Cape Peninsula
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A POWER HARVESTING TECHNIQUE TO FACILITATE ENERGY CONVERSION IN DISTRIBUTED WIRELESS SENSOR NETWORKS

by

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DECLARATION

I, Bokang Patrick Motjolopane, declare that the contents of this thesis "A power harvesting technique to facilitate energy conversion in distributed wireless sensor networks" represents my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

	1 August 2008
Signed	**Date**

ABSTRACT

Distributed wireless sensor networks (DWSNs) are applied in a variety of applications that can enhance the quality of human life or even save lives, such as in fire monitoring, where DWSN microsensors relay the exact location of the fire to water sprinkler actors to automatically extinguish the fire. Batteries are currently the predominant source of energy in DWSNs. One of the key obstacles in the adoption of DWSN technology is the limited lifetime of batteries in microsensors. Recharging or replacing depleted batteries can significantly increase costs in DWSNs. The aim of this study is to address this power challenge in DWSNs by proposing a sixteen-element equiangular spiral rectenna to harvest ambient microwave energy to supply indoor DWSNs. The study concludes that this rectenna model has the potential to generate power that enables long periods of operation of the DWSNs without human intervention in the power management process, thus reducing maintenance and administration costs. The efficiency of the rectenna model was tested in an anechoic chamber. Efficiency test results indicated that the highest efficiency of 2 % for the rectenna model was achieved at 2 GHz for an ambient power of -6 dBm across a 1 KΩ load resistance. The study further concludes that the current rectenna model size of sixteen elements is a limiting factor for the deployment of DWSNs.

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The author produced the following research outputs during this study

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Prof. R.R. van Zyl

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1 CHAPTER ONE: INTRODUCTION TO RESEARCH STUDY

1.1 Introduction

The research study focuses on Distributed Wireless Sensor Networks (DWSNs). Its purpose is to supply dc power to low-cost and low-power DWSN microsensors in order to have long periods of operation in the field without human intervention in the power management process. The latter tends to increase maintenance and administrative costs. The research study objective will be achieved by extensively reviewing literature related to the power requirements of the DWSNs and different approaches to providing power to DWSNs, examining the various rectenna designs and low-power microwave rectifying circuits to determine an optimal approach for powering the low-cost and low-power indoor DWSNs. A suitable rectenna design will be implemented and verified.

The viability of the microwave rectenna as a power source to low-cost and low-power indoor DWSN microsensors that monitor indoor comfort will be investigated. Such DWSNs have low data rates and a small active duty cycle. In addition, such DWSN microsensors typically require a maximum peak power of 5 mW for 6 ms sensing and transmission or 3.75 mW for 5 ms reception (Torres and Rincón-Mora 2005:2-26). The investigation will involve building a rectenna model to convert ambient indoor microwave energy to dc power. A capacitor bank can be used with the rectenna model to store the harvested dc power to a power level sufficient for a typical low-cost and low-power indoor DWSN microsensors application.

1.2 Background

The rapidly increasing capabilities and declining costs of computing and communication devices have made it possible to use DWSNs in a wide range of applications that can improve the quality of life, and even save lives (Agarwal *et al.* 2005:897). In case of a fire, DWSNs can relay the exact origin and intensity of the fire to water sprinkler actors to extinguish the fire. Motion and light sensors can also detect the presence of people in a room and then deliver their observations to the appropriate actors (Akyildiz & Kasimoglu 2004:351). DWSNs can be employed in smart home environments where they offer advantages of low power consumption through low duty cycles, low power and low voltage of 2.2 V to 3.6V (Grassnick 2001:4). DWSNs are typically battery-operated microsensor networks (Santi 2005:165), where a large number of low-cost and low-power sensors are scattered randomly in a specific area to collect and pre-process observations (Ammar *et al.* 2005:287; Nui *et al.* 2005:1). Such sensors are self-organising and collectively forward their measurements to a base station for further processing (Ammar *et al.* 2005:287; Waharte & Boutaba 2005:429). In addition, the large number of sensors provides fault tolerance, flexibility, enhanced surveillance coverage, robustness, mobility and cost effectiveness (Ammer *et al.* 2005:287; Nui *et al.* 2005:1).

Several authors suggest that energy limitations in DWSNs are key obstacles in the adoption of this technology (Akyildiz *et al.* 2002:393; Dolev *et al.* 2004:01; Dowla 2004:95; Kalpakis *et al.* 2002:2; Nicopolitidis *et al.* 2003:13; Wang,N. *et al.* 2005:11). Argawal *et al.* (2005:897) state that the question of how to prolong the lifetime of networks, that is limited by the finite lifetime of the battery energy, is yet to be addressed. Torres and Rincón-Mora (2005:2) suggest that a solution to the limited lifespan of microsensors, as a result of a finite lifetime offered by batteries, would be a power source with an inexhaustible energy supply to enable long periods of operation in the field without human intervention in the power management process.

1.3 Addressing power limitations of DWSN microsensors

Various approaches to addressing the power limitation in DWSNs are reported in the literature. For example, a solar powered DWSN microsensor with bi-directional optical communication was demonstrated by Warneke *et al.* (2002:1). Low-level vibrations from commonly occurring sources were targeted by Roundy, Wright & Rabaey (2003:1133) to study the potential of the vibrational energy harvesting in DWSN microsensors applications where vibrations are present. Roundy *et al.* (2003:1143) concluded that powering DWSN microsensors from ambient vibrations is viable and attractive for certain applications. A broad-band rectification of incident electromagnetic power levels from 10^{-5} mW/cm^2 to 10^{-1} mW/cm^2 for arbitrarily polarised incident radiation was investigated by Hagerty *et al.* (2004:1014) for powering of low-power indoor sensor networks. RF energy rectification and recycling were attained with a 64-element dual-circularly-polarised spiral rectenna. However, providing power for low-cost and low-power indoor DWSN microsensors with a small antenna array remains an open question. A circularly polarised sixteen-element equiangular spiral rectenna is going to be investigated in this research study for powering low-cost and low-power indoor DWSN microsensors.

1.4 Objectives of the research

The objective of this research study is to develop a power harvesting technique to facilitate energy conversion in low-cost and low-power indoor DWSN microsensors to reduce the user involvement in the power management process, and thus reduce maintenance and administrative costs. This involves investigating available power sources for low-power and low-cost indoor DWSN microsensors and the potential of electromagnetic power harvesting to power low-cost and low-power indoor DWSN microsensors. A rectenna model with a circular polarisation and wideband antenna incorporating a zero bias Schottky diode will be implemented. The developed rectenna model will be used to validate the performance of the proposed rectenna model. A conclusion will be drawn on the viability of this rectenna model to facilitate energy conversion in the low-cost and low-power indoor DWSN microsensors.

1.5 Research Process

1.5.1 Research Problem

There is a need to develop a power harvesting technique to facilitate energy conversion in low-cost and low-power indoor DWSNs to reduce the user involvement in the power management process, and thus reduce maintenance and administrative costs.

1.5.2 Research Question

How to develop and implement a power harvesting technique to facilitate energy conversion in low-cost and low-power indoor DWSNs to reduce maintenance and administrative costs?

1.5.3 Investigative questions

- What are the energy requirements of the typical low-cost and low-power indoor DWSN microsensors?
- What are the available energy harvesting techniques for low-cost and low-power indoor DWSN microsensors?
- What is the potential of the sixteen-element rectenna for powering of the low-cost and low-power indoor DWSN microsensors?
- What are the optimum energy storage techniques for low-cost and low-power indoor DWSN microsensors?

1.6 Research Design and Methodology

Leedy & Ormrod (2001:102) suggest that a quantitative approach is more suitable to test theory with known variables, established guidelines and when findings are to be communicated in numbers. A quantitative approach is suitable in this research study, as the theory of the viability of collecting ambient indoor microwave energy with a sixteen-element equiangular spiral antenna array, and rectifying it, will be tested. Mouton (2003:163) states that computer simulation research design is aimed at developing and validating accurate models of the real world. Banks (1998:10-11) adds that simulation enables designers to test every aspect of a proposed change or addition without committing resources to their acquisition, and aid in providing an understanding about how a system works rather than indicating someone's predictions about how a system will operate. Such a design is appropriate in this research study as a model of the spiral rectenna will be developed.

1.7 Delimitation

The rectenna model developed in this research study is applicable to low-cost and low-power indoor DWSN microsensors in the vicinity of wireless access points or other electromagnetic sources in the microwave range available in indoor environments. The broad frequency range under study is 1 – 6 GHz. The implementation of the array is limited to sixteen elements.

1.8 Overview of chapters

In Chapter 2, a detailed literature analysis on DWSN microsensors is provided. The literature analysis entails a discussion on DWSN microsensors' power requirements and approaches to powering DWSN microsensors. The chapter highlights various power harvesting techniques from which an electromagnetic power harvesting technique is selected as the most viable solution for the low-cost and low-power indoor DWSN microsensors. A rectenna system, together with its various components, is examined. A wide range of antennas are presented with the equiangular spiral antenna chosen as a more appropriate antenna for the rectenna model. The chapter provides different rectenna designs and a justification for the selection of a circularly polarised broadband rectenna design presented by Hagerty *et al.* (2004:1014-1024). In conclusion, the chapter proposes a research model for the research study.

Chapter 3 presents the research methodology explaining why a quantitative research approach was adopted. The chapter articulates the research design, detailing how the antenna will be designed in FEKO. FEKO is a field simulator that uses a full wave formulation which enables accurate predictions of far fields, radiation patterns and impedances (EM Software & Systems-SA 2001:Application note G.A Planarant 2). A discussion of how the rectenna will be modelled in Microwave Office, for the characteristic impedance of the equiangular spiral antenna to be matched to the impedance of the rectifying circuit for maximum power transfer, is provided. The Microwave Office/Analog Office Load Pull Wizard allows designers to perform load pull simulations on the device model using tuner elements to tune impedance points presented to the device at the load or source side (Applied Wave Research, Inc 2005:12-22-27). Chapter 3 highlights the sampling technique that will be used in the research study. The chapter concludes by reporting research relevance and rigour, and how the collected data will be analysed to determine techniques to optimise the rectenna model for supplying biasing to low-power and low-cost indoor DWSNs.

