. The patterns display omnidirectional-like shape over the five frequencies tested from 2 to 4 GHz. The main deviation from a conventional dipole antenna radiation pattern is the asymmetry in the H-plane. It is postulated that this is caused by the presence of an SMA connector located at the end of the microstrip feed line interfering with the radiated fields. To confirm this postulation, the structure is simulated using Ansoft HFSS with and without the SMA connector. These results show a slight degradation in the lateral H-plane radiation with the SMA connector. It is possible that this effect is exacerbated in the practical implementation of the antenna. Degradation effect could be reduced if the balun ground is extended during practical implementation to keep the tip of half bowtie at certain distance away (e.g. 1 cm) from RF circuit board.
The measured gain across impedance bandwidth for proposed design is shown in Figure 5.10. In average, it matches the simulated realised gain from HFSS. As
compared to previous design without modified balun, this design managed to maintain an average gain of higher than 1 dBi especially at the higher frequency band. The gain comparison setup used in the measurement only had access to standard gain values every 0.5 GHz, hence the sparsely spaced measured values. It should be noted however that the gain measurement may not have been taken at the direction of peak radiation (although much effort was expended in trying to ensure it was as close as possible) so the maximum gain could be slightly higher. The simulated efficiency of this antenna is also in excess of 90% across the impedance bandwidth, which is aided by the use of a low loss Rogers RT/Duroid 5880 substrate. For a lower cost implementation, this antenna could be scaled to employ an FR4 substrate with only a slight degradation in performance.

![Simulated and Measured Gain of MHB PDA with CPS-Tuner](image)

**Figure 5.10:** Simulated and Measured Gain of MHB PDA with CPS-Tuner

### 5.2.4 Comparison between Other Printed Dipole Designs

The antenna parameters of the proposed half bowtie antenna with integrated balun and other PDAs are presented in Table 5.2. The selection criteria for inclusion in this comparison were miniaturised printed dipoles with some form of integrated balun that cover or operate very close to the 2.4 GHz ISM band. The half bowtie dipole antenna design with novel CPS-tuner easily provides the widest impedance bandwidth of 47%, with the next closest rival being [67] at 41%. The antenna in [67] is not aimed at low profile integration, as the antenna element is mounted perpendicular to a ground plane. This design is also more than four times larger than the half bowtie dipole in this paper. Even though a bandwidth of 47% far exceeds what is needed for 2.4 GHz ISM band communication applications, the half bowtie dipole design enables the
potential to implement multi-service transmission, or to trade-off unused bandwidth for increased integration ability. The half bowtie dipole also has the second smallest overall area of any of the antennas listed. Additionally, the dielectric constant of the substrate used in this design is the lowest. Hence, a higher degree of miniaturisation is possible by using substrate with higher dielectric constant.

<table>
<thead>
<tr>
<th>Refs</th>
<th>Central Frequency (GHz)</th>
<th>Integrated Balun</th>
<th>Subs. $\varepsilon_r$</th>
<th>Antenna Size $L \times W \times H$ (mm)</th>
<th>Bandwidth (VSWR &lt; 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This design</td>
<td>2.97</td>
<td>Yes</td>
<td>2.2</td>
<td>$36.5 \times 19 \times 0.787$</td>
<td>693.5</td>
</tr>
<tr>
<td>[68]</td>
<td>2.495 &amp; 5.42</td>
<td>Yes (Chip)</td>
<td>4.9</td>
<td>$36 \times 5.5 \times 1.5$</td>
<td>198</td>
</tr>
<tr>
<td>[99]</td>
<td>2.95</td>
<td>Yes</td>
<td>10.2</td>
<td>$40 \times 18$</td>
<td>720</td>
</tr>
<tr>
<td>[96]</td>
<td>2.57</td>
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</tr>
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<td>$\approx 880$</td>
</tr>
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<td>4.6</td>
<td>$41 \times 40 \times 1.6$</td>
<td>1640</td>
</tr>
<tr>
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<td>2.1</td>
<td>Yes</td>
<td>3.0</td>
<td>$76 \times 42$</td>
<td>3192</td>
</tr>
</tbody>
</table>

Table 5.2: Comparison of MHB PDA (CPS-Tuner) with References

* ‘~’ denotes approximate values

The balanced dipole in [68] has an extremely small overall geometry. This is due to the use of a ceramic chip balun, and it has a dual band response rather than wideband performance. Using a chip balun will increase the production cost as compared to the proposed design. The novel half bowtie antenna with modified balun design in this paper has successfully achieved a low profile structure with wideband impedance characteristic which equals or exceeds the performance of similar designs.

In conclusion, this section presents a new technique to miniaturise PDA. This antenna is suitable for wireless system applications in consumer electronics. Novel CPS-tuner are introduced between the half bowtie dipole arms to resolve issues created by shortening the balun feed line (a consequence of miniaturisation), while maintaining a wide impedance bandwidth. This antenna is approximately $0.363 \lambda$ (at the central frequency of 2.97 GHz) in length and is printed on a substrate with a low dielectric constant ($\varepsilon_r = 2.2$). It provides 47% measured bandwidth and useful levels.
of gain. In contrast with other similar miniaturised dipole designs, this antenna has successfully achieved a much wider impedance bandwidth characteristic with a comparable or smaller footprint. The broad bandwidth may enable this antenna to be used in multi-service wireless transceivers. The antenna’s bandwidth covers the 2.4 GHz ISM band, so the antenna may also be useful for integrated device applications where the ample bandwidth can be traded for other performance attributes.

5.3 Half-Bowtie Yagi-Uda (HBYU) on Conductive Surface

Miniaturisation characteristic is one of the criteria to achieve consumer electronic integration. Nowadays, most of the portable devices are multi-layered embedded system inside a casing. In general practise, a thin metallic case shields the core modules and sensitive components from EM interference. Therefore, the receiving antennas of rectennas should be able to work close to the shielding to achieve low profile integration. To do this, a conductive surface is added in this proposed antenna design in order to enable the integration of rectenna into consumer electronics. The conducting surface does not have physical contact to any part of the radiator. Although the capability to be functional close to conducting surface is critical, the realisation of this property is challenging due to a few constraints, which limit the performance of the antennas, as mentioned in [102]. Firstly, the existence of conducting surface shapes the original radiation pattern when it is near to the radiator. It is analogous to the function of disc reflector. Secondly, close proximity to conductive surface results in input impedance mismatch to the antenna. It is found that the clearance required between half bowtie antenna and metallic plane is about 0.16 λ to preserve the -10 dB bandwidth over the 2.4 GHz ISM band. This happens because the capacitance between the antenna and the conducting surface stores the EM energy, which in turn affects the radiation efficiency and narrows the impedance bandwidth. As recommended in [102], the ground plane effect and attenuating surrounding structure should be taken into consideration in compact antenna design for product integration. The half bowtie antenna configuration was optimised to operate near a conducting plane. This section presents the results of this optimisation: a Half-Bowtie Yagi-Uda (HBYU) antenna.
5.3.1 Design Methodology

Figure 5.11 illustrates the HBYU antenna on a conductive plane. It consists of a modified MHB dipole antenna, a truncated ground plane and a parasitic element. The overall geometry looks like a Yagi-Uda antenna. The truncated ground plane acts as a reflector and is longer than the half-bowtie radiator while the parasitic element is a director and is shorter than the reflector. Hence, this design is actually a half-bowtie Yagi-Uda (HBYU) on a reflector. This is not exactly a patch antenna because the reflector is not wired or shorted to any point on the antenna. In other words, it is not part of the radiating body but a conductive planar obstacle that shapes the EM radiation. The reflector and director next to the driver (half-bowtie) are able to recover the antenna performance by counteracting the induction of capacitive plate beneath the antenna. Additionally, it is found that this parasitic element is able to broaden the bandwidth by ~2%.

The overall size has increased as compared to single half-bowtie antenna. The air gap between the conductive plane and the antenna board is represented by 10 cm foam layer in the experiment. The $\varepsilon_r$ for foam is 1.07, which is fairly close to 1 (free space). The conductive plane underneath eliminates the wideband characteristic when air gap is contracting. Theoretically, this is because most of the energy is induced to and stored in the gap. The geometry is redesigned to match 2.4 GHz ISM band. Modifications are mainly focused on the important parameters such as g, s, t and the CPS-tuner.
Figure 5.11: Schematic Layout of HBYU on Conductive Surface

a = b = 16 mm, c = 19.78408 mm, d = 6.5 mm, e = 17 mm, f = 25.4 mm, g = 7 mm,
h = 47.5 mm, i = 3.5 mm, j = 19.85 mm, k = 4.5 mm, l = 5.35 mm, m = 1.6 mm,
n = 1.95 mm, o = 2.7 mm, p (gap) = 0.5 mm, q = 0.3 mm, r = 7.5 mm, s = 2 mm

Via hole = 0.6 mm diameter, Feed line length (j + k + l) = 29.7 mm,
Meander line length = 6.9 mm
5.3.2 Simulation and Measurement Results

The simulated and measured $S_{11}$ is presented in Figure 5.12. The measured bandwidth is wider than the simulated result by 60 MHz. The -10 dB bandwidth starts at 2.34 GHz and end at 2.645 GHz, which is about 305 MHz or equivalent to 12.3% bandwidth.

![Simulated and Measured $S_{11}$ Magnitude of HBYU on Conductive Surface](image)

Figure 5.12: Simulated and Measured $S_{11}$ Magnitude of HBYU on Conductive Surface

The existence of metallic surface has also increased the antenna gain dramatically. This effect is analogous to the disc antenna. In this design, the realised radiation pattern and gain at 2.45 GHz ($G_{HBYU}$) is simulated with an SMA connector model by using Ansoft’s HFSS. The simulated and measured radiation patterns are shown in Figure 5.13 and both plots are fairly well matched. A drawback of this antenna is that peak $G_{HBYU}$ does not occur along the Z-axis. This is illustrated in Figure 5.13, where the simulated and measured shifting is about 25° and 17.5° respectively. This is due to the parasitic element next to the half bowtie dipole that act as a director that shift the main lobe towards its direction. The simulated and measured Front to Back Ratio (FTBR) of HBYU is about 10 dB.

The simulated realised peak gain is about 7 dBi. The measured $G_{HBYU}$ of this antenna at 2.5 GHz is about 5.5 dBi. Gain measurement covers 2.5 GHz only because the gain comparison setup used in the measurement only had access to standard gain values every 0.5 GHz. Therefore, the realised gain at 2.4 GHz (i.e. ISM band of WLAN) could be higher than 5.5 dBi, because the return loss at 2.4 GHz is better
than that of 2.5 GHz. By extrapolating the measured gain of the comparison setup (i.e. standard gain horn antenna) at 2.5 GHz to that of 2.4 GHz, the offset value can be used to predict the realised gain of HBYU at 2.4 GHz, which is about 6.7 dBi.

Figure 5.13: Measured Radiation Patterns of HBYU on Conductive Surface
(a) Simulated (b) Measured (c) Isometric View
In conclusion, miniaturised antenna that works at 2.4 GHz ISM band on a metallic plane has been designed successfully. This prototype is the fundamental model to the successive designs. The steered beam can be corrected by adding a mirror element to form a collinear pair, which will be discussed in the next design. HBYU covers 2.4 GHz ISM band so it is suitable to be used in wireless communication at this frequency band and it is able to work close to conductive material with reasonably high gain and efficiency.

### 5.3.3 Comparison between Other Printed Dipole Close to Conducting Surface or Reflector

Table 5.3 shows the parameters of several 2.4 GHz antennas for comparison with HBYU antenna. The antenna from [102] is an Alford loop antenna designed for laptop application. It is printed on FR 4 to study the degree of attenuation to the Alford loop inside the laptop. When the loop is printed next to the copper plane with 4 mm gap in between, the gain is -5.3 dBi, which is 10 times lower than HBYU. This is mainly due to the small radiator size and very close proximity to the copper plane in its setup. Another antenna with conducting surface is found in [103]. The antenna uses the conducting surface as a reflector to achieve high gain and wider bandwidth. Therefore, the distance between the conducting surface and the radiator is far, which is the standard spacing of $\lambda/4$. Although it is able to achieve 2 dBi gain higher than HBYU, the size of the entire array is about 3 times larger to compensate the wideband characteristic. This results in difficulty to integrate antenna into the consumer product.

<table>
<thead>
<tr>
<th>Refs</th>
<th>Central Frequency (GHz)</th>
<th>Type</th>
<th>Gain (dBi)</th>
<th>$\varepsilon_r$</th>
<th>Distance from GND (mm)</th>
<th>Antenna Board Size</th>
<th>-10 dB % Bandwidth (SWR&lt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[102]</td>
<td>~2.444</td>
<td>Alford Loop</td>
<td>-5.3</td>
<td>4.4</td>
<td>4</td>
<td>17.8 × 17.8 × 1</td>
<td>326.84</td>
</tr>
<tr>
<td>[103]</td>
<td>2.4</td>
<td>Dual Dipole</td>
<td>5.3 – 7.0</td>
<td>3.38</td>
<td>31.25 ($\lambda/4$)</td>
<td>77.45 × 76 × 0.51</td>
<td>5886.2</td>
</tr>
<tr>
<td>This Design</td>
<td>2.4925</td>
<td>Yagi</td>
<td>5.5</td>
<td>2.2</td>
<td>10</td>
<td>57.5 × 36 × 0.5</td>
<td>2052</td>
</tr>
</tbody>
</table>

Table 5.3: Comparison of HBYU Characteristics with References
In overall, the linearly polarised HBYU preserve a good gain while being able to work close to conducting surface. This advantage has become the fundamental to compact rectenna integration because this prevents impedance mismatch when HBYU is attached to portable devices. Antenna that suits on arbitrary conducting surface (or metallic plane) is very difficult to design because integration of antenna into consumer products is basically dependent on application. By comparing HBYU and the original antenna from Section 5.2, the board dimension is 2.96 times larger. However, the MHB antenna requires minimum of 20 mm clearance distance from any conducting surface, which is double to that of HBYU. The next section will introduce the HBYU array to achieve higher gain for longer distance WPT system.

5.4 HBYU Collinear Array

Numerical analysis in Chapter 3 has shown that single antenna is inadequate for long range WPT. Therefore, multiple elements are required. A standard collinear array antenna provides several advantages over single element in terms of EM energy harvesting potential. Firstly, antenna array is able to receive higher receiving power because the amount of receiving element has increased. Moreover, the conducting surface for HBYU array is kept about the size of portable device such as remote controller. This conducting surface is larger and so creates a larger shielding that suitable for larger circuit board integration behind the conducting surface. Additionally, the array size is expandable. It can be expanded in vertically or horizontally depends on application.