Chapter 4 presents the measured results of the implemented sixteen-element spiral rectenna model. Both a controlled efficiency measurement as well as real-life indoor laboratory measurement is carried out and reported.

In Chapter 5, research findings are concluded and recommendations made regarding the viability of the sixteen-element equiangular spiral rectenna for harvesting ambient microwave energy.

2 CHAPTER TWO: ELECTROMAGNETIC POWER HARVESTING FOR DWSN MICROSENSORS

2.1 Introduction

The chapter reviews literature to determine how to develop a power harvesting technique to facilitate energy conversion in low-cost and low-power indoor DWSN microsensors. Firstly, this chapter provides a background on the power requirements of DWSN microsensors. Secondly, approaches to powering DWSN microsensors are examined. Thirdly, the discussion focuses on rectennas by examining various designs of antennas, rectifying circuits and rectenna designs. The chapter concludes by proposing a research model for this research study.

2.2 Power requirements of DWSNs

Roundy *et al.* (2005:28) observed that the DWSN microsensor's radio transmitter could consume 2 to 3 mW and a receiver less than 1 mW of electrical power using ultra-low power techniques for an average distance of 10 m between DWSN microsensors. The power dissipation of a microsensor and its peripheral circuitry does not exceed a maximum peak power of 5 mW. A DWSN microsensor communicates for approximately 1% of its deployed life, and performs only background tasks for the remaining 99%. The peak and standby power in DWSN microsensors with these energy saving techniques employed, results in a low average power dissipation of 100 μW.

With recent developments in semiconductor circuits, it is possible for a microsensor to consume 1 mW. Most circuits can be turned off during a period of inactivity and save power. The standby power consumption of a typical microsensor is approximately 1 μW. If the microsensor is active for 1% of the time, its average power consumption is only a few microwatts (Culler, Estrin & Srivastava 2004:44). Rabaey *et al.* (2004:42) envision the power dissipation below 100 μW for the microsensor to be able to live only on the energy harvested from the environment. Jiang, Polastre and Culler (2005:4) state a current consumption of 20 mA in active mode and 5 μA in sleep mode for a Berkley's Telos Mote operating on an extremely low voltage of 1.8 V.

Torres and Rincón-Mora (2005:2-26) propose DWSN system requirements as illustrated in Table 2-1 below.

Table 2-1 Estimates of sensor energy consumption (Torres & Rincón-Mora 2005:26)

	Duration	Power	Energy
Transmission	5 ms	5 mW	25 µJ
Reception	5 ms	3.75 mW	18.75 µJ
Sensing	1 ms	10 µW	10 nJ
Total (500 ms cycle)	500 ms	88 µW	~44 µJ
Harvesting Requirement	>440 ms	100 µW	44 µJ

Warneke *et al.* (2002:4) suggest a power consumption of 26 µW at 2.1 V or 69 pJ/bit at 375 kbps for an optical receiver during reception. An analog to digital converter (ADC) of the optical receiver has an enable period of 200 µs, resulting in 360 pJ/s energy consumption per sample and a standby power consumption of 41 pW at 1 V. Callaway Jr. (2005:184-185) proposes total energy consumption of 35 µJ for the typical microsensor's transmission and reception cycle of 1 ms and power consumption of 35 mW.

2.3 Approaches to powering DWSN microsensors

There has been an exponential improvement in hardware components such as microprocessor speed. However, such improvements have not occurred in battery technology (Argawal *et al.* 2005:897; Want *et al.* 2005:15). There are four main approaches that are aimed at addressing the power challenges in low-cost and low-power indoor DWSNs: mains power, battery power, microbial fuel cells and power harvesting. Each of these will be briefly examined.

2.3.1 Mains power

Callaway Jr. (2005:139) states that mains power is a reliable source of energy that is inexhaustible and has minor operating cost when employed in DWSNs. However, mains power contradicts the inherent characteristics of DWSNs if wires are used for power distribution.

Another disadvantage presented by mains power is the need to convert from one to two hundred volts ac to a few volts dc. This approach would significantly increase costs in the DWSNs.

2.3.2 Battery power

Another approach is the use of primary battery cells. Primary battery cells cannot be recharged when they have exhausted their energy. If they are used as a power source in the large DWSNs, the cost of labour for the replacement of the battery cells becomes significantly high. Secondary battery cells can be recharged and avoid the purchase of new battery cells when the battery has lost its potential to supply power. However, secondary battery cells have lower energy densities than primary battery cells. The labour cost for charging secondary batteries is higher than replacing the primary battery cells (Callaway Jr. 2005:139).

2.3.3 Microbial fuel cells

Microbial fuel cells (MFCs) present another approach to addressing power challenges in DWSNs. MFCs show promise over batteries or solar cells for powering sensor networks (Ringeisen *et al.* 2006:1). MFCs use the catabolic activity of living cells to convert the chemical energy into electricity using sources such as sediments, sewerage sludge, or waste water streams (Niessen, Schroder & Scholz 2004:955).

Large amounts of energy contained in different forms of biomes remain unexploited and subject to microbial degradation (Niessen *et al.* 2004:955). Biological substrate degradation for the generation of electricity, according to Niessen *et al.* (2004:955), is the driving force for the development of MFCs. MFCs are not viable for the low-cost and low-power indoor applications. Roundy, Wright & Rabaey (2003:1131) state that MFCs are fixed energy sources, and would have a finite lifetime and once started, are not easily turned off. Hence, they require large energy storage reservoirs to allow for low-power operation.

2.3.4 Power harvesting

Another alternative approach to the DWSN power challenge is power harvesting, which is also known as energy scavenging (Want *et al.* 2005:15; Rabaey *et al.* 2004:42). Power harvesting is the conversion of ambient energy into usable electrical energy (Torres & Rincón-Mora 2005:4).

Power harvesting techniques are attractive for DWSN microsensors to allow indefinite lifetimes in the field (Warneke *et al.* 2002:2). Want *et al.* (2005:15-16) state that power harvesting is a promising new approach that can significantly reduce user involvement in the power management process. Furthermore, power harvesting is not a solution for all energy needs, but a compelling concept that will greatly enhance the performance of the batteries or even replace them for lower power applications. There are various approaches to power harvesting, offering differing degrees of usefulness (Want *et al.* 2005:15). Thomas, Qidwai and Kellog (2006:2) illustrate various types of non-biological power harvesting energies in Figure 2-1 that can be converted into electrical energy for use by small unmanned systems. The various energy harvesting techniques will now be discussed.

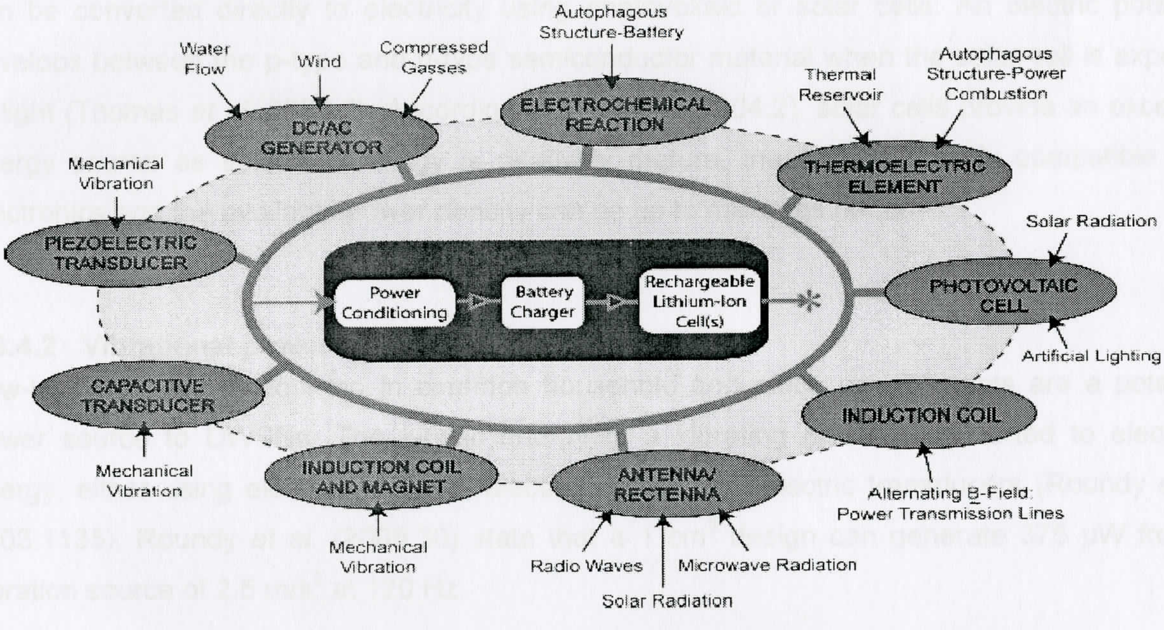

Figure 2-1 : Various harvestable energies (Thomas *et al.* 2006:2)

2.3.4.1 Solar power harvesting

Want *et al.* (2005:15) state that solar cells have long been used to power simple hardware components such as calculators, emergency telephones along the highway, and low-grade lighting for pathways at night. Figure 2-2 shows a typical solar generation system.

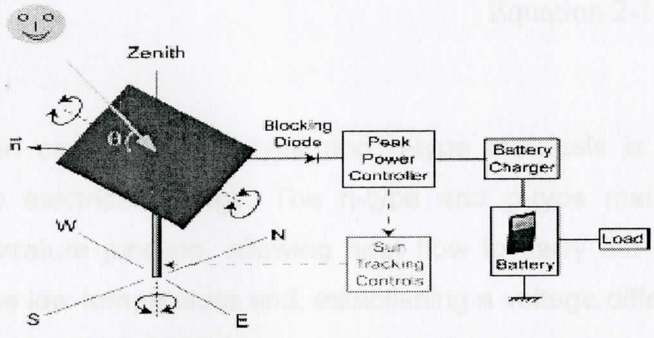

Figure 2-2 : Typical Solar generation System (Thomas *et al.* 2006:4)

Solar energy is readily available outdoors and in artificially lighted indoor locations. Solar energy can be converted directly to electricity using photovoltaic or solar cells. An electric potential develops between the p-type and n-type semiconductor material when the solar cell is exposed to light (Thomas *et al.* 2006:3). According to Yeatman (2004:2), solar cells provide an excellent energy source as solar technology is relatively mature, inexpensive, highly compatible with electronics and the available power density can be up to milliwatts per cm^2.

2.3.4.2 Vibrational power harvesting

Low-level vibrations occurring in common household and office environments are a potential power source to DWSNs. The kinetic energy of a vibrating mass is converted to electrical energy, either using electro-magnetic, electrostatic or piezoelectric transducers (Roundy *et al.* 2003:1135). Roundy *et al.* (2005:30) state that a 1 cm^3 design can generate 375 μW from a vibration source of 2.5 m/s^2 at 120 Hz.

2.3.4.3 Thermal power harvesting

Temperature differences present another environmental source of energy available for harvesting. The Carnot equation for the maximum theoretical efficiency of a heat engine founded on the first and second laws of thermodynamics serves as a "Gold Standard" for thermal-to-electrical energy conversion (Thomas *et al.* 2006:7-8). The Carnot equation for the maximum theoretical efficiency of a heat engine connected to heat reservoirs maintained at hot (T_H) and cold (T_C) temperatures is shown in Equation 2-1 below.

$$\eta_{Carnot} = \frac{T_H - T_C}{T_H} \qquad \text{Equation 2-1}$$

A thermocouple configuration consisting of n-type and p-type materials is used to convert temperature differences into electrical energy. The n-type and p-type materials are joined electrically at the high-temperature junction, allowing heat flow to carry the dominant charge carriers of each material to the low-temperature end, establishing a voltage difference across the base electrodes (Torres & Rincón-Mora 2005:12).

2.3.4.4 Electromagnetic power harvesting

On the electromagnetic spectrum as illustrated in Figure 2-3 below, radio frequency (RF) waves and microwaves are the most important frequency bands for commercial communication. RF occupies the lowest part of the electromagnetic spectrum, and microwaves refer to the high frequency radio bands on the electromagnetic spectrum (Nicopolitidis *et al.* 2003:28). According to Pozar (2005:1), microwaves refer to alternating signals with frequencies between 300 MHz and 300 GHz. In electromagnetic power harvesting, a rectenna converts RF or microwave energy into useful power. Ambient microwave energy can be harvested by broad-band rectenna arrays to provide electrical energy to low-power indoor sensor networks (Hagerty, Helmbrecht, McCalpin, Zane & Popović 2004:1014).

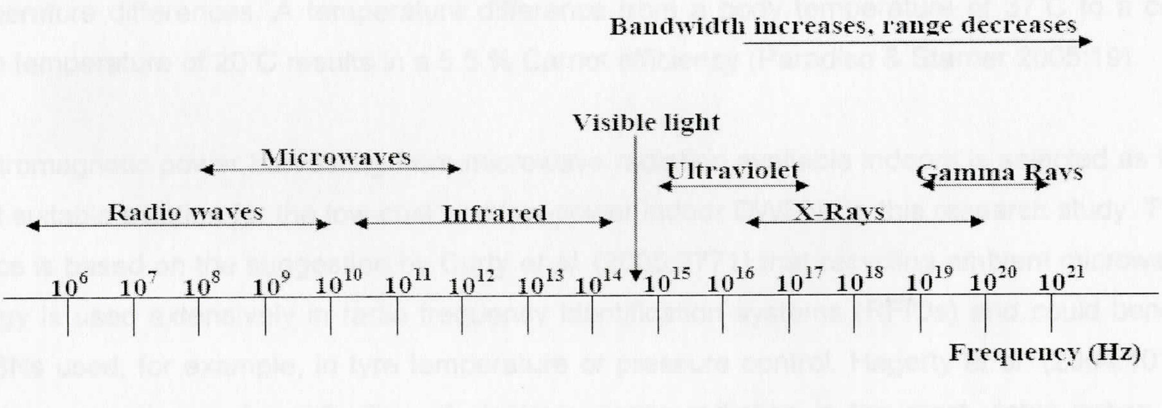

Figure 2-3 : Electromagnetic spectrum (Nicopolitidis *et al.* 2003:38)

2.3.4.5 Choice of the power harvesting technique

According to Thomas *et al.* (2006:2), identification and implementation of a viable energy harvesting technique will depend on the system's power requirements, weight and size limitations and the operational environment. In this research study the objective is to develop a power harvesting technique to facilitate energy conversion in low-cost and low-power indoor DWSNs.

Solar energy harvesting is not selected, because sensors need to be in a well-lit location, correctly oriented and free from obstructions. Solar energy harvesting is inadequate in dimly lit offices or areas with no light (Yeatman 2004:1; Roundy *et al.* 2003:1132). Furthermore Leland, Lai & Wright (2004:1) argue that indoor lighting often does not provide sufficient light for adequate power generation.

Vibrational energy harvesting is not selected as Roundy *et al.* (2003:1131) state that vibrational energy harvesting is only a viable power source where vibrations are present. Furthermore, the power sources must be affixed to a vibrating surface such as a wooden staircase with foot traffic or inside an air conditioning duct (Roundy *et al.* no date:3).

Thermal energy harvesting cannot be selected as the thermoelectric generators require high temperature sources such as hot exhaust pipes. Carnot efficiencies are limited for small temperature differences. A temperature difference from a body temperature of 37˚C to a cool room temperature of 20˚C results in a 5.5 % Carnot efficiency (Paradiso & Starner 2005:19).

Electromagnetic power harvesting from microwave radiation available indoors is selected as the most suitable solution for the low-cost and low-power indoor DWSNs in this research study. This choice is based on the suggestion by Curty *et al.* (2005:2771) that recycling ambient microwave energy is used extensively in radio frequency identification systems (RFIDs) and could benefit DWSNs used, for example, in tyre temperature or pressure control. Hagerty *et al.* (2004:1014) add that reception and rectification of electromagnetic radiation is the most viable option for powering low-power indoor sensor networks. However, there are several challenges to power harvesting.

According to Jordan (2003:18), challenges in power harvesting include the fact that harvesting power from the environment and converting it into usable electrical power is a difficult task. Callaway Jr. (2003:150) states that the harvested average output power is low. The harvested energy must be converted to a voltage or power that is compatible with the electronics of the intended application, and the current is often too small to be used directly (Jordan 2003:18).

The harvested energy is converted into electrical energy using transducers (Want *et al.* (2005:15). Brindley (1988:01) adds that a transducer converts a non-electrical physical quantity into an electrical signal, as well as converting an electrical signal to a non-electrical physical quantity. According to Chin, Xue & Chan (2005:175) a rectenna converts microwave power into dc power. A rectenna will now be discussed.

2.4 Rectenna

McSpadden *et al.* (1998:1) define the rectenna as a rectifying antenna operating in a receiving mode for reception of microwave power and subsequent conversion to dc by a diode rectifier. The rectenna consists of a receiving antenna combined with a rectifying circuit (Gómez *et al.* 2004:315). A schematic of the rectenna system is illustrated in Figure 2-4, showing the two main components namely the antenna and the rectifying circuit. The load in the rectenna schematic refers to the application of the rectenna. Low-cost and low-power indoor DWSNs will be the load in this research study.

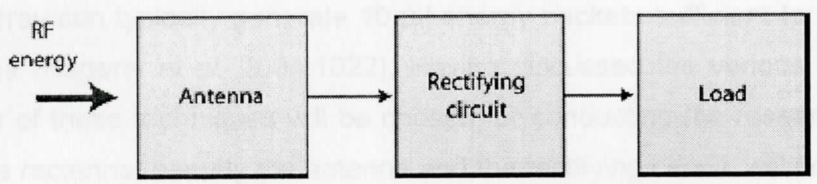

Figure 2-4 : Rectenna (Akkermans, van Beurden, Doodeman & Visser 2005:187)

Electromagnetic power harvesting with the rectenna for powering low-power indoor sensor networks is illustrated in the block diagram of Figure 2-5. The block diagram includes antenna arrays attached to their rectifying diodes, dc combining circuit, a storage element, a dc-dc converter, the controller and an application. According to Figure 2-5, multiple sources of different frequencies (f_1, f_2 and f_3) are radiating power in all directions. Ambient energy from these sources is collected by the antenna arrays attached to their rectifying diodes. The rectifying diodes convert the received electromagnetic energy into a dc power. The dc combining circuit adds dc power from many rectenna elements (Hagerty *et al.* 2004:1014). Potential electromagnetic energy sources include broadcast radio, broadcast television, mobile telephony, and wireless networks (Mateu & Moll 2005:369).

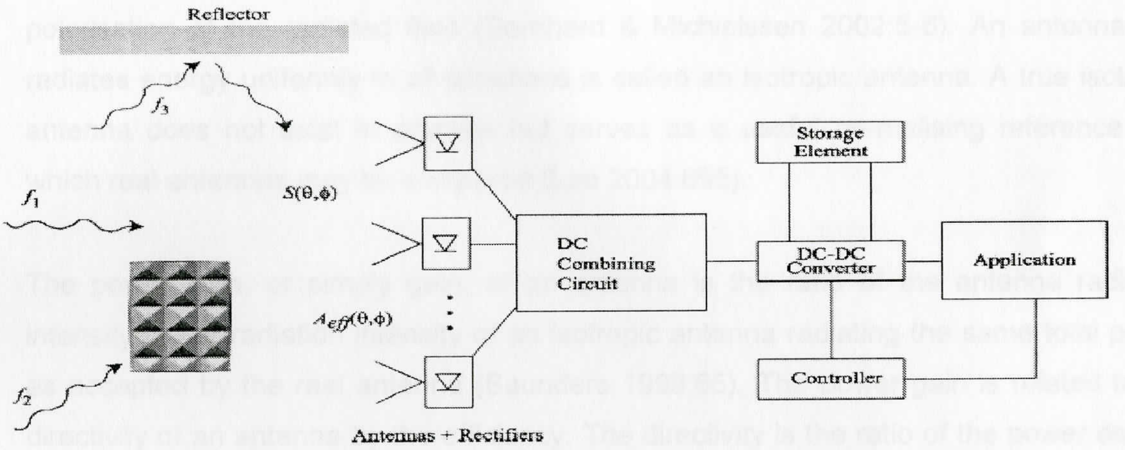

Figure 2-5 : Power harvesting (Hagerty *et al.* 2004:1015)

Since the dc power harvested in the microwave frequency range is too low for most continuous electronics functions, a storage element is used to store the dc power over time to meet the energy requirements of an application in discrete time intervals. Energy can be stored in capacitors or micro-batteries. A dc-dc converter is employed for maximum dc power generation. The rectenna array can typically generate 10 µJ energy packets sufficient for 1 mW over 10 µs load applications (Hagerty *et al.* 2004:1022). Having discussed the various energy harvesting techniques, one of these techniques will be chosen for conducting the research study. The two components in a rectenna, namely the antenna and the rectifying circuit, will now be discussed.