In this section, a 2 by 2 HBYU collinear array is introduced which consists of four HBYU units. The prototype layout is demonstrated in Figure 5.14. The conducting surface dimension is 65 mm × 164.5 mm and suitable to integrate with consumer product such as remote controller, calculator, casing of electronic appliances to harvest WLAN energy. The vertical spacing between collinear pair is about ½ λ (59.5 mm). Taper lines are used to design the feeding network and the input port is terminated at 50Ω. Truncated ground below the feeding network is at least 20% wider than the taper line to preserve proper microstrip functionality.
Figure 5.14: Schematic Layout of HBYU Collinear Array
Its impedance bandwidth is shown in Figure 5.15 and is very close to the bandwidth of single HBYU antenna. The simulated and measured radiation patterns of HBYU array at 2.4 GHz are presented in Figure 5.16. The patterns is similar to the microstrip fed patch antenna [104] except that the YX plane is narrower as trade off for higher directional gain. The simulated FTB ratio is about 19 dB whilst the measured FTB is about 17 dB. The simulated realised peak gain of HBYU array at 2.4GHz is about 9.4 dBi and the measured peak gain at 2.4 GHz is about 8.832 dBi. Both results are fairly close.

Comparison of the radiation patterns of a 2 by 2 standard patch antenna array are given in Figure 5.17. An identical feed distribution is implemented on the patch antenna array. The standard patches are designed above the edge of the ground plane and each pair is 0.5λ apart. The central frequency is at 2.45 GHz. By comparing the XZ plane, the standard 2 by 2 patches array is narrower than the HBYU collinear array, which contributes to the simulated antenna gain of higher than 10 dBi. Different to the HBYU design, the 2 by 2 standard patch array has 2 side lobes.

In short, the HBYU array antenna with high gain and capability to work close to conducting surface has been designed. This antenna is suitable for long range wireless communication system and WLAN WPT system. A demonstration of using this array antenna to prolong battery life will be presented in Chapter 6 and included in the patent attached in Appendix section.
Figure 5.16: Simulated and Measured Radiation Patterns of HBYU Collinear Array

(a) Simulated (b) Measured (c) Isometric View
5.5 Decoupled Dual Dipole (DDD) on Conducting Surface

Printed antennas are commonly used as the radiator in wireless communication system and rectenna design in wireless power transmission due to its simplicity and cost effectiveness in hardware integration. However, many of the latest high speed wireless routers use multiple antennas. This is to achieve better reliability and higher data throughput upon network expansion. This trends antenna design to be more cost effective and compactable with respect to the form factor of wireless routers. Similarly, rectennas can be tightly packed for smaller form factor integration to harvest radio frequency (RF) energy. However, problems such as mutual coupling, low radiation efficiency and impact to the radiation patterns have appeared to be critical issues when antennas are closely packed. To combat this issue, isolation characteristic has become one of the most important parameter in most of the practical communication application and now in WPT systems.

Isolation between two radiators is evaluated by referring to the forward transmission parameter, e.g. the $S_{21}$ level. Thus, lower $S_{21}$ parameter represents better isolation between two radiators. A few methods have been introduced to achieve good antenna isolation. The most commonly applied isolation technique is to insert a decoupling network between two radiators before each impedance matching.

Figure 5.17: Simulated and Measured Radiation Patterns of HBYU Collinear Array
(a) Simulated (b) Isometric View
network. Referring to Chen’s design [105], a small decoupling network comprised of discrete components and stubs are used to achieve good isolation between two chip antennas at Taiwan UHF RFID band (915 MHz) and suppressed the mutual coupling below -20 dB. The edge to edge separation between chip antennas is 22 mm (i.e. 0.067 λ). His second design [106] for 2.4 GHz MIMO wireless communication has decoupled the entire band (i.e. 2.4 – 2.5 GHz) below -12 dB. The edge to edge separation between the antennas is 5 mm (i.e. 0.04 λ). Apart from that, a numerical methodology has been developed by Weber [107] for three elements of antenna array with 0.1 λ separation. The theoretical formulas are able to compute the Decoupling and Matching Network (DMN) required for effective isolation between radiators. Simulation results have shown a very promising isolation contributed by the DMNs by his numerical approach.

An alternative to discrete components is by modifying the ground or introducing an extra microstrip structure between radiators to achieve similar isolation. This approach is more cost effective since discrete components are not necessary but can be represented by microstrip structure. The challenge is the limited board space available for these decoupling structures. Generally, two common locations for modification are either the shared ground plane or the narrow space between the radiators. Chiu [108] has introduced a slitted ground plane to achieve antenna isolation lower than -20 dB for PIFAs in MIMO wireless communication system at 2.4 GHz. The edge to edge separation between PIFAs antennas is about 10 mm (i.e. 0.082 λ) and the centre to centre spacing is about 15 mm. In fact, the slitted ground structure works like a band stop filter and it traps most of the current and prevents cross propagation. Besides, Zhu [109] has proposed another dumb-bell-like ground plane structure for 7.5 GHz PIFA antenna to achieve isolation lower than -40 dB with 10 mm (i.e. 0.25 λ) edge to edge separation. Apart from ground plane modification, a microstrip structure between two WLAN monopoles with 3.6 mm edge to edge separation has been introduced by Mak [110] to achieve isolation better than -15 dB across 2.4 GHz WLAN band. This structure is located between two folded monopole and used to cancel out the mutual coupling induction.

Similarly, this paper will present a pair of closely packed dual dipole antennas, which possesses good isolation characteristic. For convenience, the dual antenna is known henceforth as Decoupled Dual Dipole (DDD). This antenna is a further transformation
from [111] and the isolation is achieved by adding microstrip structure between antennas. A conducting surface is included below DDD because one of the development objectives is to maintain normal functionality next to conducting surface in consumer electronics. Each antenna possesses good coverage and high efficiency. DDD is cost effective since has no discrete component and the decoupling structure occupies only little board space. It is suitable to be implemented on top or beneath the desired hardware where high degree of integration is essential such as requirement to combine rectenna very near to circuit board or conducting pieces without affecting its impedance bandwidth. Detail methodology will be described in the next section to make a narrowest possible separation between antennas and a comparison with literatures will be provided in Section 6.

5.5.1 Proposed DDD on Conducting Surface

As aforementioned, the desired rectenna design should possess capability to be packed closely, functional near to conducting surface and having good gain for WPT. The radiator in DDD is a miniaturised dipole antenna from [111] that covers ISM band at 2.4 GHz. The antenna can be enhanced for compact hardware integration in MIMO wireless communication system or WPT applications. First and foremost, the antenna should be modified to be functional near to conducting surface or metallic objects in wireless instruments such as discrete components, steel casing, PCB traces, connectors, cables and switches. As a result, a conducting plane (i.e. separate PCB) representing these metallic objects is included in the design simulation and fixed at 5 mm beneath the antenna. The existence of a conducting plane beneath an antenna narrows the impedance bandwidth due to capacitive structure formed by the plate and antennas. Therefore, the parameters of [111] is partially redesigned to work on conducting plane by transforming it into Yagi-Uda like structure as depicted in Figure 5.18. Two of these antennas are placed back to back on the same PCB and is spaced by a foam piece of 5 mm on top of the conducting as shown in Figure 5.18 and the bottom layer is depicted in Figure 5.19. The conducting surface is 62.5 mm × 55 mm in size and is also the overall dimension of the DDD.

The centre to centre distance between both elements is about 29 mm. At the centre of the PCB, this design has only 3 mm edge to edge separation. Two pieces of PCB
probes are designed particularly for antenna characterisation. PCB probes are used because SMA connectors are basically oversize and the connector pins will also subject to coupling due to close proximity of both feed points. In contrast, the thin PCB probes can fit in without difficulty and also can be used to solve the minor impedance mismatch introduced by the 90° joins by tuning the truncated stepping ground plane. The PCB probes are initially hard to be soldered onto the DDD PCB but the use of soft conducting surface has solved the issue because it is bendable. Other major tuning parameters are similar to [111] and also including the dimension of new director and reflector (i.e. decoupling structure) adjacent to the half bowtie radiator.

Figure 5.18: Schematic Layout of DDD

a = 13.7 mm, b = 14.75 mm, c = 19.7675 mm, d = 14.25 mm, e = 21 mm, f = 1.5 mm, g = 52.25 mm, h = 2.5 mm, i (edge to edge) = 3 mm, j (center to center = 29 mm,
5.5.2 The Decoupling Structure

To overcome mutual coupling, a microstrip structure that acting as band stop filter is designed between the half-bowtie radiators. This structure is analogous to the coplanar stripline (CPS) filters [112]. As depicted in Figure 5.18, the decoupling structure is created between the half-bowtie radiators. It is effectively a band stop resonator that prevents the coupling of 2.4 GHz band across the gap. It is found that the impedance bandwidth is affected if the stubs are longer than the directors at the edge of the board. This is because the decoupling structure (i.e. reflectors) requires a specific length to become a 2.4 GHz band stop resonator in order to reflect the energy of this band towards the directors.

A parametric study has been performed on the decoupling microstrip structure. This is to show the effect of S parameter with respect to the variation in length (e), width (f) and gap (i) of the decoupling microstrip lines. The simulation results are compiled in Figure 5.20. It is obvious that the lines in red have both the best impedance bandwidth and isolation among other combinations. As a result, the length, width and gap of the decoupling structure are determined to be 21 mm, 1.5 mm and 3 mm.

For better understanding, the current distribution of such structure is simulated to reveal the functionality of the decoupling ability. The current distribution at 2.45 GHz is demonstrated in Figure 5.21. The arrow heads represent vector surface current on the microstrip structure. At the maximum (phase = 90°), there is only very little current being coupled to the opposite side. As a result, the mutual coupling has been reduced dramatically and the S21 parameters are very low in this stop band.
Figure 5.20: Parametric Study of Decoupling Structure

(a) Variation in length, $e$  
(b) Variation in width, $f$  
(c) Variation in gap, $i$
5.5.3 Simulation and Measurement Results of the DDD

DDD is designed and finalised by using Ansoft's HFSS v11.2 and printed on RT/Duroid 5880 (i.e. 20 mils, $\varepsilon_r = 2.2$). The simulated input impedance of both input ports are depicted in Figure 5.22 whilst the simulated S parameters are shown in Figure 5.23.

From the simulated S parameters, the -10 dB bandwidth covers from 2.39 GHz to 2.51 GHz, which is about 6.5% bandwidth centralised at 2.45 GHz. The isolation is lower than -30 dB until 2.48 GHz and then it ramps up to -20 dB at 2.5 GHz. The measured S-parameters are displayed in Figure 5.24.
Figure 5.22: Simulated Input Impedance of DDD

Figure 5.23: Simulated S-parameters of DDD
The bandwidth for each element is well matched with minor difference due to fabrication error especially the alignment of conducting surface. However, the isolation parameters are almost equal. Therefore, the overall -10 dB bandwidth is the overlap bands of both input ports and is between 2.35 GHz and 2.485 GHz, which is 5.6% bandwidth centralised at 2.4175 GHz. The measured degree of isolation is better than -25 dB across the -10 dB bandwidth and inclines to -20 dB at 2.5 GHz, similar to the simulation results. Practically, Wi-Fi range is allocated between 2.4 GHz and 2.483 GHz. Thus, this antenna is still having reasonably good impedance bandwidth and isolation across 2.4 GHz WLAN frequency band. The isolation of [111] separated by 29 mm (centre to centre) without decoupling network is averagely -9.5 dB across WLAN 2.4 GHz band. By comparison, the DDD has achieved a further isolation by an average of 13 dB.

The simulated radiation patterns for antenna are shown in Figure 5.25. Patterns in Figure 5.25(a) are Antenna A whilst patterns in Figure 5.25(b) are from the Antenna B. They are mirrored patterns due to mirrored structure. Owing to the existence of conducting surface, the dipoles no longer possess an omnidirectional pattern at the horizontal plane (i.e. XZ plane). The peak of the main lobe is at 20° off the central origin and the HPBW (-3dB) is about 100° from each antenna at the XZ plane.
Figure 5.25: Simulated Radiation Patterns of DDD

(a) Antenna A (energized) (b) Antenna B (energized) (c) Isometric View

*Radiation patterns are taken when one element is energized and the opposite element is 50 Ω terminated
The measured patterns are displayed in Figure 5.26. The directional patterns of XZ planes are approximately matched with the simulation result but the measurement is comparatively stronger on E plane at the bottom side. The simulated front to back ratio of YZ plane is 16.3 dB and the measured value is about -11 dB. Referring to the measured patterns on XZ planes, the peak angle is about 25° off the central. The measured HPBW of antenna B at 2.4 GHz, 2.483 GHz and 2.5 GHz are approximately 120°, 158° and 121° respectively on the main lobe. For Antenna A, measured HPBW at 2.4 GHz, 2.483 GHz and 2.5 GHz are roughly 118°, 119° and 81° respectively on the main lobe. The difference between two antennas is due to tolerance of fabrication error as there is 1 mm to 1.5 mm of misalignment at the edge and spacing between conducting surface PCB and Antenna PCB. Misalignment at spacing in between two PCBs affects the input impedance of DDD whilst misalignment at the edge shifted the direction of peak gain. Due to the decoupling, the DDD effectively behaves like two separate antennas in free space (with the minor perturbation of a conducting element – the other antenna – close by). If they are separated, the radiation pattern of individual HBYU unit will be observed.
The simulated peak gain of the Antenna A and B at 2.45 GHz is about 4.15 dBi at 340°. The gain comparison setup used in the measurement only had access to standard gain values every 0.5 GHz from a horn antenna. Therefore, the gain at 2.45 GHz is obtained from relative comparison to the gain at 2.5 GHz. The gain is different from each DDD element. The Antenna B has peak gain of 4.969 dBi at 2.4 GHz and 4.561 dBi at 2.5 GHz whereas the Antenna A has peak gain of 4.341 dBi at 2.4 GHz and 3.746 dBi at 2.5 GHz. The reason of having less gain in antenna A at 2.5 GHz is because of the antenna alignment and the use of bendable conducting surface. It is observed that the gain changes when the distance of conducting surface at one edge is not perfectly flat. Due to the use of PCB probes, the 20 mils thick substrate is soft and difficult to be aligned exactly at 5 mm from edge to edge beneath the DDD PCB. Moreover, is not a completely flat surface because it is a soft substrate selected to ease the soldering of PCB probe feeds. It is difficult to recover the flatness after bending it for soldering and thus affecting the measured gain. However, all issues caused by the soft conducting plane are eliminated in the rectenna version because the PCB probe is used in antenna characterisation only. In short, DDD is capable to

Figure 5.26: Measured Radiation Patterns of DDD
(a) yz Plane of Antenna B (b) xz Plane of Antenna B
(c) yz Plane of Antenna A (d) xz Plane of Antenna A
work perfectly close to conducting surface in MIMO wireless communication system and WPT application. As compared to standard patch antenna that would have occupied about 42 mm × 50 mm board space on the same type of substrate, this design allows two inputs at the same frequency but with only 62.5 mm × 55 mm in size. In other words, this is equivalent to 37% smaller than two standard patch antennas without decoupling network (i.e. assume λ/4 spacing).

### 5.5.4 Comparison of Antenna Designs with Isolation Characteristic

A summary of comparison is shown in Table 5.4, where the measurement results of DDD and other references are tabulated. The DDD uses larger board size among the others as the trade off for higher gain. Other reasons of larger size are due to the Yagi like structure of each element and the use of thinner substrate with lower dielectric coefficient. However, DDD is able to maintain an average isolation of lower than -20 dB across the entire WLAN 2.4 GHz band as compared to others. Furthermore, it has narrowest edge to edge distance of 3 mm. Unlike the references, the unmodified conducting surface added beneath it acts as a shield and enables it to work closely to the metallic surface of general electronics. When the external conducting surface is larger and the proposed dimension in DDD, the S parameter is affected but recoverable by tuning of the parameters aforementioned in Section 5.5.1.

<table>
<thead>
<tr>
<th>Refs</th>
<th>Antenna Type</th>
<th>Central Freq. (GHz)</th>
<th>Peak Gain (dBi)</th>
<th>$S_{12}$ Before Isolation (dB)</th>
<th>$S_{12}$ After Isolation (dB)</th>
<th>Antenna Separation (mm)</th>
<th>Substrate Size $W \times L \times H$</th>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Max</td>
<td>Max</td>
<td>Min</td>
<td>C to C</td>
<td>E to E</td>
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<tr>
<td>[113]</td>
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<td>-13</td>
<td>~13</td>
<td>~10</td>
</tr>
<tr>
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<td>~12.5</td>
<td>~3</td>
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<td>-17</td>
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<td>-9.5</td>
<td>-20</td>
<td>-30</td>
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</tr>
</tbody>
</table>

Table 5.4: Comparison of DDD Characteristics with References

*All the measurement readings are approximate values taken within the -10 dB bandwidth, which is the overlap region of $S_{11}$ and $S_{22}$
5.6 Conclusion

Chapter 5 presents five printed antennas which are specifically designed for the proposed WPT system. The novel MHB PDA is a wideband printed dipole antenna with half bowtie shape. Its unique shape enables reasonably smaller board layout with larger impedance bandwidth (>40%) as compared to other reported designs. Due to the E field distortion of feed line on the edge of the balun, the omnidirectional pattern is skewed off the H plane. As a result, a novel CPS-Tuner on balun is implemented in the second MHB PDA design. The CPS-Tuner utilises the balun ground plane as part of the input impedance tuning parameter without affecting the overall layout. This enables the feed line to be freely adjusted without length restriction on the balun region. Therefore, the feed line is moved further away from the left dipole arm to resolve the pattern skewing issue.

However, wireless harvester needs to be integrated into consumer products, which is impossible to omnidirectional printed antenna because of the conducting surface coupling effect. As a result, HBYU antenna located 1 cm on conducting surface is designed. It is a customised MHB PDA with CPS-Tuner on a conducting surface. The conducting surface has contributed to higher gain (>6 dBi) and more directional radiation pattern, which is an advantage to harvest higher power. However, the Yagi-Uda geometry has caused the peak gain skewed off the broadside direction of the HBYU. As a result, HBYU collinear array with 2×2 HBYU elements is designed. The collinear configuration enables a symmetrical and directional radiation pattern (>8 dBi) at the broadside direction, which is similar to the printed patch antenna.

Unfortunately, the height of HBYU collinear array unit is comparatively larger than common battery-powered devices as it requires 1 cm spacing on conducting plane. As a result, novel DDD is designed. DDD has two antenna units with a microstrip decoupled network, which enabled 3 mm spacing from adjacent antenna unit. It requires only 5 mm spacing on top of conducting surface, hence occupying less space in product integration. Although DDD is larger than some of the reported designs as the trade off for higher antenna gain (>4 dBi each), it is capable to harvest higher DC power in the proposed WPT system.
CHAPTER 6: RECTENNA FOR PORTABLE DEVICE INTEGRATION

This chapter will present several useful miniaturised rectennas for the proposed WLAN EM energy harvesting system. These rectennas include Miniaturised Half Bowtie Printed Dipole Rectenna (MHB PDR), HBYU Collinear Rectenna Array (HBYU CRA) and DDD Rectenna (D³R). They are designed using the printed antennas introduced in Chapter 5 and the rectifier from Chapter 4. The output loads used in the rectenna experiments include NiMH batteries and Li-Po cell pack. The identical experimental setup will be used for each rectenna test and the measurement results will be shown in tables and graphs. Discussion and conclusion will be appended at the end of each section.

6.1 Experimental Setup

The experiment setup for rectenna characterisation in laboratory environment is depicted in Figure 6.1. In Figure 6.1, the essential equipments such as RF signal synthesizer and power amplifier are required to generate EM energy at 2.4 GHz, which is the desired frequency for the proposed WLAN energy harvesting system. A 9 dBi standard horn antenna is used as the transmitter and the transmitting power is set to 27 dBm. Basic measuring apparatus such as multimeter, ruler are needed at the receiving side. All the rectennas in this chapter are measured at the broadside direction of the transmitter without obstacle in between in order to receive maximum incident power. In other words, the rectenna is placed at the centre of the main lobe of the horn antenna, as shown in Figure 6.1 and the polarisation has to be matched. In this research, the MHB PDR, HBYU CRA and D³R are vertical polarised and the transmitter is radiating constant power continuously towards the unit under test.

Figure 6.1: Experimental setup for Rectennas Measurement
6.2 Miniaturised Half Bowtie (MHB) Printed Dipole Rectenna (PDR)

The MHB PDR for ISM band at 2.4 GHz is introduced in this section. It is designed as the fundamental reference for succeeding creations in the next few sections. This rectenna is a combination of miniaturised half bowtie dipole antenna and rectifier from Chapter 5 and Chapter 4 respectively. Figure 6.2 presents the layout of MHB PDR. The physical dimension of this rectenna is 36.5 mm × 29 mm × 0.787 mm and the antenna gain is about 2 dBi. The antenna is the same as depicted in Section 5.2 with minor changes on the CPS-tuner, which is performed for impedance matching. The rectifier is connected to the antenna directly at the dotted intersection shown in the Figure 6.2.

![Schematic Layout of MHB PDR](image)
6.2.1 Measured Open Circuit $V_{\text{DC}}$ of MHB PDR

Figure 6.3 shows the open circuit $V_{\text{DC}}$ of the MHB PDR. The minimum power required by it to produce an open circuit voltage of more than 0.1 $V_{\text{DC}}$ is at -23 dBm. In the experiment, the $V_{\text{DC}}$ produce by this rectenna is inconsistence at the distance range is further than 2 meter and the $V_{\text{DC}}$ is inconsistence, unpredictable and close to 2 V at several points further than 2.5 m. This is mainly due to the indoor environment where unpredictable multipath effect from the surroundings is the dominant incident energy to the omnidirectional rectenna. When the unit under test is getting closer to the transmitter within 2 meter range, the power from the transmitter has become dominant and then consistent increment of $V_{\text{DC}}$ can be observed. The MHB PDR is able to produce higher than 1 V within 2 m.

![Figure 6.3: Measured Open Circuit $V_{\text{DC}}$ of MHB PDR](image)

Apart from that, a secondary test is performed to power on a microwatts electronics device, i.e. scientific calculator (Casio fx-570MS). The battery of the calculator (1.5 V, 0.2 mW) is removed and replaced by a pair of jumper wires connected to the $V_{\text{DC}}$ terminal of the rectenna adjacent to the calculator. It is certified that the micropower calculator can be power on within the tested range without battery whenever the harvested $V_{\text{DC}}$ is higher than 1.5 V. The monochrome LCD will dim if the voltage dropped lower than 1.3 V. In conclusion, the performance of the MHB PDR is suitable for portable electronics in microwatts range or maybe in milliwatts range at shorter distance.
6.3 HBYU Collinear Rectenna Array (CRA)

The HBYU CRA consists of two pairs of HBYU units stacking in series and the schematic layout is depicted in Figure 6.4. The detailed layout and antenna characteristic is identical to the HBYU collinear array antenna in Section 5.4. It has two pairs of HBYU units designed back to back and then connected in a collinear configuration, which is the stacking of antennas in vertical axis. The receiving power is collected by the array feeding network (i.e. solid traces) and is connected to rectifier given in Chapter 4. The rectifier is able to fit in the layout of HBYU CRA without extra board space requirement. The minimum incident power required to produce more than 0.1 V\text{DC} is at -19 dBm. A conducting surface is fixed at 1 cm behind the rectenna array PCB by using a foam layer. The antenna gain of this rectenna is about 8.8 dBi. Apart from the higher antenna gain and higher power harvesting capability, HBYU CRA is designed to compare with portable solar charger of similar size, which will be presented in Section 6.5.2.

![Schematic layout of HBYU CRA](image)

Figure 6.4: Schematic layout of HBYU CRA

6.3.1 Measured Open Circuit V\text{DC} of HBYU CRA

The open circuit V\text{DC} of the HBYU CRA is shown in Figure 6.5. In average, the V\text{DC} harvested by HBYU CRA is higher than 1 V within the tested range. The V\text{DC} is higher than 2 V within 2.5 m range. It reaches the peak voltage at 9 V when the range is shorter than 0.5 m. At each point of measurement, the calculator power-on test is carried out and it works successfully except when the V\text{DC} dropped lower than 1.3 V at certain points of distance.
6.4 Decoupled Dual Dipole Rectenna (D³R)

The D³R is designed by combining the rectifier and the DDD from Chapter 4 and 5 respectively. The minimum power required by it to produce more than 0.1 VDC is at –19 dBm. The DDD Rectenna (D³R) has the same top layer as the DDD and the bottom layer of the rectenna is depicted in Figure 6.6. The peak gain of the antenna pair in D³R is about 4.5 dBi. According to the radiation pattern of DDD in Chapter 5, however, the peak gain of D³R is not at the 90°, where the transmitter is transmitting power. Since the rectenna measurement is defined at the broadside direction of transmitter, the actual gain of D³R at 90° is about 3.5 dBi. This is the gain value used for the analysis in this Chapter.

The low profile rectifier is intentionally designed to fit in the balun region between the half bowtie arms. Therefore, the rectifier is able to be integrated completely on the ground plane of the balun without extra board space requirement. The DC wires are to be directed through via holes as shown in the Figure 6.6. Similar to the DDD, a foam layer of 5 mm thickness is used between the ground plane and the antenna board. Therefore, holes are created in the foam and conducting surface for DC wires to get through for battery charging. It is noted that the foam layer spacing is half the thickness used for HBYU CRA, which is an advantage as the D³R can work closer to conducting surface when integrated into the consumer product.
6.4.1 Measured Open Circuit $V_{DC}$ of $D^3R$

A $D^3R$ module has a pair of rectennas and each rectenna is connected to a rectifier. Both rectennas are identical and the $V_{DC}$ of the rectifiers can be connected either in parallel or in series. In series configuration, the voltage stacks up like batteries in series and the current remains unchanged. In parallel configuration, the total current is the summation of every branch whereas the potential difference of individual terminal is preserved. The open circuit $V_{DC}$ and $I_{DC}$ measurements for both cases within 4.5 meters range are recorded and presented in Figure 6.7. When both elements of the $D^3R$ are connected in parallel, the measured open circuit $V_{DC}$ at 3 meters and further is lower than 1 V whilst the $I_{DC}$ is about 0.3 mA. The voltage ramps up consistently to 2 V at 1 meter distance from the transmitter and then increases exponentially to the 9 V peak limit at shorter range. The $I_{DC}$ is higher than 1 mA within 1.6 m range and higher than 10 mA within 20 cm range from the transmitter. If the $D^3R$ elements are in series, the average $V_{DC}$ is higher than the paralleled $D^3R$ and the difference is noticeable when the measuring distance is shorter than 2 meters where the $V_{DC}$ in series configuration is two times higher than the $V_{DC}$ in parallel configuration. However, the $I_{DC}$ of such configuration is halved when comparing to the parallel connection. This is the expected outcome analogous to the series stacking of batteries where the total potential difference is the summation of all elements in the series configuration.
The non-linearity variation of rectifying power along the tested distance can be interpreted from Figure 6.7. As referred to Figure 6.7, the DC power increases geometrically when the rectenna is within 2 meters range. It is because the VVD rectifier is originally optimised to the receiving power of about 6 to 12 dBm. At this power range, the conversion efficiency is high and the rectenna reflection loss is very low, which has been presented in Section 4.2. The DC power produced further than 2 meters remains constantly low is mainly due to the low receiving power which causes impedance mismatch between the antenna and rectifier and the additional free space attenuation.

![Figure 6.7: Measured Open Circuit VDC and IDC of D3R Elements in Series and in Parallel](image)

6.4.2 Comparison of Rectennas

A comparison of open circuit VDC of three rectennas are presented in Figure 6.8. In average, HBYU CRA, D3R in series and parallel configuration can provide better consistency and higher VDC at near range as compared to single MHB PRA unit. This is basically due to the antenna gain. The MHB PDR is an omnidirectional rectenna at 2 dBi gain whilst the others are directional rectenna. The gains of the HBYU CRA and D3R at the broadside direction of the transmitter are 8.8 dBi and 3.5 dBi respectively. Higher gain yields better sensitivity in reception but the beamwidth is narrower. Although the D3R has lower gain than HBYU CRA, it has thinner air gap, which is critical for low profile product integration. Furthermore, the output of D3R is flexible and could be connected in series and parallel depend on input requirement of the load. When higher current is desired, D3R in parallel configuration can be
adopted whilst series configuration is suitable for high voltage load with low current requirement.

![Figure 6.8: Comparison of Open Circuit VDC between Rectenna Designs](image)

### 6.5 Performance of D³R and HBYU CRA on Battery Charging

#### 6.5.1 Battery Charging with D³R and HBYU CRA

In this section, the HBYU CRA and D³R in parallel configuration are used in charging experiment with two types of batteries, they are the NiMH batteries and Li-ion cell pack. Battery charging applications require higher constant current supply (e.g. commercial charger) than voltage driven TTL electronics (i.e. calculator). As aforementioned, D³R in parallel configuration provides higher current as the VDC is connected in parallel. As a result, parallel configuration is recommended in battery charging.