2.5 Antennas

Saunders (1999:56) defines an antenna as a way of converting the guided waves present in a waveguide into radiating waves travelling in free space or vice versa. Bernhard and Michielssen (2002:5-1) add that antennas serve as transducers between electromagnetic waves travelling in free space and electromagnetic signals in circuits. The antenna characteristics are defined in terms of transmitting antennas and the definitions apply to receiving antennas as antennas are reciprocal devices (Raisanen & Lehto 2003:205). Antennas are characterised by the radiation pattern, power gain, bandwidth and efficiency. These four key characteristics are briefly discussed.

- The radiation pattern of an antenna is a graphic representation of the radiation properties of an antenna that could include information on the energy distribution, phase and polarisation of the radiated field (Bernhard & Michielssen 2002:5-6). An antenna that radiates energy uniformly in all directions is called an isotropic antenna. A true isotropic antenna does not exist in practise but serves as a useful normalising reference with which real antennas may be compared (Lee 2004:695).

- The power gain, or simply gain, of an antenna is the ratio of the antenna radiation intensity to the radiation intensity of an isotropic antenna radiating the same total power as accepted by the real antenna (Saunders 1999:65). The power gain is related to the directivity of an antenna by the efficiency. The directivity is the ratio of the power density radiated in the particular direction to the power density radiated by the antenna that radiates equally in all directions (Paul 2004:369).

- The antenna efficiency is determined by the resistive impedance of the antenna that is split into radiation resistance and loss resistance. The power dissipated in the radiation resistance is the power radiated by the antenna. The power lost within the antenna is represented by the loss resistance. The antenna efficiency is defined in Equation 2-2 as the ratio of power radiated to the input power at the antenna terminals (Saunders 1999:64).

$$efficiency = \frac{power\ radiated}{input\ power} \qquad \text{Equation 2-2}$$

In addition to power lost in the antenna, the effective loss of transmit power is also due to impedance mismatch at the input of the antenna, or polarisation mismatch with the receive antenna. These losses are external to the antenna and can be eliminated by using matching networks or the proper choice and positioning of the receive antenna (Pozar 2005:639).

- The bandwidth of an antenna expresses the ability of the antenna to operate over a wide frequency range. The bandwidth of an antenna is defined as the range where the power gain is maintained within 3 dB of its maximum value, or the range where the voltage standing wave ratio (VSWR) is not greater than 2:1 (Saunders 1999:66).

In designing antennas, these four key characteristics have to be taken into consideration. Bernhard and Michielssen (2002:5-1) suggest that designing antennas for portable devices that meet the operational requirements and packaging, is becoming very challenging. Engineers rely on a combination of theory, simulation and experimental investigation to design antennas that meet al.l the demands for the particular application. Various types of antennas discussed in the literature are illustrated in Table 2-2.

Table 2-2 : Antennas

Antenna	Reference
Wire antennas	
(i) Dipole Antennas	(Paul 2004:355;Losee 1997:379-380; Whitaker & Benson 2002:11-111-112)
(ii) Monopole antennas	(Bernhard & Michielssen 2002:5-23; Saunders 1999:78)
(iii) Loop antenna	
a) Air-core loop antennas	(Losee 1997:388)
b) Ferrite-core loop antenna	(Losee 1997:389)
(iv) Sleeve antennas	(Losee 1997:386)
(v) Yagi-Uda arrays	(Young 2004:638-640)
Dielectric resonator antenna	(Bernhard & Michielssen 2002:5-32-33)
Planar antennas	
(i) Planar inverted-F antennas	(Bernhard & Michielssen 2002:5-30;Soras, Karaboikis, Tsachtsiris & Maikos 2002:37)
(ii) Microstrip antennas	
a) Rectangular microsrip antennas	(Garg, Bhartia, Bahl & Ittipiboon 2001:253)
b) Circularly polarised patch	(Garg *et al.* 2001:494)
c) Equiangular spiral antenna	(Stutzman & Thiele 1998:252-254;Whitaker & Benson 2002:11-115;Losee 1997:392-393)
d) Archimedean spiral antenna	(Losee 1997:393;Milligan 1985:374)
e) Conical spiral antenna	(Losee 1997:394)
f) Log-periodic dipole array	(Losee 1997:394)
g) Trapezoidal-toothed log-periodic antenna	(Losee 1997:397-398)
h) Triangular-toothed log-periodic antenna	(Losee 1997:400)
Aperture antennas	
(i) Reflector antenna	(Stutzman & Thiele 1998:322-338;Raisanen & Lehto 2003:236)
(ii) Horn antenna	(Räisänen & Lehto 2003:236; Losee 1997:400)
(iii) Lens antenna	(Losee 1997:408-410)
(iv) Array antenna	(Balanis 1997:249;Räisänen & Lehto 2003:239;Coleman 2004:246;Whitaker & Benson 2002:11-115)

Each of these antenna designs will be briefly discussed so as to enable the researcher to choose the most viable antenna for the reception of the ambient microwave energy to supply low-cost and low-power indoor DWSNs. The first group of the antenna designs to be examined is wire antennas.

2.5.1 Wire antennas

Linear wire antennas are built from solid or tubular wire and are very popular in many applications (Bernhard & Michielssen 2002:5-17). Wire antennas include dipoles, monopoles, loops, sleeve dipoles and Yagi-Uda arrays. Wire antennas are most often used at lower frequencies and generally have low gains. Wire antennas possess advantages of light weight, low cost, and simple design (Pozar 2005:634-635).

2.5.1.1 Dipole antennas

The dipole antenna consists of two arms of equal lengths. The most common dipole antenna is the half-wave dipole ($l = \lambda_o/2$). The total length of the half-wave dipole antenna is one-half wavelength (Paul 2004:355). The impedance of the dipole is high and capacitive when the distance from the end is small compared to a quarter wavelength. The dipole antenna is at resonance when its arms of are each a quarter wavelength. The bandwidth of the dipole antenna can be large when the dipole elements become large (Losee 1997:379-380). Whitaker and Benson (2002:11-111-112) add that the dipole antenna is the simplest of all antennas and the building block of most other designs. The half-wave dipole antenna is shown in Figure 2-6.

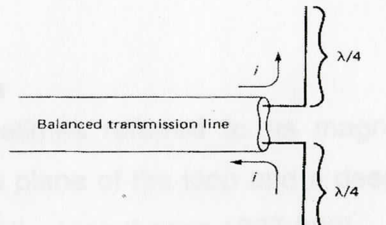

Figure 2-6 : Half-wave dipole antenna (Young 2004:629)

2.5.1.2 Monopole antennas

A monopole antenna is a wire connected to a ground plane and excited at its base, or close to its base. The monopole antenna is constructed by connecting the outer conductor of the coaxial line to a perfectly conducting ground plane and using the extended inner conductor as the radiating element (Bernhard & Michielssen 2002:5-23). Saunders (1999:78) adds that the monopole antenna results from applying image theory to the dipole as illustrated in Figure 2-7. Directivity is doubled and the radiation resistance is halved. The quarter-wave monopole (L/2 = λ/4) approximates the half-wave dipole and is a very useful configuration in practice for mobile antennas, where the conducting plane is a car body or handset case.

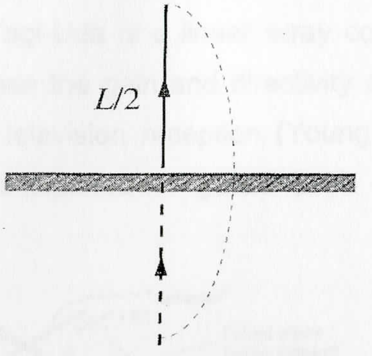

Figure 2-7 : Monopole antenna (Saunders 1999:78)

2.5.1.3 Loop antennas

Loop antennas are used extensively as receiving antennas at lower frequencies and for direction-finding systems. The two main types of loop antennas are air-core loop and ferrite-core loop antennas (Losee 1997:387-388).

2.5.1.3.1 Air-core loop antennas

Air-core loop antennas are sometimes referred to as magnetic dipoles. The air-core loop antenna has maximum gain in the plane of the loop and a deep null normal to the plane of the loop. Polarisation is in the plane of the loop (Losee 1997:388).

2.5.1.3.2 Ferrite-core loop antenna

A ferrite core is used in the ferrite-core loop antenna to improve the radiation resistance of the loop antenna. A ferrite-core multiturn is often called a loop-stick antenna. The ferrite-core loop antenna's pattern and polarisation are the same as that of the air-core loop antenna. Ferrite-core loop antennas are used for many AM broadcast receivers (Losee 1997:389).

2.5.1.4 Sleeve antennas

In the case of sleeve antennas, an additional sleeve is added to a monopole or a dipole. This increases the bandwidth by more than an octave (Losee 1997:386).

2.5.1.5 Yagi-Uda antenna

The Yagi-Uda, or Yagi, is named after the two Japanese men responsible for the research and publication work of this antenna. Yagi-Uda is a linear array consisting of a dipole and two or more parasitic elements that increase the gain and directivity of the antenna. Yagi-Uda is the most commonly used antenna for television reception (Young 2004:638-640). A basic three-element Yagi using a folded dipole is depicted in Figure 2-8.