In this experiment, four NiMH (4.8V) batteries are connected in series. The NiMH battery has a peak open circuit voltage at 1.35 V [114]. Therefore, four fully charged NiMH batteries in series should have an open circuit voltage of about 5.4 V. The VDC
from a D³R is connected to the terminals of battery directly through the holes on the conducting surface behind the rectenna. Using the same experimental setup as Figure 6.1, the D³R is placed 23 cm away from the radiating source. At this distance, each antenna element of D³R is capable to receive about 10 mW of wireless energy. Since the peak DC conversion efficiency of rectifier-B is above 70% when input power is at 10 mW, the total DC power is estimated to be 14 mW (i.e. 2 × 7 mW). When the D³R and HBYU CRA are connected to the NiMH battery, the measured total charging currents are 3.0 mA (0.0033C) and 4.5 mA (0.0050C) respectively. For Li-Po cell pack charging, the measured total charging currents of the D³R and HBYU CRA are 4.3 mA (0.0039C) and 4.9 mA (0.0045C) respectively. It is observed that the voltage drops back quickly if the rectenna is disconnected from the NiMH batteries too early, due to the memory effect [115]. For this reason, the recommended charging duration from [115] is implemented, which is 4 to 5 hours. Therefore, the experiment duration for NiMH batteries is set around 300 minutes.

The results of charging the two commercial batteries are shown in Figure 6.9. The charging result of the 4.8 V NiMH batteries is depicted in Figure 6.9 (a). For D³R, the voltage level ramps up rapidly at the beginning. It reaches \( V_{\text{nominal}} \) of 4.8 V within 50 minutes. The NiMH is charged to 5.2 V after 100 minutes, and continues to rise gradually until the experiment is halted at 280 minutes. For HBYU CRA, it charges to 5.2 V in 10 minutes and 5.3 V in 50 minutes. The voltage then rises gradually to 5.35 V at 280 minutes. In short, this has proved that the higher charging current supplied by HBYU CRA is much closer to the minimum trickle charging requirement of 0.01C (i.e. 9 mA) to fully charge the 4.8 V, 900 mAh NiMH batteries at that specific distance. It is noted that the NiMH voltage is not falling back immediately after the rectenna is disconnected. This is because the recommended charging duration of 4 to 5 hours is adopted in this experiment [115].

A different result is observed from BlackBerry’s Li-Ion cell pack charging. The battery is removed from the phone socket to eliminate discharging from the phone and the rectenna output is connected to the battery terminals directly. The Li-Po cell pack does not have the memory effect as the voltage is not seen to fall back when the charging source is removed at any time. The measurement results are shown in Figure 6.9 (b). When charging the Li-Po cell pack with D³R, the cell pack voltage is raised from 3.5 V to 3.6 V in 330 minutes, which is insignificant as compared to NiMH
batteries. For the case using HBYU CRA, the Li-Po cell pack is charged from 3.46 V to 3.6 V in 270 minutes and 3.62 V in 330 minutes. The starting voltage is 0.05 V lower than the case for D³R because it is very difficult to control the battery capacity precisely. However, it is obvious that the charging rate of HBYU CRA is quicker than D³R due to the higher current of 4.9 mA.

The charging of Li-Po failed to achieve its full capacity within 5 hours as compared to the NiMH charging. This is mainly due to the internal power consumption as described in Section 4.2.5. The internal battery monitoring circuit (i.e. SMBus) of the Smart Battery System (SBS) is constantly drawing power from the call pack for safety monitoring purposes. As a result, the efficiency to trickle charge Li-Po cell pack using low charging rate at 0.0045C has reduced. The trickle charging is only possible if the minimum recommended charging rate of 0.02C is available from multiple rectenna modules.

In conclusion, both HBYU CRA and D³R are showing positive results in charging unused batteries as they can increase the charge capacity in 300 minutes. Although HBYU CRA can provide higher current, the physical dimension is bulky as compared to D³R. The D³R is more suitable for consumer product integration owing to the advantages of the DDD. In short, regular NiMH batteries can be charged fairly efficiently by using D³R or HBYU CRA from 36 dBm EIRP source whilst larger array expansion is highly possible and indispensable to overcome the current requirement of smart battery such as Li-Po cell pack or for longer distance WPT applications.
Figure 6.9: Comparison of Li-Po and NiMH Battery Charging using HBYU CRA and D³R

(a) 4 × Rechargeable 1.2 V NiMH Batteries in Series
(b) BlackBerry’s 3.7 V Li-Po Cell Pack

6.5.2 Extending Li-Po Cell Pack Battery Life with HBYU CRA

The charging result of Li-Po cell pack is very insignificant in the previous section. Here, a discharging experiment is carried out by using HBYU CRA. This is to investigate whether the low charging rate could still be useful during discharging process of device with Li-Po cell pack. In this section, Nokia N73 mobile phone is used to test with HBYU CRA. The genuine Nokia battery is used, which is a Li-Po cell pack (Nokia BP-6M series, i.e. 3 terminals Smart Battery System). This battery is rated at 3.7 V with a large charge capacity of 1100 mAh. The genuine Nokia charger is able to supply 6.2 V at 890mA and this electrical property will be the reference output. The transmitted WLAN energy is very limited over 20 cm of distance and it is insufficient to produce high current as compared to the Nokia charger. It is found that 5.2 V$_{DC}$ is the essential voltage level to acknowledge the charging monitoring circuit (i.e. SMBus interface) in the Li-Po cell pack and to activate the LED charging indicator on the LCD screen. Prior to the experiment, the Nokia N73 is fully charged to the peak voltage of 4.1 V. The charging indicated is activated when the rectenna is fixed to a distance of 10 cm with 5.2 V$_{DC}$, 7.65 mA (~ 40 mW) flowing into the N73.
Self discharge of a battery with a large capacity in idle mode can take many hours. Consequently, the mobile phone is set to perform continuous video playback to amplify the power consumption. The voltage is recorded every 30 minutes. Voltage recording stops when the battery reaches critical level and the phone is switched off automatically. The objective of this experiment is to compare the discharge duration with and without the use of HBYU CRA. This experiment relies on the charging indicator on LCD screen to feedback the condition of the battery. The battery is fully charged before the looping of video playback. The peak battery voltage ($V_{bat}$) for experiment with and without rectenna is 4.085 V and 4.126 V respectively. The recorded results are shown in Figure 6.10.

![Figure 6.10: Comparison of Battery Discharge with and without HBYU CRA](image)

In Figure 6.10, the discharge curves converge after about 30 minutes. Without the rectenna, the N73 is switched off automatically by internal monitoring circuit when $V_{bat}$ is about 3.58 V, which is about 165 mA of current discharging after 400 minutes. However, if the rectenna is connected, it is switched off automatically when $V_{bat}$ reaches 3.27 V, which is about 153 mA of current discharging in 431 minutes. Discharging to 3.27 V will not damage the battery since the typical $V_{cut\_off}$ of Lithium-ion battery is between 2.5 V to 2.7 V according to [116]. The use of rectenna has extended the video playback by 31 minutes. The rectenna is suppling 7.65 mA of current at 5.2 V to the mobile phone and this result has shown that low charging current from rectenna can effectively slow down the typical discharging rate and enables longer service life when the phone is active.
Although the result is positive, this application is considered impractical because the distance between the rectenna and transmitter has to be very close, which is 10 cm in this case. Moreover, the battery life extension is insignificant by comparing the discharge curves except the additional 31 minutes at the end of experiment. When this experiment is repeated with BlackBerry’s Li-Po battery (i.e. 4 terminal smart battery), it is observed that the charging indicator is flickering. This implies insufficient charging current. Although both battery models are made of Li-Po electrochemical architecture, it is believed that the SMBus system of N73 consume less power than BlackBerry’s system because Nokia’s BP-6M cell packs has only 3 terminals (i.e. power output, thermistor and ground), which is less complicated as compared to Blackberry. Therefore, the input power requirement of Blackberry’s cell packs is probably higher than N73.

A comparison of output power between the HBYU CRA and a portable solar panel, Freeloader SC8088 is presented in Table 6.1. The optimal output current is taken when the Freeloader is under direct sunlight and the HBYU CRA is in the configuration of battery discharging experiment. The Freeloader is able to supply current at about 16 times larger than the output of HBYU CRA. In other words, a rectenna of the same size as the portable solar panel can only provide 1/16 of the output power from the portable solar panel.

<table>
<thead>
<tr>
<th>Device</th>
<th>Dimension (mm × mm × mm)</th>
<th>Optimal Output Current (mA)</th>
<th>Equivalent C-rate for 1000 mAh Li-ion battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeloader SC8088</td>
<td>188 × 62 × 17</td>
<td>120</td>
<td>0.12000C</td>
</tr>
<tr>
<td>HBYU CRA</td>
<td>164 × 55 × 10</td>
<td>7.65</td>
<td>0.00765C</td>
</tr>
</tbody>
</table>

Table 6.1: Comparison of Output Current between Portable Solar Panel and HBYU CRA

In conclusion, the experiment relies on the HBYU CRA being 10 cm from the transmitter. If HBYU CRA is over a meter away from the transmitter, it will not produce the same result because it is unable to supply the same amount of current as it could at the distance of 10 cm. The battery life extending feature may be effective to other type of portable electronics using different type of battery or at lower power consumption. For WLAN energy harvesting system over several meters
distance, the output of the HBYU CRA is more useful for applications in milliwatts and microwatts range. As stated earlier, a calculator can be powered on within 4 meters range in a room as long as the broadside of the transmitter is within line of sight, with polarisation matched. Other rectenna designs such as MHB PDR and D³R are found unable to deliver such higher current at the same distance (i.e. 10 cm) as the HBYU CRA due to lower gain. To increase the gain, a larger array of rectennas is necessary. As a result, extending battery life of the Li-Po cell pack in a mobile phone during active application discharge is impractical in real life WLAN wireless energy harvesting system unless a very high gain rectenna array is manufactured. Instead of application discharging, a battery charging experiment by using D³R when the device is inactive (i.e. switched off) will be presented in the next section.

6.6 Optimal Distribution of D³R Array
Integration of D³R into consumer products for WLAN energy harvesting is possible since it is smaller in dimension. Its open circuit V\text{DC} can be higher than 1 V within 4 meters range and higher than 2 V within 2 meters range. It is specifically designed to be configurable to form a larger array for higher power harvesting capability. However, multiple modules may not work optimally without appropriate topology due to mutual coupling. Using D³R units as example, an optimal D³R array distribution is introduced.

The experiment is performed by using two D³R modules with the same experimental setup depicted in Figure 6.1. The D³R-A is aligned to the broadside of the transmitter and the second module, D³R-B is aligned next to D³R-A as shown in Figure 6.11. The original V\text{DC} of D³R-A is defined as V₁ while V₂ represents the V\text{DC} of the D³R-A when D³R-B is located in close proximity. The V₂ is measured and recorded for every 1 cm D³R-B is moved towards D³R-A.

The incident power to the D³R-A is 10 mW at 23 cm away from transmitter and the DC conversion efficiency of the D³R-A at this point is about 74%. The V₁ is constant and the DC power, P\text{DC1} from of D³R-A when D³R-B is not present, can be derived as follows.
\[ P_{DC1} = \frac{V_1^2}{R} \]  

Where,

\( R = \text{Load resistance} \)

When \( D^3\text{R-B} \) exists, \( P_{DC2} \) is

\[ P_{DC2} = \frac{V_2^2}{R} \]  

Since \( R \) is constant throughout the entire experiment, thus ratio of \( V^2 \) is directly proportional to the variation in ratio of \( P_{DC} \).

\[ \frac{P_{DC2}}{P_{DC1}} = \frac{V_2^2}{V_1^2} \]  

Therefore, the changes in receiving sensitivity of \( D^3\text{R-A} \) due to \( D^3\text{R-B} \) will reflect on \( P_{DC2} \) and \( V_2 \). In Figure 6.11, the measured \( P_{DC2}/P_{DC1} \) when \( D^3\text{R-A} \) and \( D^3\text{R-B} \) are within a wavelength distance (i.e. \( \sim 12 \text{ cm} \)) for three angular displacements is presented.

In Figure 6.11 (a), it is observed that the \( P_{DC2}/P_{DC1} \) ratio is lower when \( D^3\text{R-B} \) is at 12 cm away from \( D^3\text{R-A} \). The ratio recovers to unity when \( D^3\text{R-B} \) is at 10 cm away from \( D^3\text{R-A} \). The \( V_2^2 \) of \( D^3\text{R-A} \) is 56% higher than its original \( V_1^2 \) when \( D^3\text{R-B} \) is at 7 cm away. This spacing distance is known henceforth as optimal horizontal distribution. Similar test is repeated to vertical and diagonal distribution. The measurements results are presented in 6.11 (b) and (c). The optimal vertical distribution is at 5 cm where 5% of power gain is acquired. For diagonal distribution, there is no significant power gain except at 5 cm, where 3% of power gain is observed. As a result, the diagonal mutual coupling is negligible assuming that the optimal vertical and horizontal distributions are both implemented.

The \( V_{DC} \) is seen to be higher than of single \( D^3\text{R} \) module because the existing of adjacent module has altered the radiation pattern to be more directional. Consequently, the main lobe has become more directional and the gain is slightly higher. These results will be supported by the measurement of radiation patterns later.

The optimal distribution is selected as presented in Figure 6.12. With this configuration, the DC power is raised 56% as compared to single \( D^3\text{R} \) unit. To reduce the overall size further, minimum distributions can be adopted, which 5 cm for
horizontal spacing and 3 cm for vertical is spacing. In this configuration, the performance of the D³Rs is equivalent to that of single module. For consumer products integration, the D³R array allocation can be in any planar form such as rectangle, cylindrical, cubical, spherical etc. as long as the polarization is matched and abided by the minimum or optimum array distribution.
6.6.1 Radiation Patterns of Two Close Distance D³R modules

Variation in performance when two D³R modules are placed near together can be explained by radiation pattern measurements. The effect on the radiation patterns are illustrated in Figure 6.13. Three measurements are taken for each element in both E and H planes. During the experiment on horizontal distribution, the H planes in Figure 6.13 (c) and Figure 6.13 (d) show that the maximum directivity is shifted towards 90° as compared to single module. In Figure 6.13 (c), the H-plane of the Antenna A in D³R-1 next to the D³R-B is compressed at 180° and gained higher directivity at +75° and -105°. This has contributed to minor increment in gain at +90°.
by about 1.2 dB. This is the reason of DC power amplification by 56% as shown in previous section when the D$^3$R is at the broadside direction of the transmitter.

The presence of D$^3$R-B introduces mutual coupling to both antennas in D$^3$R-A. For this reason, it redirects the original main lobes of the antennas in D$^3$R-A towards 90$^\circ$. As a result, the reception sensitivity (i.e. gain) of D$^3$R-A at 90$^\circ$ has increased by about 1.2 dB according to Figure 6.13 (c) and (d), which is equivalent to a power gain of 32% to each antenna in D$^3$R-A. The DC conversion efficiency of the rectifier in D$^3$R-A is about 74% during the optimal distribution test. Therefore, the P$_{DC}$ of each antenna has increased by approximately 25% when both D$^3$R modules are in optimal distribution. Assuming both antennas in D$^3$R-A are identical, the total P$_{DC}$ gain is about 50%. This is close to the 56% in Figure 6.11 (a).

The impact on E-plane shaping in vertical array distribution is insignificant as compared to that of H-plane in horizontal array distribution as can be seen in Figure 6.13(a) and (b). As a result, the DC power gain in optimal vertical distribution is insignificant.
Figure 6.13: Radiation Pattern of Two $D^3R$ modules at 2.4 GHz with Optimal Spacing

(a) E-Plane of Antenna A (b) E-Plane of Antenna B
(c) H-Plane of Antenna A (d) H-Plane of Antenna B
6.6.2 Conclusion of the Rectenna Designs

The characteristics of rectenna designs in this Chapter can be summarised in Table 6.2. The MHB PDR is a low profile rectenna suitable for microwatts electronic. It has 2 dBi gain with omnidirectional power reception capability. The HBYU CRA is designed to overcome the low gain issue of MHB PDR. The HBYU CRA possesses 8.8 dBi gain. It is able to harvest at least 1 V DC within 4.5 meter range at the broadside direction of the transmitter. It is able to power up microwatts devices and charge up NiMH batteries. Due to its high gain characteristic, the output current is highest among the rectenna designs and suitable for charging large capacity battery at close range from transmitter. For this advantage, it is also able to prolong Li-Po cell pack by 31 minutes. A D3R is a pair of compact decoupled rectenna. It is designed to be output configurable and more compact than HBYU CRA. It is configurable in terms of output voltage and current because the output of the rectenna pair can be connected in series or parallel depends on requirement. The average output V DC is higher than MHB PDR. It has narrower spacing between conducting surface as compared to the HBYU CRA for better integration in consumer product. Due to the isolation characteristic, the array distribution occupies smaller dimension than HBYU CRA. As compared to the dimension of HBYU CRA (164.5 mm × 65 mm × 10 mm), two D3R modules (130 mm × 55 mm × 5 mm) in optimal vertical distribution can accommodate four rectennas with 33% board space reduction. In future work, additional decoupling can be performed between D3R modules in vertical and horizontal arrangement to enable the closest gap possible between the D3R modules in the optimal distribution in order to provide better harvesting capability.

<table>
<thead>
<tr>
<th>Rectenna</th>
<th>Radiation Pattern</th>
<th>Approximate Gain at 90°</th>
<th>Tested range to harvest 1 V DC</th>
<th>Charging Rate (C rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dBi</td>
<td>m</td>
<td>NiMH</td>
</tr>
<tr>
<td>MHB PDR</td>
<td>Omnidirectional</td>
<td>2</td>
<td>≤ 2</td>
<td>N/A</td>
</tr>
<tr>
<td>HBYU CRA</td>
<td>Directional</td>
<td>8.8</td>
<td>≤ 4.5</td>
<td>0.0050</td>
</tr>
<tr>
<td>D3R</td>
<td>Directional</td>
<td>3.5 × 2</td>
<td>≤ 3</td>
<td>0.0033</td>
</tr>
</tbody>
</table>

Table 6.2: Summary of Rectenna Characteristics

6.7 Possible Integration of D3R into Consumer Products

Historically, most low power consumer electronics such as wireless mouse, remote controllers, children’s toys, electric mini torch and alarm clocks require several AA,
AAA cylindrical batteries or a 9 V cubic cells. High end consumer products such as mobile phones and portable audio or video players utilise a Li-ion cell pack at 3.6 V or 3.7 V. This reflects the trend of a declining input voltage requirement in the present day applications. Although certain handheld products such as calculators only require 1.5 V, the 3.3 V input voltage standard remains the most common among TTL standard electronics. By referring to the optimum array distribution requirement of D³Rs in Section 6.6, several examples of product integration are demonstrated in Figure 6.14. For example, a brief case can be modified to fit 12 units in each of the front and back panels, with 3 units in each side. For smaller portable handsets such as mobile phones, a D³R can fit behind the back casing.

Figure 6.14: Possible D³R Array Integration into Consumer Products

\[ a = 7 \text{ cm}, \ b = 5.5 \text{ cm}, \ c = 6 \text{ cm}, \ d = 5\text{cm} \]
6.8 Possible Implementation of Wireless Power Transmission

A simple model of one possible implementation of wireless power transmission is presented in Figure 6.15. The model includes an omnidirectional radiator transmitting constantly at 30 dBm with a 6 dBi antenna (36 dBm EIRP), and the briefcase and mobile phone models which are integrated with D³R modules. A numerical analysis using the Friis Transmission Equation has been performed based on the gain characteristic of D³R optimal distribution in order to investigate the feasibility of WPT at the 2.4 GHz. Figure 6.16 presents the numerical result of received power available within 4.5 meters range when broadside of the D³R (90° gain) is at the broadside direction of the transmitter, whilst Figure 6.17 shows the receiving power when the edge of the D³R (180° gain) is at the broadside of transmitter.

![Figure 6.15: Possible Model of WPT System](image-url)
Figure 6.16: Receiving Power at 90° Gain of D³Rs at the broadside of Transmitter

(a) Receiving Power in mW  (b) Receiving Power in dBm

*All the numerical results has taken a pair of rectennas in D³R into account
Figure 6.17: Receiving Power at 180° Gain of D³Rs at the broadside of Transmitter
(a) Radiation from 180° Gain of D³R (b) Receiving Power in mW (c) Receiving Power in dBm

*All the numerical results has taken a pair of rectennas in D³R into account
Assuming that the front panel of the briefcase is facing the broadside of the transmitter, the gain of the each D³R array at the front panel is given by

\[ G_{D^3R_{\text{front}}} = 3.5 \text{ dBi} + 1.2 \text{ dBi} = 4.7 \text{ dBi} \]

Where,

1.2 dBi is the gain amplification for D³R elements in the optimal distribution.

When the broadside of transmitter is directed towards the edge of the D³R modules on the side panel of the briefcase, the D³R will have different receiving gain on each element. By referring to the radiation pattern of D³R in Figure 5.24, the gain at 180° of Antenna A that is facing the broadside of transmitter is given by

\[ G_{\text{side}_A} = 4.5 \text{ dBi} - 0.8 \text{ dBi} = 3.7 \text{ dBi} \]

The gain at 180° of the Antenna B facing the broadside of transmitter is given by

\[ G_{\text{side}_B} = 4.5 \text{ dBi} - 7.1 \text{ dBi} = -2.6 \text{ dBi} \]

Under the suggested possible model in Figure 6.15, the total power received by the D³R modules on briefcase and mobile phone within 4 meters range is given as follows.

When 90° gain of D³R on the briefcase front panel is at the broadside direction of the transmitter,

\[
\text{Total } P_{r_{\text{briefcase}}} = \text{Front (90°)} + \text{Side (180° of A + 180° of B)} \times 2
\]

At 1 meter, \( P_{r_{\text{briefcase}}} = 27.9005 + (2.7703 + 0.6494) \times 2 = 34.7399 \text{ mW} \)

At 2 meter, \( P_{r_{\text{briefcase}}} = 6.9751 + (0.6926 + 0.1621) \times 2 = 8.6845 \text{ mW} \)

At 3 meter, \( P_{r_{\text{briefcase}}} = 3.1001 + (0.3078 + 0.0722) \times 2 = 3.8601 \text{ mW} \)

At 4 meter, \( P_{r_{\text{briefcase}}} = 1.7438 + (0.1731 + 0.0406) \times 2 = 2.1712 \text{ mW} \)

When 90° gain of D³R on the mobile back panel is at the broadside direction of the transmitter,

\[
\text{Total } P_{r_{\text{phone}}} = \text{Front (90°)}
\]

At 1 meter, \( P_{r_{\text{phone}}} = 1.7637 \text{ mW} \)

At 2 meter, \( P_{r_{\text{phone}}} = 0.4409 \text{ mW} \)

At 3 meter, \( P_{r_{\text{phone}}} = 0.1960 \text{ mW} \)

At 4 meter, \( P_{r_{\text{phone}}} = 0.1102 \text{ mW} \)
When $180^\circ$ gain of $\text{D}^3\text{R}$ on the briefcase front or back panel is at the broadside direction of the transmitter,

\[
\text{Total } P_r_{\text{briefcase}} = \text{Side (90°)} + \text{Front (180° of A + 180° of B) } \times 2
\]

At 1 meter, $P_{r_{\text{briefcase}}} = 5.2912 + (11.0811 + 2.5977) \times 2 = 32.6488 \text{ mW}$

At 2 meter, $P_{r_{\text{briefcase}}} = 1.3228 + (2.7703 + 0.6494) \times 2 = 8.1622 \text{ mW}$

At 3 meter, $P_{r_{\text{briefcase}}} = 0.5879 + (1.2312 + 0.2886) \times 2 = 3.6275 \text{ mW}$

At 4 meter, $P_{r_{\text{briefcase}}} = 0.3307 + (0.6926 + 0.1624) \times 2 = 2.0407 \text{ mW}$

When $180^\circ$ gain of $\text{D}^3\text{R}$ on the mobile back panel is at the broadside direction of the transmitter,

\[
\text{Total } P_r_{\text{phone}} = \text{Side (180° of A + 180° of B)}
\]

At 1 meter, $P_{r_{\text{phone}}} = 0.9234 + 0.2165 = 1.1399 \text{ mW}$

At 2 meter, $P_{r_{\text{phone}}} = 0.2309 + 0.0541 = 0.2850 \text{ mW}$

At 3 meter, $P_{r_{\text{phone}}} = 0.1026 + 0.0241 = 0.1267 \text{ mW}$

At 4 meter, $P_{r_{\text{phone}}} = 0.0577 + 0.0135 = 0.0712 \text{ mW}$

The theoretical receiving power is summarised in Table 6.3 and 6.4.

<table>
<thead>
<tr>
<th>Model Product</th>
<th>$P_r$ when 90° gain of Front or Back Panel is at the Broadside Direction of Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range (m)</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mobile Phone</td>
<td>mW</td>
</tr>
<tr>
<td>Briefcase</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 6.3: Total Receiving Power when the 90° gain of Front or Back Panel is at the Broadside Direction of Transmitter

<table>
<thead>
<tr>
<th>Model Product</th>
<th>$P_r$ when 180° gain of Front or Back Panel is at the Broadside Direction of Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range (m)</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mobile Phone</td>
<td>mW</td>
</tr>
<tr>
<td>Briefcase</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 6.4: Total Receiving Power when the 180° gain of Front or Back Panel is at broadside of transmitter
From earlier sections, the charging power provided by D$^3$R for NiMH and Li-Po experiment is at least 14 mW. The power harvested by the briefcase within 2 meters range from the transmitter could be more than 10 mW and sufficient to trickle charge NiMH batteries at a slow pace. The charging rate will be faster if the briefcase is placed closer to the transmitter on higher ground. At range further than 2 meters, the amount of power is fairly low but may be adequate to power up microwatts electronics such as calculator, or to charge the battery for microwatts device when kept in the briefcase.

When the side panel of the briefcase is facing the broadside of transmitter, the overall receiving power is reduced by approximately 6%. The reduction is insignificant as the 180° gain of both front and back panels has contributed to the total output DC power. Conversely, the back panel has no input when the front panel is at the broadside of transmitter. For the case of mobile phone, single D$^3$R can only harvest more than 1 mW at 1 m distance from the transmitter. When it is not optimally facing the broadside of the transmitter, the receiving power is less than 1 mW at a distance further than 1 meter. This power might be useful for certain independent features in the mobile phone that requires very low power to operate.

If multiple transmitters were used, it is possible that the overall receiving power for each case will be increased. An example is shown in Figure 6.18.

![Figure 6.18: Possible Model of WPT System with Multiple Transmitters at Different Locations](image)
Assuming that the brief case is in a room of 5 m × 5 m and there are four identical transmitters of 36 dBm EIRP at four corners on the ceiling. The briefcase is placed at four locations as depicted in the Figure 6.18 and the front panel is facing the broadside of Transmitter. The possible receiving power of the D³R modules in the briefcase can be predicted and summarised in Table 6.5.

<table>
<thead>
<tr>
<th>Location</th>
<th>P_r (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tx-A</td>
</tr>
<tr>
<td>Centre</td>
<td>2.2</td>
</tr>
<tr>
<td>A</td>
<td>13.5</td>
</tr>
<tr>
<td>B</td>
<td>1.2</td>
</tr>
<tr>
<td>C</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 6.5: Approximate Total Receiving Power of the Briefcase at Various Locations in a Room

Assuming the briefcase is initially located on the floor at the centre of the room, the distance between the transmitter and the briefcase is about 4 meters instead of 3.5 meters due to the downward directed angle. If the briefcase is at the centre and its front panel is facing the broadside of Transmitter-A, the total receiving power of the D³R modules in the briefcase is 8.4 mW. This is sufficient for NiMH battery trickle charging. When the briefcase is located at Location-A with its front panel facing the broadside of Transmitter-A, the total receiving power is about 15.5 mW. Placing the briefcase at Location-B and facing the broadside of Transmitter-B, it would collect about 9.9 mW of DC power. At Location-C with the briefcase front panel facing the broadside of Transmitter-C, the total receiving power is about 8.5 mW. Hence, the overall receiving power is still highest when the front panel of the briefcase is closer to the broadside of a particular transmitter. However, at distances further away the total received power can be significantly boosted (by up to almost 4 times) by using multiple transmitters.

In conclusion, this Chapter has presented the performance of three rectennas and demonstrated the performance with consumer batteries by using HBYU CRA and D³R. It has proven that the HBYU CRA and D³R could be used to trickle charge NiMH batteries efficiently and Li-Po cell pack at a much slower pace in comparison. In a theoretical model, a briefcase integrated with 30 D³R modules is possible to
harvest more than 10 mW within 2 meters range from a transmitter of 36 dBm EIRP. The rectenna on smaller mobile device will only offer limited power below 0.3 mW at a distance further than 2 meters. Multiple transmitters maybe implemented to increase the incident energy to the rectennas in the consumer products.