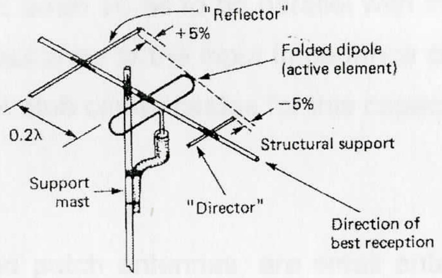

Figure 2-8 : Yagi-Uda antenna (Young 2004:639)

2.5.2 Dielectric resonator antenna

The Dielectric Resonator Antenna (DRA) is made of low-loss dielectric material. The resonant frequency, impedance bandwidth and radiation pattern of the DRA are functions of the dielectric structure's shape, size and permittivity. Dielectric resonators of different shapes can offer options in frequency and radiation characteristics, as well as packaging. Patterns range between broadside to nearly omnidirectional and may be significantly affected by the size and shape of the ground plane on which they reside. Proposed resonator shapes for the DRA include circular sectors, annular sectors, rectangular and equilateral triangles (Bernhard & Michielssen 2002:5-32-33).

2.5.3 Planar antennas

Planar antennas possess advantages of low-profile and durable form factors, light weight and low cost. Planar antennas include planar inverted-F antennas and microstrip antennas (Bernhard & Michielssen 2002:5-17-30).

2.5.3.1 Planar inverted-F antennas

The planar inverted-F antenna (PIFA) consists of a top plate element, a feed wire attached to the top element through a hole in the ground plane and a shorting wire that is directly connected between the top element and the ground plane (Bernhard & Michielssen 2002:5-30).

According to Soras *et al.* (2002:37) the inverted–F antenna is a variant of the monopole where the top section has been folded down so as to be parallel with the ground plane. Therefore, the parallel section introduces capacitance to the input impedance of the planar inverted-F antenna and implementing a short-circuit stub compensates for this capacitance.

2.5.3.2 Microstrip antennas

Microstrip antennas, also called patch antennas, are small antennas printed over a grounded dielectric substrate with thickness often very small in wavelength (Lo, Wright, Navaro & Davidovitz 2003:776). Patch antennas are sometimes known as printed antennas because they are easily implemented using printed circuit techniques (Coleman 2004:263). Microstrip circuits make a variety of antennas possible through the use of photoetching techniques. A microstrip consists of a metal strip on a dielectric substrate covered by a ground plane on the other side. The microstrip patch antennas consist of metal patches that are large with respect to normal transmission line widths. A patch radiates from fringing fields around its edges. The antenna achieves peak impedance when it is matched. In microstrip (patch) antennas, a match occurs when the patch resonates as a resonant cavity (Milligan 1985:99). The microstrip antenna configuration is illustrated in Figure 2-9.

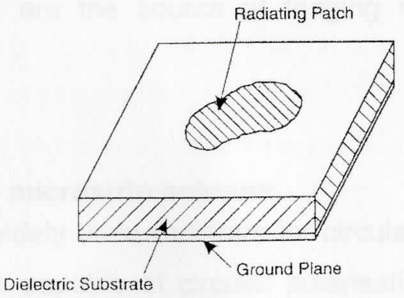

Figure 2-9 : Microstrip antenna (Garg *et al.* 2001:494)

Microstrip antennas in their pure form suffer from poor radiation efficiency and small bandwidths. Patch antennas, despite their disadvantages, have been utilised in many applications because of their advantages of low profile, conformal nature, light weight, low cost of production, robust nature and compatibility with microwave monolithic integrated circuits and optoelectronic integrated circuit technologies (Waterhouse 2002:6-1). Garg *et al.* (2001:54) add that the advantages of microstrip antennas far outweigh their limitations.

Common patch conductor shapes include rectangular, square, circular, elliptical, triangular, disk sector, and annular ring. Rectangular conductors have the largest impedance bandwidth. Square patches can be used to generate circular polarisation. Circular and elliptical patches' gain and bandwidth are slightly lower than the rectangular patches. Triangular and disk sector patches have both their gains and bandwidth lower than the rectangular and circular patches. Triangular patches generate higher cross-polarisation levels. Annular rings have the smallest bandwidth and gain (Waterhouse 2002:6-5).

2.5.3.2.1 Rectangular microstrip patch antennas

The rectangular microstrip antenna is the simplest patch configuration. The basic antenna element is the strip conductor on a dielectric substrate backed by a ground plane. When a charge is excited by a feed, a charge distribution is established on the underside of the patch metallisation and ground plane. The attractive forces between these sets of charges hold a large percentage of charges between the two surfaces. The repulsive force between positive charges on the patch pushes some of the charges toward the edges and results in large charge density at the edges. These charges are the source of fringing fields and radiation (Garg *et al.* 2001:253).

2.5.3.2.2 Circularly polarised microstrip antenna

Microstrip is one of the most widely used radiators for circular polarisation generation. Various shapes for microstrip antennas capable of circular polarisation operation in the literature are square, circular, pentagonal, equilateral triangular, ring and elliptical shapes. Square and circular patches are widely utilised in practice (Garg *et al.* 2001:494).

2.5.3.2.3 Equiangular spiral antenna

According to Stutzman and Thiele (1998:252-254) the equiangular spiral curve represented by Equation 2-3 is used to create the planar equiangular spiral antenna,

$$r = r_0 e^{a\phi} \qquad \text{Equation 2-3}$$

where r_o is the radius for $\Phi = 0$ and a is the constant controlling the flare rate of the spiral. The impedance, pattern and polarisation of the planar equiangular spiral antenna remain nearly constant over a wide range of frequency. Spirals of one-and-a-half turns are optimum. The radiation pattern of planar equiangular spiral antennas are bidirectional with two wide beams broadside to the plane of the spiral. The polarisation of the radiation is close to circular over wide angles. The equiangular spiral antenna is illustrated in Figure 2-10 below.

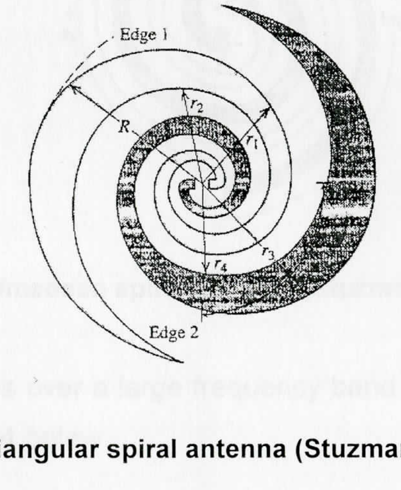

Figure 2-10 : Equiangular spiral antenna (Stuzman & Thiele 1998:253)

Whitaker and Benson (2002:11-115) state that the bandwidth limitations of antennas based on the natural change in the radiating elements caused by differing wavelengths can be overcome by the spiral antenna designs. The radiating elements in the spiral antenna are specified only in angles and the circular polarisation is inherent in the antenna.

Losee (1997:392-393) states that the two arms of the equiangular spiral antenna start at the centre and spiral outwards. The antenna is fed at the centre by a coaxial feed line that is wound along one of the two arms toward the feed points. The outer conductor of the coaxial feed line is connected at the feed location to one of the feed arms, and the centre conductor is connected to the other antenna arm. Bandwidths of 8:1 are typical for the equiangular spiral antenna. A high bandwidth of 20:1 can be obtained with the equiangular spiral antenna. Typical input impedance for the equiangular spiral antenna is 164 Ω.

2.5.3.2.4 Archimedean spiral antenna

The properties of the Archimedean spiral antenna are similar to those of the equiangular spiral antenna. It is a circularly polarised antenna and a single beam can be obtained by placing a cylindrical cavity on one side of the spiral (Losee 1997:393). The Archimedean antenna is illustrated in Figure 2-11.

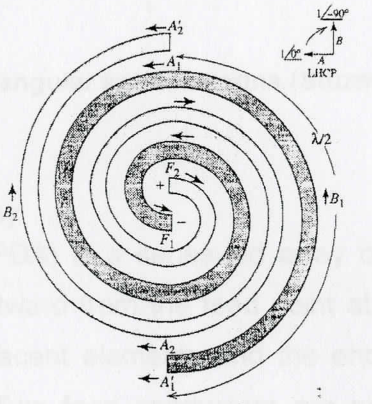

Figure 2-11 : Archimedean spiral antenna (Stuzman & Thiele 1998:255)

The Archimedean spiral radiates over a large frequency band and its radius increases uniformly with the angle as in Equation 2-4 below

$$r = r_o + a_\phi$$ Equation 2-4

where r_o is the initial radius and a_Φ is the growth rate. A balanced line feeds the Archimedean spiral from the centre. The Archimedean spiral must have a perimeter of 1.25λ at the lowest operating frequency and the spacing between feed points must be limited to λ/4 for the upper frequency truncation size (Milligan 1985:374).

2.5.3.2.5 Conical spiral antenna

The conical spiral antenna is a non-planar type of the spiral antenna. A single beam is produced off the tip of the cone. The polarisation is circular and the beamwidth is controlled by the cone angle and the length of the cone (Losee 1997:394). Figure 2-12 shows the conical equiangular spiral antenna.

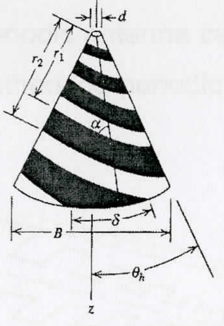

Figure 2-12 : Conical equiangular spiral antenna (Stuzman & Thiele 1998:257)

2.5.3.2.6 Log-periodic dipole array

The Log–Periodic Dipole Array (LPDA) is a series-fed array of parallel or thin rod dipoles of successively increasing lengths outward from the feed point at the apex. The inter-connecting feed lines cross over between adjacent elements and the enclosed angle bounds the dipole lengths in a single plane LPDA. Two feed conductors are parallel and closely spaced with monopole arms alternating in direction and the coaxial transmission line is run through the inside of one of the feed conductors in a two-way plane. The outer conductor of the coaxial cable is attached to the conductor at the apex and the inner conductor of the coaxial cable is connected to the other conductor of the LPDA transmission at the apex (Losee 1997:394). Figure 2-13 shows the log-periodic dipole antenna.