6.9 Conclusion

Chapter 6 has presented three novel rectennas which are specifically designed for the proposed WPT system. The rectenna experiments apply the FCC’s 36 dBm EIRP standard by using a 9 dBi horn fed by 27 dBm transmitting power. Commercial NiMH batteries and Li-Po cell pack have been used as the DC load in the experiment. The setup configuration is preserved throughout the experiments. A conclusion has been provided in Section 6.6.2 regarding the rectenna open circuit measurement and battery charging performance.

Apart from individual rectenna performance, this chapter has also included the possible integration of D³R into consumer products. A briefcase and mobile phone are taken as the examples in this research study. Possible implementation of WPT system with the same transmitter setup and suggested samples in a room has been presented together with the numerical computation results. Positive result has shown that the D³Rs inside the briefcase could receive more than 2 mW within 4 m range.

Furthermore, numerical study of multiple power sources has been presented. Separate sectoral transmitters could be attached at each corner on the ceiling in the room (5 m × 5 m) to enhance the harvested DC power of the D³Rs inside the briefcase. Numerical results have proven that the D³Rs in the briefcase could have harvested more than 8 mW at the centre of the room, where each of the transmitters is about 4 m away. Practically, this is adequate to charge a NiMH battery up to the nominal voltage in 5 hours.
CHAPTER 7: CONCLUSION

Wireless Power Transmission (WPT) technology has been gaining interest in recent years. The WPT technology by electromagnetic propagation coupling has been under active research and development due to the emergence of wireless technology. Plenty of recent technologies have been developed to achieve wireless power transmission. These include the wireless power transmission by resonance coupling, magnetic resonance coupling and electromagnetic propagation coupling. Owing to the common application of wireless communication, 2.4 GHz ISM band is selected as the medium of wireless power transmission using rectenna.

This dissertation presents an analytical and experimental study to design rectenna prototypes and to investigate the feasibility of a WPT system which harvests WLAN energy at the 2.4 GHz ISM band. The WPT system using rectenna consists of several components such as the transmitter, receiver and rectifier. The analytical study of the transmitter side includes the numerical analysis of permissible output power level based on the Federal Communications Commission (FCC) regulation, propagation loss and the available energy over applicable distance of interest. According to the FCC regulation, a WLAN transmitter is required to abide by the FCC’s guideline for Equivalent Isotropic Radiated Power (EIRP) output, which is stated as 36 dBm. The analysis has shown that the power available within several meters range from an FCC’s certified wireless transmitter could be converted into DC power by using efficient rectennas. The resultant DC power is suitable for low power consumption electronics or battery trickle charging applications at close distance.

Rectenna is the wireless power receiver. Majority of this research has included the design and development of suitable rectennas for battery charging. Several novel techniques in printed antenna and rectifier development have been presented to resolve the research questions. Firstly, these components are specifically designed to occupy the smallest form factor possible for consumer device integration. The antenna and rectifier are designed with respect to the proposed system model described in the earlier chapters. The low profile and efficient rectifier used throughout the design and development of rectenna is the Villard’s Voltage Doubler (VVD). It consists of Schottky barrier diodes and capacitors. As compared to the other rectifiers, the Villard’s voltage doubler has been optimised to provide over 70% DC conversion efficiency at 2.4 GHz ISM band. It supplies sufficient DC power to
charge the batteries while being able to be integrated in to the rectenna designs without the need for any extra space on the PCB board.

Various new innovative techniques and methodologies have been investigated and implemented in the rectenna designs in order to succeed the miniaturisation. A Miniaturised Half Bowtie Printed Dipole Antenna (MHB PDA) with integrated balun is designed and proven to work successfully. The half bowtie shape is the key element to achieve shorter vertical dimension of antenna board than the traditional approach. It possesses 47% bandwidth with only 0.36 λ size, centralised at 2.97 GHz. It covers ISM band at 2.4 GHz and suitable for multiple wireless communication standards and the wireless power transmission system. Apart from that, the CPS-Tuner is created to achieve shorter balun and feed line length of a dipole antenna as well. The low profile characteristic and simplicity of MHB PDA have enabled the possibility of consumer product integration.

However, omnidirectional dipole cannot work close to conducting surface. In the next stage of the research, further enhancement is achieved by reducing the capacitive ground plane effect caused by nearby conducting surface. For this reason, a conducting backplane is included in the development of the antennas. As a result, the Half Bowtie Yagi-Uda (HBYU) antenna is designed. It is a customisation of single element MHB PDA. To preserve impedance bandwidth at 2.4 GHz band, the CPS-Tuner and Yagi-Uda topology are utilised in the modification. HBYU is located 1 cm on the conducting surface. The peak gain of HBYU is about 6.7 dBi.

Although HBYU is able to operate on conducting surface without affecting its S-parameters, the radiation pattern is 20° off the maximum broadside direction. The unwanted skewing is due to the Yagi-Uda topology applied in the design. To combat this issue, four elements of HBYU are used in HBYU collinear array design in order to produce higher gain and symmetrical broadside radiation pattern. In a 2×2 collinear array, the radiation patterns of HBYU elements resembles the pattern of microstrip patch antenna. The peak gain of HBYU collinear array is 8.8 dBi at the broadside direction.

High gain antenna can harvest more DC power. Unfortunately, the size of HBYU collinear array is generally larger than common handhelds in the market and hence
inappropriate for consumer device integration. Owing to this limitation, decoupling network is required to enable close spacing between the elements of an antenna array. Therefore, the Decoupled Dual Dipole (DDD) antenna is designed. The DDD is a pair of customised HBYU antennas with a compact microstrip decoupling structure in between. The decoupling structure works as microstrip filter which enables integration of two HBYU antennas (4.5 dBi) into a compact device with narrow spacing (3 mm) in between. It is noteworthy that the DDD is intentionally designed to operate at 5 mm on top of the conducting surface, which closer to conducting surface comparing to HBYU antenna. This is an advantage for device integration.

In all of the experiment setup, a 9 dBi horn antenna is used to transmit 27 dBm signals, which is equivalent to a maximum of 36 dBm EIRP. The rectennas are placed at the broadside of the transmitter during the measurements. Three rectenna designs are investigated with constant load throughout the research. The first rectenna is the MHB Printed Dipole Rectenna (PDR), which is designed by integrating the rectifier into the MHB PDA. The minimum power required to produce an open circuit voltage ($V_{DC}$) of more than 0.1 $V_{DC}$ is at -23 dBm. The range required by MHB PDR to harvest 1 V from the transmitter is 2.3 meter.

The second rectenna is the HBYU Collinear Rectenna Array (HBYU CRA). On average, the $V_{DC}$ harvested by HBYU CRA is higher than 1 V within 4 meters range. It is able to harvest 10 mW at about 63 cm away from transmitter. Furthermore, it can fully charge NiMH batteries (4.8 V, 900 mAh) up to 5.3 V at 23 cm away from transmitter. For a Li-Po cell pack (3.7 V, 1100mAh), the HBYU CRA is able to charge it from 3.46 V to 3.62 V in 330 minutes. At 10 cm from the transmitter, it is capable to prolong Nokia Li-Po cell pack cycle life by 31 minutes when the cell pack is discharging heavily during video playback.

The last rectenna is the DDD Rectenna ($D^3$R). Similar to the HBYU CRA, it is designed by integrating the VVD at the centre of the DDD without a requirement for extra board space. The feed line is shortened by using CPS-Tuner and the VVD is fitted on the balun region. Due to DDD’s antenna characteristics, the $D^3$R is the most suitable for the proposed harvesting system among the created rectennas though it does not possess high gain like the HBYU collinear rectenna. Apart from its smaller physical dimensions than the HBYU CRA, the output of $D^3$R is configurable like the
batteries. The rectenna pair in a D³R can be connected in parallel or series configuration depending on the applications. In series configuration, the rectenna output voltage is added and the current remains unchanged. In parallel configuration, the total current is the sum of every element whereas the voltage remains unchanged. The D³R is also able to charge NiMH batteries and Li-Po. However, the gain of D³R is lower than HBYU CRA. Therefore, the DC current harvested by D³R is slightly lower than HBYU CRA at the same distance from the transmitter. Experiments revealed that the D³R can charge NiMH batteries and a Li-Po cell pack up to 5.2 V and 3.60 V respectively, at a slower pace as compared to HBYU CRA. To combat this issue, D³R optimal array distribution is investigated. The optimal topology for D³R modules in an array is introduced and the recommended spacing is able to improve the DC power output of each module by 56%, which in turn accelerates the charging time.

By referring to the experimental results in this dissertation, it is possible to extrapolate the feasibility of harvesting constant WLAN signal energy. Numerical analysis has been performed by taking example of D³R optimal distribution array on a briefcase and single D³R module on a mobile phone. Power of more than 10 mW can be harvested within 2 meters using multiple rectenna units integrated to the briefcase. The power in this model is sufficient for powering up microwatt electronics within 2 to 3 meters range. Multiple transmitters in a room will increase the receiving power of the rectennas in the consumer products.

This research study has clearly demonstrated the possibility of implementing the wireless power transmission technology in battery powered applications within 1 meter range. The feasibility of the WLAN energy harvesting system is highly application-specific in terms of power requirement and physical dimension. In conclusion, wireless power transmission technology in the WLAN band is possible to be a successful energy harvesting technology for low-power applications.
7.1 Future Recommendations

Future research and development should emphasise on the further size reduction of the antenna elements, the D$^3$R optimal array distribution and the design of rectifier. Printed antenna miniaturisation will enable more rectenna elements to be integrated to any device. The microstrip decoupler presented in this dissertation demonstrates that the mutual coupling between antenna elements can be reduced. With a good decoupler, the module spacing in an array may be further reduced both horizontally and vertically. Therefore, the power harvested per unit area could be improved significantly. This is essential to achieve an even higher degree of integration while increasing the wireless power harvesting capability.

The rectifier is another key element in many WPT technologies. The efficiency of the rectifier has the potential to achieve better performance. Possible methodology such as integrated circuit transistor rectifier is able to achieve higher efficiency and smaller form factor. Rectifier made of transistor and fabricated into a chip has lower dissipation loss and very low profile.
REFERENCES


[99] Y. Wen, Z. Xue, S. Yang, W. Ren, and W. Li, "Design and analysis of a 3GHz printed dipole antenna," in 4th International Conference on Microwave and Millimeter Wave


LDO Regulator Schematic and Layout
LDO Regulator Schematic and Layout
Appendix B
PROVISIONAL SPECIFICATION

2008906194 filed 1st December 2008

Invention Title: Wireless Power Transfer

Applicant: RMIT University

Inventor: Wai Siang YEOH
Alan WONG
Wayne ROWE

The invention is described in the following statement:
WIRELESS POWER TRANSFER

This invention relates to a method and apparatus for providing power to portable electronic devices such as mobile phones and laptop computers using radio frequency radiation.

Background to the Invention

There have been a number of attempts to provide wireless power to electronic devices to charge batteries.

USA patent 6856291 discloses an energy harvester with a tuned antenna with regenerative feedback for use in IC chips.

USA 7084605 discloses a device for converting ambient RF energy into DC power comprising an antenna, a rectifier, a tuning circuit and a storage device such as a battery.

USA 2007/0173214 discloses wireless autonomous devices with energy harvesting circuitry and RF transmitting circuitry. The transmitter can transmit information.

USA 7027311 and USA 2006/0164866 disclose a device for converting ambient RF energy into DC power which includes an antenna, an inductor with its impedance tuned to the antenna, and a rectifier and storage device. A related USA application 2007/108819 is directed to incorporation of the charge device into a phone.

USA application 2006/0160517 discloses a power supply using an array of antennas to harvest ambient RF and convert to DC power.

Japanese abstract 2005261187 discloses a a power supply for a mobile phone uses a rectenna and an ISM frequency.

USA application 2006/0264593 discloses a wireless battery charging system in which communication is established between a transmitter and a wireless device and if the devices battery needs charging the transmitter focuses an energy beam toward the device to charge the battery.

USA application 2008/0122297 discloses a control system that allows energy harvesting to supplement power supply to a portable electronic device.

USA application 2005/0206490 discloses a double transformer balun for matching the impedance of an antenna.

The harvesting efficiency of these proposals is generally below 50%.
It is an object of this invention to provide an efficient energy harvesting device and a system that allows wireless charging of batteries when needed preferably, with wireless energy directed specifically towards authenticated mobile user devices.

Brief Description of the Invention

To this end the present invention provides an energy harvesting device for converting RF signals to DC current for charging electrical energy in electronic devices which incorporates a dipole antenna with a balun and a vector network analyser for impedance matching.

The device preferably uses a miniaturised microstrip dipole antenna which is fine-tuned to receive electromagnetic waves at the WiFi wireless channel of 2.45GHz based on the IEEE 802.1X networking protocol. However, the frequency of operation is not be limited to 2.45 GHz, as the design can be scaled to between (but not limited to) 30 MHz to 65 GHz.

Printed antennas are commonly used in wireless communication due to the simplicity in design and fabrication. These types of antenna are also suitable to be integrated into wireless electronic devices. Microstrip technology is used for impedance matching, which can be tuned more effectively than arrangements of discrete inductors and capacitors, due to lower component counts and lower tolerances on achievable inductance and capacitance.

The impedance matching circuit is optimised using a Vector Network Analyser, and then further with a practical load attached in order to reduce the degree of mismatch in the circuit. Furthermore, the design of this invention has considered the effect of the jumper wires, connectors or other supporting circuits and components of the system in order to obtain close to ideal impedance matching between rectifier and the receiver. This method has enabled a DC power conversion efficiency well in excess of 50% to be achieved and yields a stable harvesting system. The miniaturised printed dipole antenna also saves a lot of printed circuit board space as compared to other antennas described in the prior art. This characteristic provides an advantage when multiple receivers are used on the same device, e.g. receiver arrays. The antenna produces a radiation pattern similar to that of a standard dipole antenna, having an omnidirectional shape. This means it has power receiving capabilities in almost all directions. If an increase in gain is required (i.e. a
directional antenna), the miniaturised printed dipole element may be arranged in an array structure, or a metallic plane can be placed near the antenna to act as a reflector. The post-design flexibility of this printed dipole type antenna with a voltage doubling circuit (rectenna) is superior to other patch based rectennas which have a pre-designed ground plane. With the microstrip dipole antenna, a gain of approximately 2 dBi can be achieved in an omnidirectional pattern.

Unlike prior art harvesting technology that produces power by harvesting RF energy across a large range of frequencies, the wireless power receiver of this invention boosts its power using a built-in voltage doubler circuit. This rectenna can also be implemented in an array of multiple rectenna elements, which simultaneously capture and convert the energy into DC voltage. Antenna arrays are formed by assembling identical antenna element to form a large antenna aperture. Each rectenna element will contribute to the overall power harvesting. For example, if a single rectenna element produces 1.44mV, 20 rectenna elements may produce a total output of approximately 28.8mV, subject to changes in omnidirectional radiation pattern and antenna gain due to mutual coupling between each element. In another aspect this invention provides a system of providing wireless power to electronic devices registered to a LAN which includes:

1. a transmitter with beam forming capability
2. energy harvesting devices incorporated in electronic devices registered to the LAN
3. an authentication protocol for establishing communication between the transmitter and the energy harvesting devices
4. a control means for focussing the transmitted beam toward the authenticated energy harvester to maximise power transfer.

The power transfer technology of this invention has the potential to significantly reduce battery charging time, as long as the wireless power signal can be detected in the environment. Using the industry-standard hand-shake and authentication protocol for wireless communications, it is possible to program the power receiver to accept the "energy streaming" only when the identity of the device is authenticated.

This invention enables

- the existing wireless communication infrastructure to transfer the power.
• radiation to be kept within FCC regulation or IEEE 802.11x WIFI radiation standard.
• sufficient power for low-power applications such as portable electronic devices
• high power conversion rate
• utilize array structure to increase the power
• flat packaging and small size to fit into a typical portable electronic device
• medium transmission range (up to 5 m)
• stable and regulated power output even when the receiver is close to the source.

Detailed description of the invention
Preferred embodiments of the invention will be described with reference to the drawings in which:

Figure 1 illustrates the layout of a miniaturised half bowtie dipole antenna of this invention;
Figure 2 displays the simulated S11 of the miniaturized half bowtie dipole antenna of figure 1;
Figure 3 shows the simulated impedance variation of the miniaturized half bowtie dipole antenna of figure 1;
Figure 4 is the radiation pattern of the miniaturized half bowtie dipole antenna of figure 1;
Figure 5 is a representation of one embodiment of an arrayed energy harvesting device pertaining to this invention;
Figure 6 illustrates the selective power streaming of this invention due to the authentication ability;
Figure 7 illustrates the scope for increasing the power harvested by a device by utilizing idle time slots in one of the preferred embodiments of the invention where the wireless power transmitted is integrated into a IEEE 802.11x router;
Figure 8 illustrates a multi-point power transmission in accordance with the invention.
A dipole antenna with an integrated balun has better bandwidth than the conventional balanced dipole. This balun consists of a microstrip feed line grounded to one arm of the dipole antenna located on the other side of the substrate, with via hole that shorts the line to the opposing arm. A miniaturized half bowtie printed dipole antenna is used in this invention and illustrated in figure 1. It is a two layered printed antenna with the feed line on the top surface of a dielectric substrate, while the radiating arms are on the bottom surface.

The main objectives of the miniaturization of a printed antenna are shrinking and optimizing the overall dimensions of an antenna in order to achieve a smaller board size while preserving its performance. The antenna used in this invention is different from an ordinary dipole in that the dipole arms are replaced by half bowtie shapes. In principle, a bowtie antenna requires shorter arm length than a normal dipole antenna that operates at the same resonance frequency. This can be observed by comparing a bowtie antenna with a normal dipole antenna that operates at same frequency. The wider the flare angle of the bowtie, the shorter the length of the arms is required for the particular frequency of choice.

The half bowtie shape is shown to closely resemble the characteristics of a full bowtie antenna, in that it achieves a wide impedance bandwidth with a short dipole arm length. The half bowtie dipole design consists of merely two geometries, which are the balun feed line and radiating arms. No additional structure is required to achieve this performance such as external impedance matching elements.

A schematic diagram of the proposed half bowtie dipole antenna with integrated balun is presented in Figure 1. The overall dimensions of the antenna are 37.5 mm × 19 mm which is 11% smaller in size than similar designs. The design resides on a Rogers RT/duriod 5880 substrate with 0.787 mm thickness.

Tuning parameters such as the width and length of the balun feed line, position of the via hole, and the gap between the arms allows many degrees of freedom to improve the overall antenna performance. The input impedance of the balun feed line can be adjusted to match that of the bowtie and yield a wide bandwidth characteristic. Moreover, the simulated efficiency can be increased when feed length is close to λ/4 at the desired central frequency. The depth and width of the gap between the dipole arms also affects the antenna response. An analysis of
these parameters to tune the input impedance of the antenna will be presented at
the conference.

The half bowtie dipole antenna provides a 10 dB return loss bandwidth of 1.17 GHz
and centralized at 2.845 GHz (41%) as shown in Figure 2. Figure 3 depicts the
impedance locus of this antenna on a Smith chart. The impedance locus circulates
the center of the chart, which yields the wide bandwidth of the antenna.

The simulated radiation patterns of the antenna exhibits the traditional dipole shape
as shown in Figure 4 over the entire impedance bandwidth. Note that the simulation
tool (Agilent Momentum) used to generate these figures is based on Moment
Method analysis which employs an infinite ground plane, hence the nulls appearing
at ± 90 degrees in the H-plane. The simulated efficiency of the half bowtie dipole
antenna is between 93% and 94%. The simulated gain remains above 1.85 dBi
which is close to the performance of a typical dipole antenna.

The rectenna as described in Figures 1 to 4 can be used in an energy harvester to
power/charge batteries in portable electronic devices. Array formation (one
functional example of which is schematically shown in Figure 5) can also be
implemented to increase harvested power. A preferred system embodiment
suitable of this invention will now be described with reference to Figures 6 to 8.

Authentication:

The Wireless Power Transmitter (WPT) system of this invention utilises a steerable
antenna and user authentication technology. The user is first identified using
802.11x authentication methods (or similar) before the wireless power is allowed to
flow to the user’s device as shown in Figure 6. In 802.11x authentication methods
each mobile client (called a station) must authenticate to the Access Point (AP).

The station requests authentication and the AP responds with an encrypted
challenge. The station can decrypt the challenge and respond only if it has the
correct password. This form of communication may also allow a station to inform
the transmitter when it no longer requires wireless power (i.e. its battery is fully
charged) to reduce power consumption in the transmitter.

Beamforming:

Once the user is authenticated, the radiation of the transmitter will be directed
towards the authenticated user for maximum power delivery using antenna beam
forming technology. Beamforming changes the directionality of the transmitter.
antenna array. When transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of radiation to delivery maximum power to the authenticated user. Beamforming techniques can be broadly divided into two categories: conventional (fixed) beamformers/switched
beam smart antennas, and adaptive beamformers/adaptive array smart antennas.

**Full Transmission Utilisation:**

Wireless data transmissions are often time division multiplexed to enable separate slices of time to be allocated to different authenticated users. Data transmission (e.g. internet traffic) is also very sporadic, and may consist of large periods of time where no data is transmitted. When there is no data communication taking place, a multifunction wireless transmitter (which incorporates the WPT system of this invention) will use idle time slots to continuously transmit “dummy” signals as shown in Figure 7, hence the energy can be continually captured by the mobile device and converted into DC voltage to maximise power transfer. Wireless transmission standards such as IEEE 802.11x also define multi-channel transmission.

Depending on the data transmission activity, it may also be possible to utilise unused channels to increase the level of wireless power transfer.

**Multipoint Transmission:**

It is envisaged that the wireless power transmission scheme of this invention may form part of multiple existing radiation mechanisms around the home, workplace or neighbourhood. As an example, it may form part of a user home WiFi router, cordless telephone transmitters, etc, as well as the possibility of strategically placed, dedicated power transmitters as depicted in Figure 8. This multi transmitter environment can magnify the power transmission to the rectenna enabled mobile devices.

The single-unit receiver of this embodiment produces approximately 1.3 volts from a 27 dB or 500 mW, 2.4 GHz source located at 1 meter away. The power harvesting device of this invention has a power conversion rate well in excess of 50%. In the second phase of our prototype development, the single-unit receiver will be arranged into an array form to maximise the power received. The power captured by the receiver can be used to trickle charge a battery or directly energise any low power electronic devices.
Those skilled in the art will realise that this invention provides a unique improvement in RF energy harvesters. Those skilled in the art will also realise that the invention may be implemented in embodiments other than those described without departing from the core teachings of the invention.
CLAIMS

1. An energy harvesting device for converting RF signals to DC current for charging electrical energy in electronic devices which incorporates a dipole antenna with a balun and a vector network analyser for impedance matching.

2. An energy harvesting device as claimed in claim 1 in which the dipole antenna is a miniaturized half bowtie printed dipole antenna.

3. A system of providing wireless power to electronic devices registered to a LAN which includes
   a) a transmitter with beam forming capability
   b) energy harvesting devices incorporated in electronic devices registered to the LAN
   c) an authentication protocol for establishing communication between the transmitter and the energy harvesting devices
   d) a control means for focussing the transmitted beam toward the authenticated energy harvester to maximise power transfer.

4. A system of distributing wireless power to registered electronic devices which includes:
   e) a transmitter with beam forming capability provide directional power transfer.
   f) energy harvesting devices incorporated in electronic devices with a specific device identifier.
   g) an authentication protocol for identifying valid energy harvesting devices.
   h) a control means for focussing the transmitted beam toward the authenticated energy harvester to maximise power transfer, and to enable the beam to track any movements made by the harvesting device.
   i) a flexible wireless power transmission module that can be incorporated into a range of existing wireless transmitter devices (or as a stand alone device) to enable multipoint power transmission.
ABSTRACT

This invention provides a flexible system of distributing wireless power only to registered electronic devices. A miniaturized half bowtie printed dipole antenna with an integrated balun is used as the basis for an RF energy harvesting circuit. Several techniques for increasing harvested power are described, including transmitter beamforming and tracking, rectenna arrays, and multipoint transmission. The transmission system and energy harvester may find application in portable electronic devices operating within wireless local area networks.
Figure 1

FIGURE 2
Figure 3

Figure 4
Appendix C
Miniaturized Half-Bowtie Printed Dipole Antenna with an Integrated Balun

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Introduction

Printed antennas are commonly used in wireless communication due to the simplicity in design and fabrication. These types of antennas are also suitable to be integrated into wireless electronic devices. Hence, research towards the miniaturization of printed antennas becomes very important.

A dipole antenna with an integrated balun is reported to have better bandwidth than the conventional balanced dipole [1]. The previously reported designs of similar printed dipole antennas can be found in [2 - 5]. All of these reference designs are designed to operate between 2 GHz and 3 GHz. A size and performance comparison of these antennas is given in Table 1. The configuration of these antennas is very similar, in which the balun is integrated into the printed dipole antenna. This balun consists of a microstrip feed line grounded to one arm of the dipole antenna located on the other side of the substrate, with via hole that shorts the line to the opposing arm.

In this paper, a miniaturized half bowtie printed dipole antenna is presented. It is a two layered printed antenna with the feed line on the top surface of a dielectric substrate, while the radiating arms are on the bottom surface. Agilent Momentum is used to simulate the performance of this design. It is proven to have better performance than the previously reported miniaturized printed dipole [5] in terms of its size and percentage bandwidth.

Half-Bowtie Printed Dipole Antenna

The main objectives of the miniaturization of a printed antenna are shrinking and optimizing the overall dimensions of an antenna in order to achieve a smaller board size while preserving its performance. The design presented in this paper is different from an ordinary dipole in that the dipole arms are replaced by half-bowtie shapes. In principle, a bowtie antenna requires shorter arm length than a normal dipole antenna that operates at the same resonance frequency. This can be observed by comparing a bowtie antenna with a normal dipole antenna that operates at same frequency. The wider the flare angle of the bowtie, the shorter the length of the arms is required for the particular frequency of choice [6].

In this work, the half bowtie shape is shown to closely resemble the characteristics of a full bowtie antenna, in that it achieves a wide impedance bandwidth with a short dipole arm length. The half bowtie dipole design consists of merely two geometries, which are the balun feed line and radiating arms. No additional structure is required to achieve this performance such as external impedance matching elements, as were used in [5].
A schematic diagram of the proposed half bowtie dipole antenna with integrated balun is presented in Figure 1. The overall dimensions of the antenna are 37.5 mm × 19 mm which is 11% smaller in size than previously reported miniaturized dipoles [5]. The design resides on a Rogers RT/Duriod 5880 substrate with 0.787 mm thickness.

Tuning parameters such as the width and length of the balun feed line, position of the via hole, and the gap between the arms allows many degrees of freedom to improve the overall antenna performance. The input impedance of the balun feed line can be adjusted to match that of the bowtie and yield a wide bandwidth characteristic. Moreover, the simulated efficiency can be increased when feed length is close to λ/4 at the desired central frequency. The depth and width of the gap between the dipole arms also affects the antenna response. An analysis of these parameters to tune the input impedance of the antenna will be presented at the conference.

The half bowtie dipole antenna provides a 10 dB return loss bandwidth of 1.17 GHz and centralized at 2.845 GHz (41%) as shown in Figure 2(a). Figure 2(b) depicts the impedance locus of this antenna on a Smith chart. The impedance locus circulates the center of the chart, which yields the wide bandwidth of the antenna.

The simulated radiation patterns of the antenna exhibits the traditional dipole shape as shown in Figure 3 over the entire impedance bandwidth. Note that Agilent Momentum is based on Moment Method analysis, hence the nulls appearing at ± 90 degrees in the H-plane. The simulated efficiency of the half bowtie dipole antenna is between 93% and 94%. The simulated gain remains above 1.85 dBi which is close to the performance of a typical dipole antenna.

![Table 1](image)

<table>
<thead>
<tr>
<th>Reference Designs</th>
<th>Central Frequency (GHz)</th>
<th>Substrate εr</th>
<th>Antenna Size</th>
<th>Bandwidth (SWR&lt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2]</td>
<td>2.55</td>
<td>4.6</td>
<td>41mm × 40mm</td>
<td>1640</td>
</tr>
<tr>
<td>[3]</td>
<td>2.95</td>
<td>10.2</td>
<td>40mm × 18mm</td>
<td>720</td>
</tr>
<tr>
<td>[4]</td>
<td>2.52</td>
<td>4.4</td>
<td>44mm × 20mm</td>
<td>820</td>
</tr>
<tr>
<td>[5]</td>
<td>2.57</td>
<td>3.88</td>
<td>41mm × 19.6mm</td>
<td>803.6</td>
</tr>
<tr>
<td>Our Design</td>
<td>2.85</td>
<td>2.2</td>
<td>37.5mm × 19mm</td>
<td>712.5</td>
</tr>
</tbody>
</table>

*This is a miniaturized antenna

Table 1 Comparison between References and Proposed Design

The centre frequency, substrate dielectric constants, antenna size and bandwidth of the referenced dipole designs are listed in Table 1 for comparison. The proposed half bowtie dipole occupies the smallest physical board size on the lowest permittivity material, while supplying the highest bandwidth.