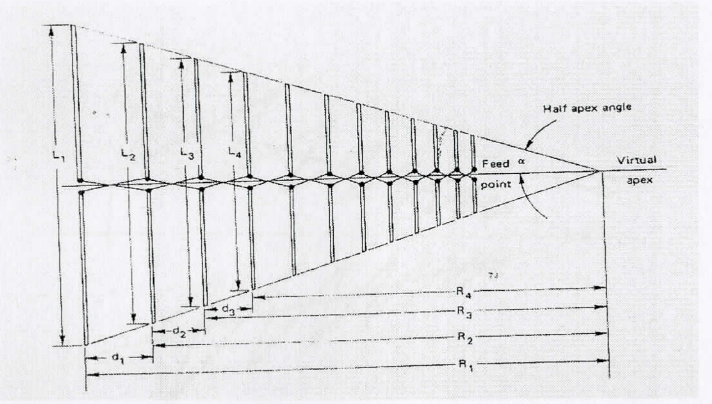

Figure 2-13 : Log-periodic dipole antenna (Milligan 1985:384)

2.5.3.2.7 Trapezoidal-toothed log-periodic antenna

The trapezoidal-toothed log-periodic antenna is unidirectional and has the main beam in the direction of the apex. The polarisation is linear and in the same direction as the teeth of the antenna. The trapezoidal-toothed log-periodic antenna can be fed by a coaxial wide-band balun (Losee 1997:397-398). A trapezoidal-toothed log-periodic antenna is illustrated in Figure 2-14.

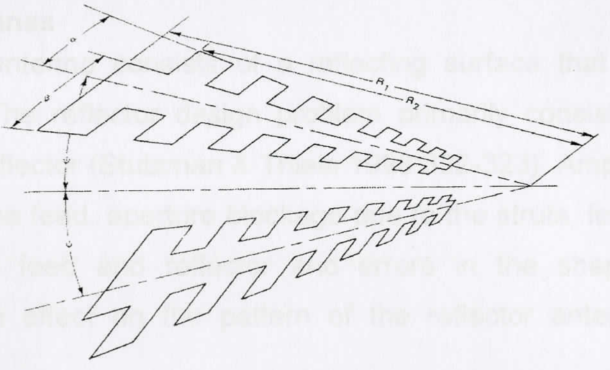

Figure 2-14 : Trapezoidal tooth log-periodic antenna (Milligan 1985:394)

2.5.3.2.8 Triangular-toothed log-periodic antenna

The performance of the triangular-toothed log-periodic antenna is similar to the performance of the trapezoidal-toothed log-periodic antenna (Losee 1997:400). The triangular-toothed log-periodic antenna is illustrated in Figure 2-15.

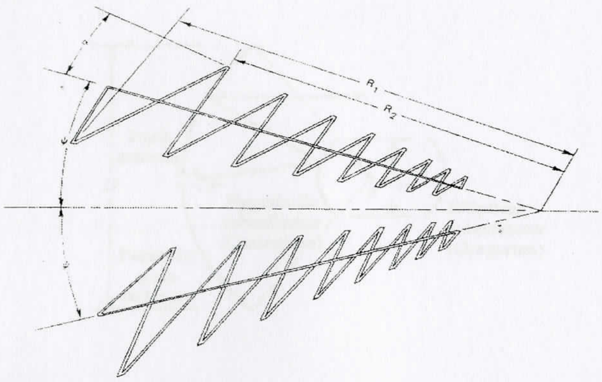

Figure 2-15 : Triangular tooth log-periodic antenna (Milligan 1985:395)

2.5.4 Aperture antennas

Aperture antennas are antennas that have a well-defined aperture area from which radiation occurs. Examples of aperture antennas include reflector antennas, horn antennas, lens antennas and array antennas (Pozar 2005:640).

2.5.4.1 Reflector antennas

The simplest reflector antenna consists of a reflecting surface that is large relative to the operating wavelength. The reflector design problem primarily consists of matching the feed antenna pattern to the reflector (Stutzman & Thiele 1998:322-323). Amplitude and phase pattern of the feed, position of the feed, aperture blockage due to the struts, feed, subreflector, multiple reflections between the feed and reflector and errors in the shape of the reflector and subreflector all have an effect on the pattern of the reflector antenna (Raisanen & Lehto 2003:236).

A subreflector can be introduced between the feed and main reflector of a single reflector to form a dual reflector antenna. The axisymmetric Cassegrain antenna shown in Figure 2-16 is the most popular dual reflector antenna. The main reflector is parabolic and the subreflector is hyperbolic. The Gregorian reflector antenna that offers perfect focusing is the second form of the dual reflector antenna. The Gregorian reflector antenna has a concave rather than a convex subreflector that is located beyond the virtual focal point as shown in Figure 2-16 and has an elliptical subreflector (Stutzman & Thiele 1998:335-338).

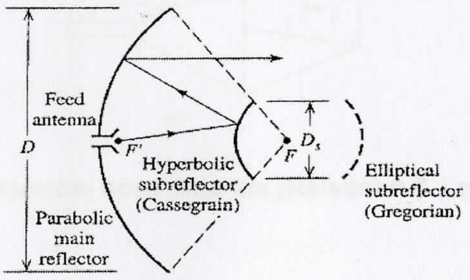

Figure 2-16 : Cassegrain and Gregorian reflector (Stutzman & Thiele 1998:335)

2.5.4.2 Horn antennas

A horn antenna is obtained by widening the waveguide end to have a better antenna than the simple waveguide end. An open waveguide end operates as a simple antenna. However, this simple antenna has a broad, asymmetrical beam and a large impedance mismatch. The H-plane horn is widened along the broadside of the waveguide and the E-plane horn is widened along the narrow side of the waveguide. The pyramidal horn is broadened in both directions of the waveguide ends (Raisanen & Lehto 2003:232).

Horn antennas are often used as feeds for parabolic dish antennas. Horn antennas are used separately when the gain requirements are not too high and as standards in measuring the performance of other antennas. Three types of horn antennas are the H-plane sectoral horn, the E-plane sectoral horn and the pyramidal horn (Losee 1997:400). An H-plane sectoral horn is illustrated in Figure 2-17a, and an E-plane sectoral horn in Figure 2-17b. Figure 2-18c illustrates the pyramidal horn antenna.

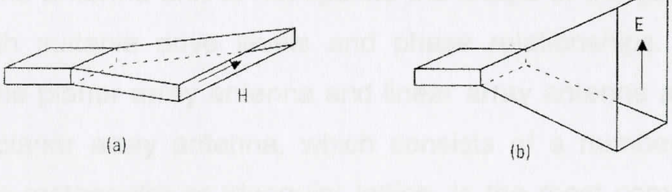

Figure 2-17 : H-plane and E-plane sectoral horn (Räisänen & Lehto 2003:232)

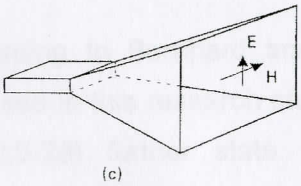

Figure 2-18 : Pyramidal horn antenna (Räisänen & Lehto 2003:232)

2.5.4.3 Lens antennas

Lens antennas can be dielectric, Luneburg or metal-plate. Dielectric lenses and metallic-plate lenses convert a spherical wavefront emanating from a point source to a planar wavefront. The dielectric lens is made thick at the centre and progressively thinner toward the edges of the lens, whilst metallic-plate lenses are thin near the centre and progressively thicker towards the edges of the lens. The gain and beamwidth of the dielectric lens antenna depend on the area of the lens and the wavelength. Luneburg is a special case of the dielectric lens that is spherical in shape. A practical Luneburg lens can be constructed from a large number of spherical shells of constant index of refraction (Losee 1997:408-410).

2.5.4.4 Array Antenna

A single element antenna provides low directive gain. The directivity can be increased by enlarging the dimensions of the single element, or by forming an array. The array is an assembly of radiating elements in an electrical or geometrical configuration (Balanis 1997:249). Array antennas are antennas that consist of two or more element antennas. Antenna arrays may have many good properties such as high gain, narrow beam, shaped beam, scanning beam or adaptive beam, which cannot be achieved with a single element. The array may be linear, planar or conformal (Räisänen & Lehto 2003:239). Coleman (2004:246) adds that it is possible to increase the gain of the antenna and to manipulate the shape of the gain pattern by combining several antennas with suitable drive levels and phase relationships. Whitaker and Benson (2002:11-115) state the planar array antenna and linear array antenna as the common types of array antenna. The planar array antenna, which consists of a number of radiating elements regularly spaced on a rectangular or triangular lattice, is the most common configuration. The radiating elements are placed in a single line in the linear array antenna configuration.

2.5.5 Choice of Antenna

Whilst linear wire antennas, according to Bernhard and Michielssen (2002:5-17), are very popular, they are not going to be used in this research study. Planar antennas will be used, as Bernhard and Michielssen (2002:5-28) further state that planar antennas possess the advantages of low-profile and durable form factors, light weight and low cost that make planar antennas ideal for implementation in wireless communication applications. According to Park, Han and Itoh (2004:52) circularly polarised antennas offer reception with less polarisation mismatch and the broadband antennas enable relatively high RF power to be received from various sources in the frequency range. Furthermore, one of the stated advantages of microstrip technology is the relative ease to generate circular polarisation (Bernhard & Michielssen 2002:6-15). In particular, the equiangular spiral antenna array is selected as it offers the benefits of circular polarisation and its impedance remains constant over a wide range of frequencies (Stutzman & Thiele 1998:253). In addition, Chin *et al.* (2005:175) state that an antenna array is an effective means to increase the receiving power for rectification, as opposed to a single antenna. Having selected an antenna for the research study, one needs to examine how the harvested electromagnetic energy from the antenna will be transferred to the rectifying circuit by matching the characteristic impedance of the antenna to the impedance of the rectifying circuit. Impedance matching will now be examined.

2.6 Impedance matching

Green (1982:58) states that the impedance of the source must be equal to the conjugate of the impedance of the load for maximum power transfer. Therefore, to optimise the antenna design and achieve optimum power transfer of the received microwave energy to the rectifying circuit, the impedance of the antenna should be matched to the impedance of the rectifying circuit. Although Hagerty *et al.* (2004:1016) used Diode Source-Pull using Agilent ADS (Agilent 2000 - 2007:1), Microwave Office/Analog Load Pull Wizard (Applied Wave Research, Inc 2005:12-22-27) is used to determine the optimal impedance match for maximum power transfer in this research study. The Microwave Office/Analog Load Pull Wizard allows designers to perform load pull simulations on the device model using tuner elements to tune impedance points presented to the device at the load or source side. HBTUNER is the Microwave Office tuner element used to match the characteristic impedance of the antenna to the impedance of the rectifying circuit for optimum power transfer. HBTUNER is a frequency-dependent, lossless, 2-port network that transforms the impedance seen at port 2 to the user-defined impedance seen at port 1. The magnitude and angle of the reflection coefficient for the fundamental, second-harmonic, and third harmonic frequencies can be adjusted independently when using the HBTUNER (Applied Wave Research, Inc 2005:12-22-27). See Figure 4-1 for the circuit schematic of the source-pull analyses described above. (The analyses applied in this work varies the source impedance for optimum output power, hence it is referred to as "source-pull".)

Pozar (2005:513) states that the square-law behaviour is the usual operating condition for detector diodes and can be obtained only over a restricted range of input powers as illustrated in Figure 2-19. At very low signal levels, the input is lost in the noise floor of the device. If the input power is too large, the output will become saturated and approach a linear and then a constant V_{out} versus P_{in} characteristic. The square-law region will be used in the research study to convert the received microwave energy into dc power.

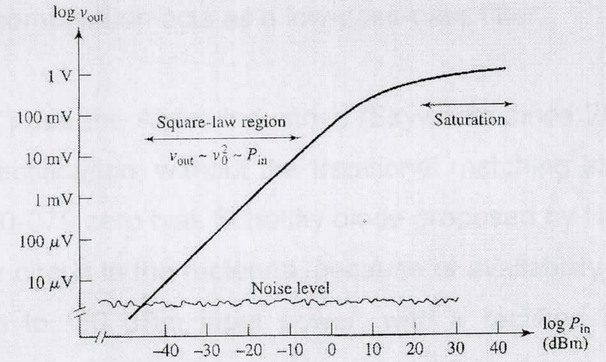

Figure 2-19 : Square-law region (Pozar 2005:513)

Once the optimal impedance match between the equiangular spiral antenna and the rectifying circuit is achieved, the received microwave energy may now be rectified and a discussion of the rectifying circuit will now follow.

2.7 Rectifying circuits

According to Akkermans *et al.* (2005:315) the Schottky diode is the main component of rectifying circuits. Strassner and Chang (2003:356) add that rectifying circuits are instrumental in rectifying antennas and passive RFID applications. The incoming microwave energy is converted into dc power by the Schottky diode. Heikkinen and Kivikoski (2003:331) suggest the diode pair connected as a voltage doubler as depicted in Figure 2-20 below.

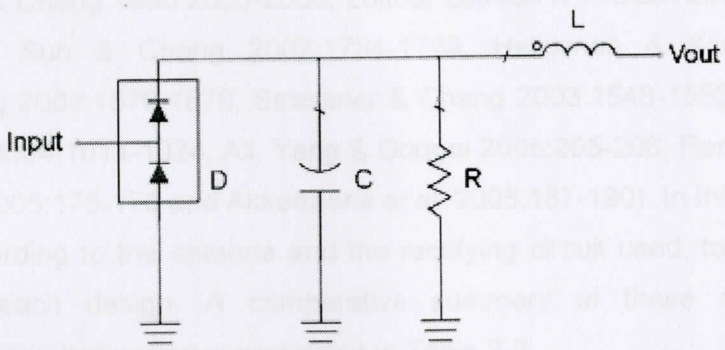

Figure 2-20 : Rectifier Circuit (Heikkinen & Kivikoski 2003:331)

In addition to the Schottky diode, a 68 pF capacitor, 8.2 kΩ resistor and 15 nH inductor choke were used for the low-band rectification at 2.45 GHz. The purpose of the choke of Figure 2-20 is to suppress the effect of output dc voltage measurements wires on the performance of the rectifier. The parallel RC combination acts as a low-pass-pass filter.

Hagerty *et al.* (2004:1017) use the Alpha Industries (Skyworks since 2002) SMS7630-079 zero bias Schottky diode for rectification, without the traditional matching and filtering sections. The Alpha Industries SMS7630-079 zero bias Schottky diode proposed by Hagerty *et al.* (2004:1016) is selected for the rectifier circuit in the rectenna, because of availability and low turn-on voltage. It typically rectifies down to -30 dBm input power, with a rectified output voltage of a few millivolts. The rectified power may now be used to power the load.

2.8 Load

The load in the rectenna system refers to the application of the rectenna. Indoor low-cost and low-power DWSNs for monitoring indoor building comfort will serve as the load for the proposed rectenna model, because they have low data rates and small active duty cycles, therefore meet the specified power requirements of 5 mW of power for 6 ms sensing and transmission operation. The discussion of the load concludes the rectenna system. However, there are various rectenna designs in the literature and one needs to select a viable rectenna design for the research study. Rectenna designs will now be examined.

2.9 Rectenna designs

Several microwave rectennas are cited in the literature (McSpadden *et al.* 1998:1-8, McSpadden, Fan & Chang 1998:2053-2060, Zbitou, Latrach & Toutain 2006:147-152, Gómez *et al.* 2004:315-318, Suh & Chang 2002:1784-1789, Heikkinen & Kivikoski 2003:330-333, Strassner & Chang 2002:1870-1876, Strassner & Chang 2003:1548-1553, Park *et al.* 2004:52-54, Hagerty *et al.* 2004:1014-1024, Ali, Yang & Dougal 2005:205-208, Ren & Chang 2006:1495-1502, Chin *et al.* 2005:175-178 and Akkermans *et al.* 2005:187-190). In this study, the rectennas are classified according to the antenna and the rectifying circuit used, to examine the benefits emanating from each design. A comparative summary of these rectenna designs for electromagnetic power harvesting is presented in Table 2-3.

Table 2-3 : Comparative summary of the rectenna designs for electromagnetic power harvesting

Author&Year	**Type**	**Design**	**Input power**	**Results**	**Application**
McSpadden, Dickinson, Fan&Chang 1998	Half-wave dipole rectenna	Half-wave dipole and GaAs IMPATT diode	Not available	85% conversion efficiency across 165Ω resistive load at 2.45 GHz	Microwave power transmission
McSpadden, Fan&Chang 1998	Half-wave dipole rectenna	Half-wave dipole and MA40150-119 Si Schottky diode	50 mW	82% conversion efficiency across 327Ω load resistor at 5.8 GHz	Microwave power transmission
Gómez,García, Mediavilla&Tarzón 2004	E-pHEMT technology rectenna	Microstrip antenna and an E-pHEMT detector	14.12 mW	85.4% overall efficiency at 900 MHz	Microwave power transmission, Actuators & RFID sensors
Suh&Chang 2002	Dual-frequency rectenna	Dual-frequency dipole and MA4E1317 GaAs Schottky diode	89.84mW at 2.45 GHz and 49.09mW at 5.8 GHz	84.4% efficiency at 2.45 GHz and 82% at 5.8 GHz	Microwave power transmission
Heikkinen& Kivikoski 2003	Dual-frequency rectenna	Shorted ring-slot and HSMS-2862 Si Schottky diode pair	-5 dBm	49% efficiency at 2.45 GHz and 14% at 5.8 GHz	Microwave power transmission
Strasner&Chang 2002	Circularly polarised rectenna	DLRA and MA4E1317 detector diode	Not available	80% conversion efficiency at 5.8 GHz across a 250 Ω load resistor	Microwave power transmission
Strasner&Chang 2003	Circularly polarised rectenna	Folded dipole and MA4E1317 Schottky diode	2mW/cm^2 (115 mW)	82% efficiency at 5.8 GHz for a 150Ω load	Microwave power transmission
Park,Han&Itoh 2004	Circularly polarised rectenna	Circular sector and HSMS-2820 Schottky diode	10 dBm	77.8% efficiency at 2.4 GHz across 150Ω load resistor	Not available

Author&Year	Type	Design	Input power	Results	Application
Hagerty, Helmbrecht, McCalpin,Zane& Popović 2004	Circularly polarised rectenna	Equiangular spiral and SMS7630-079 Schottky diode	0.1 mW/cm^2	20% rectification efficiency	Indoor sensor networks & energy recycling
Ali,Yang&Dougal 2005	Circularly polarised rectenna	Patch antenna and MA4E1317 detector diode	2.55 mW/cm^2	57.3% conversion efficiency at 5.5 GHz for 300Ω load impedance	Embedded wireless sensor and data telemetry
Ren&Chang 2006	Circularly polarised rectenna	Truncated patch and two model MA4E1317 Schottky diodes	Not available	76% efficiency at 5.8 GHz for 100Ω loading and 6.22V dc output voltage	Microwave power transmission
Chin,Xue&Chan 2005	FG-CPW rectenna	Patch antenna and HSMS-8202 Schottky diode	18 dBm	68.5% conversion efficiency at 5.8 GHz	Microwave power transmission & RFID sensors
Akkermans, Beurden, Doodeman&Viser 2005	Probe-fed microstrip patch rectenna	Microstrip patch and HSMS-2852 Schottky diode	0 dBm	40% conversion efficiency across 470Ω	Low-power wireless sensor
Zbitou,Latrach& Toutou 2006	Hybrid rectenna	Patch antenna array and HSMS2820 Schottky diode	-20 dBm	20% conversion efficiency at 2.45 GHz	Not available

Each of these rectenna designs will now be discussed in detail. The first rectenna design to be examined is the half-wave dipole rectenna.

2.9.1 Half-wave dipole rectenna

McSpadden *et al.* (1998:2) experimented with a half wave dipole, low pass filter, a GaAs IMPATT diode and a 30 pF capacitor rectenna. A high conversion efficiency of 85% was obtained across a 165 Ω resistive load. The conversion efficiency is the ratio of output dc power to the power difference of the incident RF power and the reflected RF power (Curty *et al.* 2776).