Conclusion

This paper presents a miniaturization method for a printed dipole antenna. Compare to a previously reported design [5], simpler and more effective miniaturization have been achieved by replacing the radiating element with half bowtie geometry. This yields a 41% bandwidth centralized at 2.85 GHz. The overall dimensions of this design are 37.5 mm × 19 mm. As a result, this miniaturized dipole will be useful in compact wireless electronic applications. Future works
on this antenna includes practical measurement of the hardware prototype, parametric analysis, and further optimization. Up to date results of these studies will be presented at the conference.

References


Figures

![Figure 1. Layout of Miniaturized Half Bowtie Dipole Antenna](image-url)
Figure 2. Simulated $S_{11}$ of the Miniaturized Half Bowtie Dipole Antenna
(a) $S_{11}$ Magnitude  (b) Smith Chart

Figure 3. Radiation Pattern of Miniaturized Half Bowtie Dipole Antenna
Appendix D
Wideband Miniaturized Half Bowtie Printed Dipole Antenna with Integrated Balun for Wireless Applications

W. S. Yeoh, Student Member, IEEE, K. L. Wong and W. S. T. Rowe, Member, IEEE

Abstract — A linearly polarized miniaturised printed dipole antenna with novel half bowtie radiating arm is presented for wireless applications including the 2.4 GHz ISM band. This design is approximately 0.36λ in length at central frequency of 2.97GHz. An integrated balun with inductive transitions is employed for wideband impedance matching without changing the geometry of radiating arms. This half bowtie dipole antenna displays 47% bandwidth, and a simulated efficiency of over 90% with miniature size. The radiation patterns are largely omnidirectional and display a useful level of measured gain across the impedance bandwidth. The size and performance of the miniaturised half bowtie dipole antenna is compared with similar reduced size antennas with respect to their overall footprint, substrate dielectric constant, frequency of operation and impedance bandwidth. This half bowtie design in this paper outperforms the reference antennas in virtually all categories.

Index Terms — miniaturized antenna, half bowtie, dipole, wideband antenna

I. INTRODUCTION

Variations of the printed dipole antennas are very common in today’s wireless communication applications. They are commonly introduced for more cost effective design cycles and fabrication processes because they are simply a metallic geometry printed on a microwave substrate. Printed dipole antennas also provide good radiation coverage with reasonable gain when integrated into a wireless communications device. Hence, research towards the miniaturization of printed antennas is becoming an extremely important field, gaining more attention as the trend for integration technology minimizes electronics in applications such as mobile phones, mini-laptops/compact PCs, PDAs, etc. Printed dipole antennas with integrated baluns are able to provide omnidirectional coverage while also having the potential to be miniaturised. Miniaturisation is important trend for wireless embedded design integration in the consumer market. A plethora of research has been aimed at creating an antenna with a smaller form factor, such as producing a smaller radiating arm, shorter feed line etc. The performance of the finely tuned radiating arms can be enhanced by a balun which has been designed as part of the body of the radiator. Many recent articles have reported dipole-like antenna geometries with an integrated balun. A conventional 2.4 GHz printed dipole antenna was introduced by Chuang and Kuo [1] in 2003 which incorporated an integrated balun. Wen et al. [2] designed an arrow shaped dipole at 3 GHz by using similar balun to that in [1]. This antenna design concept is also very similar to the 2.4 GHz radiator from the reetens design of [3]. In 2005, Chiu and Popovic [4] introduced some improvement techniques for printed dipole antennas, with the integrated balun being one such technique. A similar antenna with wider bandwidth can also be found in [5]. Sud et al. presented a miniaturised balanced dipole using a meander line on the dipole arms [6], designed for use on a laptop. These and other references typically focus on tuning the dimensions of dipole arms and/or the balun feed lines to either obtain enhanced performance or smaller lateral dimensions.

In this paper, a new miniaturised half-bowtie printed dipole antenna with a modified integrated balun is presented for wireless applications. An extremely wide impedance bandwidth of 47% is achieved with very small form factor, which incorporates the popular 2.4 GHz ISM band. The half bowtie dipole antenna has previously been proven to have a much wider bandwidth than conventional printed dipole antenna [7]. However, a novel tuning technique to control the integrated balun performance is introduced here, which enhances the gain without changing the overall dimensions of the antenna. Sections II and III discuss the design of the half bowtie dipole antenna, and the details of the tuning technique applied to the modified balun. Simulated and measured validation of the concepts is provided in Section IV. A comparison is made to similar antenna configurations in Section V to highlight the exceptional performance of this antenna, and conclusions are drawn in Section VI.

II. HALF BOWTIE DIPOLE DESIGN

The antennas presented in this paper is a variant of an ordinary dipole where the dipole arms have been replaced by half-bowtie shapes. A conventional bowtie antenna has an intrinsically wideband characteristic. The bowtie concept (as seen in [8] for example) assisted in the realization the miniaturised design because as a general rule the wider the flare angle of the radiating arms, the shorter the arm length required for a particular design frequency. To achieve an
even smaller antennas footprint while preserving reasonable performance, the bowtie shaped radiating arms were slised in half along their length.

An integrated balun can be implemented as a microstrip feed line on a truncated ground plane (formed by the dipole arm itself). The smaller the dimensions of the radiator, the shorter the integrated balun structure needs to be if it is to remain within the extents of the antenna footprint. Excessive modification to conventional printed baluns may incur changes in radiator shape or overall lateral dimension of the antenna. Chip baluns like those employed in [6] are extremely small, but may not suffice if broadband performance and assembly costs are key considerations.

In the design presented in this paper, the general half bowtie shape of [7] has been preserved. Modification has been made to the balun structure to enable the wide impedance bandwidth to be maintained whilst providing a more useful level of gain. It was desirable that these changes to the balun structure would not create any major change to the dimensions of the half-bowtie shape. The proposed technique of shifting the microstrip feed line, and adding inductive tuning components between the dipole arms is depicted in Figure 1. Detailed dimensions for this layout are listed in the caption of Figure 1. The antenna is fabricated on a 31mil Rogers RT/duriod 5880 substrate.

![Fig. 1: Schematic of the miniaturized half bowtie printed dipole antenna with integrated balun](image)

III. MINIATURIZATION OF THE INTEGRATED BALUN

To achieve miniaturization of the lateral antenna dimensions, a smaller balun is essential. Reducing the feed line length of a printed microstrip balun has two major consequences. Firstly, the inductive component of the antenna feed has been reduced, which leads to input impedance mismatch. Secondly, the traditional microstrip balun no longer provides a path of half a wavelength since it has been shortened. This section describes the methodology to achieve small form factor and wide impedance bandwidth half bowtie printed dipole by using inductive meander line in balun ground plane.

Traditionally, printed dipole arms have a capacitive gap between the arms. Usually, this is countered by the inductance from the feed line structure. Without sufficient feed length the feed structure has become more capacitive. Inductive meander lines are introduced at balun ground to repair the function of the balun by introducing a propagation delay with small amount of inductance. It is well known in Coplanar Stripline (CPS) design techniques that a meander line of folded shorted or open stubs between a balanced high frequency parallel transmission line possesses certain amount of inductance and capacitance [9]. They are similar to parallel LC pi-networks in CPS filter theory.

The design of the inductive transitions (known henceforth as the “CPS-tuner”) is as follows: First, a safe region of the radiator has to be determined, where minimal radiation activity is occurring. Second, a clear area is created between the two conductors of the dipole arms within the safe region. A rule of thumb is that the size of this clear area is half the length and width of the balun ground region, i.e. $W = \frac{d}{2}$ and $L = \frac{e}{2}$. Third, the inductive meander lines can be added into this clear area. The equivalent circuit of the CPS-tuner is depicted in Figure 2. Each line in the CPS-tuner contributes certain amount of inductance (dominant) and capacitance while serving as additional current path. Its operation is similar to a common LC tuner or pi-network in RF circuit design. The line gap widths are fixed at 0.5mm in width ($=94 \, \Omega$), which is about half the width of the 50 Ω feed line which forms the rest of the balun structure.

![Fig. 2: Equivalent circuit of the CPS-tuner](image)

The CPS tuner provides three effective tuning parameters for optimising performance, which are the length, width and gaps of the lines. Generally, the length is proportional to delay added and the line width can control impedance and bandwidth performance. The position of the CPS-tuner can also be changed to provide impedance matching. When CPS-tuner transitions are moved towards the half bowtie arms (decreasing the value of $g$), the inductive locus circulates anticlockwise. When the gap width of CPS-tuner is increased (the value of $g$ is larger), the locus shifted towards inductive region. Additional tuning can be performed by adjusting the feed line near the via hole, which can translate the impedance locus along the real axis. Optimizing these parameters can attain a good match across wide range of frequencies. Apart from impedance control, the CPS-tuner also allows the microstrip feed line to be shortened to almost any length providing that there is enough space to create a sufficient current path with the inductive lines. This can provide significant miniaturization to this antenna architecture.

Additionally, having two parallel inductive transitions will form a less volatile RF tuner, with minimal performance impact arising from fabrication error. This is because small
geometric changes the inductive transitions in parallel produce less variation to overall inductance than a single transition.

IV. SIMULATION AND MEASUREMENT RESULTS

The half bowtie printed dipole antenna with integrated balun design was simulated using Agilent Momentum. The simulated and measured S21 magnitudes are shown in Figure 3. Very good agreement is observed between simulation and measurement, and the simulated and measured bandwidths (VSWR < 2) of 46% and 47% respectively.

![Figure 3](image)

Fig. 3 Simulated and measured S21 magnitude of the miniaturized half bowtie dipole antenna

The simulated and measured gain across impedance bandwidth for proposed design is shown in Figure 4. The gain comparison setup used in the measurement only had access to standard gain values every 0.5 GHz, hence the sparsely spaced measured values. It should be noted however that the gain measurement may not have been taken at the direction of peak radiation (although much effort was expended in trying to ensure it was as close as possible) so the maximum gain could be slightly higher. The measured gain remains above 1 dB over almost the entire 47% impedance bandwidth. The simulated efficiency of this antenna is also in excess of 90% across the impedance bandwidth, which is aided by the use of a low loss Rogers RT/duriod 5880 substrate. For a lower cost implementation, this antenna could be scaled to employ an FR4 substrate with only a slight degradation in performance.

![Figure 4](image)

Fig. 4 Measured peak gain of the wideband half bowtie dipole antenna

The measured far field radiation patterns of this antenna are presented as Figure 5. The patterns display omnidirectional-like shape over the five frequencies tested from 2 to 4 GHz. The main deviation from a conventional dipole antenna radiation pattern is the asymmetry in the H-plane. It is postulated that this is caused by the presence of an SMA connector located at the end of the microstrip feed line interfering with the radiated fields. To confirm this postulation, the structure is simulated using Ansoft HFSS with and without the SMA connector. These results show a slight degradation in the lateral H-plane radiation with the SMA connector. It is possible that this effect is exacerbated in the practical implementation of the antenna.

![Figure 5](image)

Fig. 5 Measured Radiation Patterns of the half bowtie dipole antenna

V. COMPARISON TO OTHER SIMILAR DESIGNS

The antenna parameters of the proposed half bowtie antenna with integrated balun and other similar small printed dipole antennas are presented in Table 1. The selection criteria for inclusion in this comparison were miniaturised printed dipoles with some form of integrated balun that cover
or operate very close to the 2.4 GHz ISM band. The half bowtie dipole antenna design with novel CPS-tuner easily provides the widest impedance bandwidth of 47%, with the next closest rival being [5] at 41%. The antenna in [5] is not aimed at low profile integration, as the antenna element is mounted perpendicular to a ground plane. This design is also more than four times larger than the half bowtie dipole in this paper. Even though a bandwidth of 47% far exceeds what is needed for 2.4 GHz ISM communication applications, the half bowtie dipole design enables the potential to implement multi-service transmission, or to trade-off unused bandwidth for increased integration ability. The half bowtie dipole also has the second smallest overall area of any of the antennas listed.

In addition to this, the dielectric constant of the substrate used in this design is the lowest. Hence, a higher degree of miniaturization is possible by using substrate with higher dielectric constant.

The balanced dipole in [6] has an extremely small overall geometry. This is due to the use of a ceramic chip balun, and it has a dual band response rather than wideband performance. Using a chip balun will increase the production cost as compared to the proposed design.

The novel half bowtie antenna with modified balun design in this paper has successfully achieved a low profile structure with wideband impedance characteristic which equals or exceeds the performance of similar designs.

VI. CONCLUSIONS

This paper presents a new miniaturized half bowtie printed dipole antenna. This antenna is suitable for wireless system applications in consumer electronics. Novel inductive transitions are introduced between the half bowtie dipole arms to resolve issues created by shortening the balun feed line (a consequence of miniaturization), while maintaining a wide impedance bandwidth. This antenna is approximately 0.36\% (at the central frequency of 2.97 GHz) in length and is printed on a substrate with a low dielectric constant (\(\varepsilon_r = 2.2\)). It provides 47% measured bandwidth and useful levels of gain. In contrast with other similar miniaturized dipole designs, this antenna has successfully achieved a much wider impedance bandwidth characteristic with a comparable or smaller footprint. The broad bandwidth may enable this antenna to be used in multi-service wireless transceivers. The antenna’s bandwidth covers the 2.4 GHz ISM frequency band, so the antenna may also be useful for integrated device applications where the ample bandwidth can be traded for other performance attributes.

**REFERENCES**


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### Table 1 Characteristics of Various Low Profile Dipole Antennas

<table>
<thead>
<tr>
<th>Reference Design</th>
<th>Central Frequency (GHz)</th>
<th>Integrated Balun</th>
<th>Substrate (\varepsilon_r)</th>
<th>Antenna Size</th>
<th>Bandwidth (VSWR &lt; 2)</th>
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<td></td>
<td></td>
<td></td>
<td>Length x Width x Height (mm)</td>
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<td>Half Bowtie Dipole</td>
<td>2.97</td>
<td>Yes</td>
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<td>36 x 19 x 0.877</td>
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<td>Sih et al. [6]</td>
<td>2.495 &amp; 5.42</td>
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<tr>
<td>Wen et al. [3]</td>
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<td>Yes</td>
<td>10.2</td>
<td>40 x 18</td>
<td>720 mm</td>
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<tr>
<td>Chu and Popovic [5]</td>
<td>2.57</td>
<td>Yes</td>
<td>3.48</td>
<td>41 x 19.5</td>
<td>799.5 mm</td>
</tr>
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<td>2.52</td>
<td>Yes</td>
<td>4.4</td>
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<td>= 880 mm</td>
</tr>
<tr>
<td>Chang and Kuo [2]</td>
<td>2.55</td>
<td>Yes</td>
<td>4.6</td>
<td>41 x 40 x 1.6</td>
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* denotes approximate values