McSpadden, Fan and Chang (1998:2054-2058) suggest a half-wave dipole antenna attached to a low-pass filter, an MA40150-119 Si Schottky diode placed in shunt across the transmission line and an output filter consisting of a large capacitor to convert power when the power density is low. A maximum conversion efficiency of 82% is achieved at an input power of 50 mW. The main elements of the half-wave dipole rectenna are shown in Figure 2-21 below.

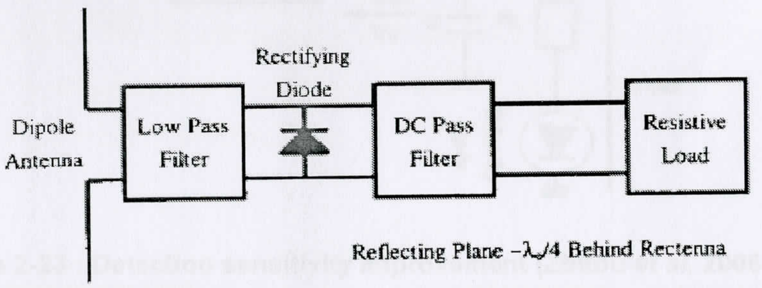

Figure 2-21 : Rectenna elements (McSpadden, Fan & Chang 1998:2054)

2.9.2 Hybrid rectenna

Zbitou, Latrach & Toutain (2006:147) used a series configuration with a single HSMS2820 zero-bias Schottky diode presented in Figure 2-22 that can be integrated with a patch antenna to achieve a rectenna system.

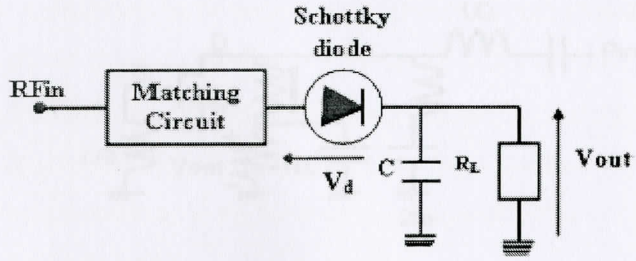

Figure 2-22 : Series rectifier (Zbitou *et al.* 2006:147)

Zbitou *et al.* (2006:148) further improved the detection sensitivity and simultaneously improved the conversion efficiency as depicted in Figure 2-23 by using the same Schottky diode in series with R_L. In the detection sensitivity improvement configuration, the threshold detection is -25 dBm and the measured efficiency is 20% for an input power of -20 dBm.

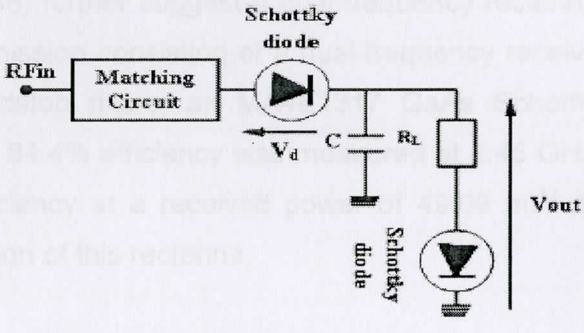

Figure 2-23 : Detection sensitivity improvement (Zbitou *et al.* 2006:148)

2.9.3 Rectenna using E-pHEMT technology

Different FET detector circuits have been proposed but were not applied to the rectenna elements, because of the dc gate biasing voltage required (Gómez *et al.* 2004:315). Gómez *et al.* (2004:315) propose the Enhancement mode Pseudomorphic High Electron Mobility Transistor (E-pHEMT) in the rectenna elements because of its little threshold voltage and a high conversion efficiency for an unbiased detector. In this rectenna element design, 85.4% overall efficiency was obtained at an input power of 11.5 dBm. The schematic of the E-pHEMT detector circuit is shown in Figure 2-24.

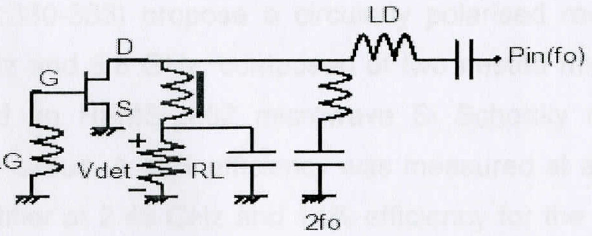

Figure 2-24 : E-pHEMT detector (Gomez *et al.* 2004:316)

2.9.4 Dual-frequency rectenna

Suh and Chang (2002:1784) state that microwave power transmission was traditionally focussed on 2.45 GHz and recently moving to 5.8 GHz as these two frequencies have comparably low atmospheric loss, cheap component availability, and reported high conversion efficiency. Suh and Chang (2002:1784-1788) further suggest a dual-frequency rectenna for 2.45-GHz and 5.8-GHZ wireless power transmission consisting of a dual-frequency receiving dipole antenna, low-pass input filter, two bandstop filters, an MA4E1317 GaAs Schottky barrier diode and a microwave block capacitor. 84.4% efficiency was measured at 2.45 GHz at a received power of 89.84 mW and 82.7% efficiency at a received power of 49.09 mW at 5.8 GHz. Figure 2-25 shows the circuit configuration of this rectenna.

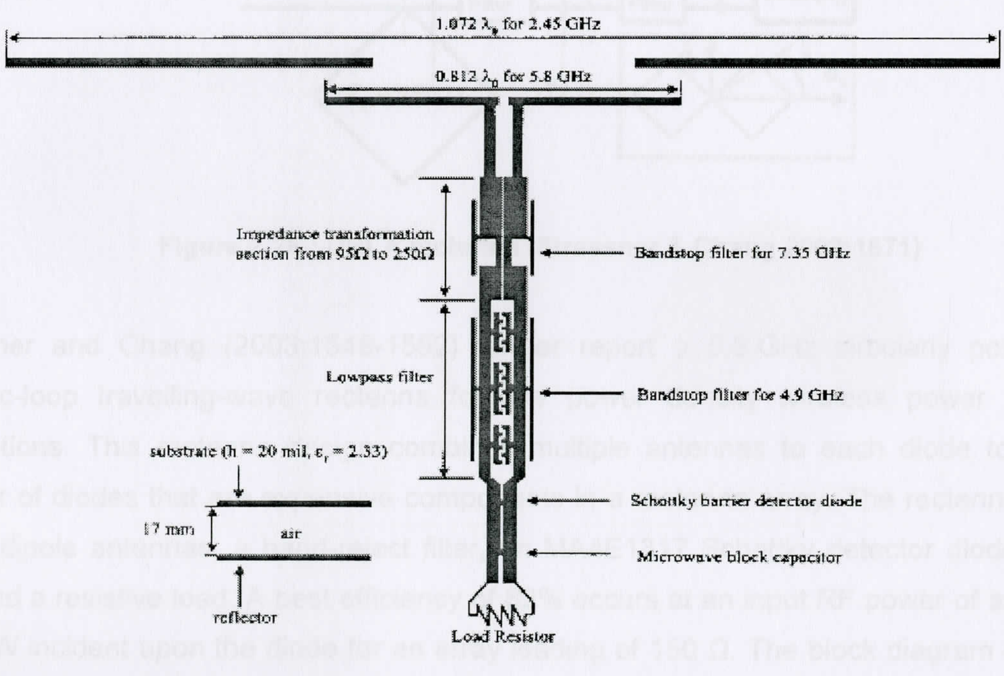

Figure 2-25 : Dual-frequency rectenna (Suh & Chang 2002:1785)

Heikkinen and Kivikoski (2003:330-333) propose a circularly polarised rectenna for wireless power transmission at 2.45 GHz and 5.8 GHz, composed of two nested microstrip-fed shorted annular ring-slot antennas and an HSMS-2862 microwave Si Schottky detector diode pair connected as a voltage doubler circuit. A 49% efficiency was measured at an input power level of -5 dBm for the low-band rectifier at 2.45 GHz and 14% efficiency for the 5.8 GHz high-band rectifier for the same input power level.

2.9.5 Circularly polarised rectennas

Strassner and Chang (2002:1870-1874) report a 5.8 GHz circularly polarised rectenna for wireless microwave power transmission. A dual rhombic loop antenna (DRLA), an MA4E1317 detector diode, a dc-pass filter and a 250 Ω load resistance rectenna system achieved conversion efficiency above 80%. The block diagram and spatial orientation of the DRLA rectenna are shown in Figure 2-26.

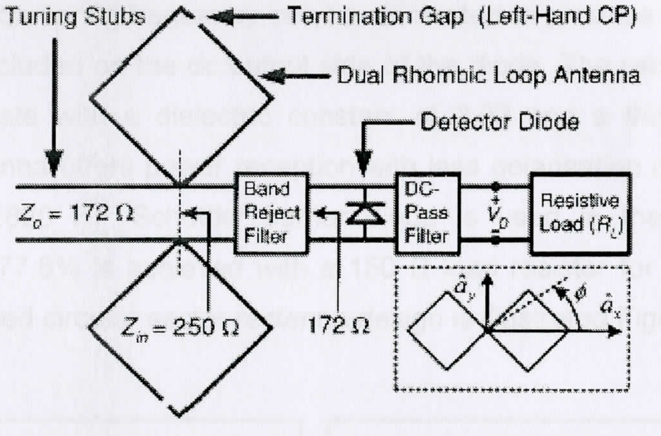

Figure 2-26 : DRLA rectenna (Strassner & Chang 2002:1871)

Strassner and Chang (2003:1548-1552) further report a 5.8-GHz circularly polarised dual-rhombic-loop travelling-wave rectenna for low power density wireless power transmission applications. This rectenna design combines multiple antennas to each diode to reduce the number of diodes that are expensive components in a rectenna array. The rectenna consists of folded dipole antennas, a band-reject filter, an MA4E1317 Schottky detector diode, a dc-pass filter and a resistive load. A best efficiency of 82% occurs at an input RF power of approximately 115 mW incident upon the diode for an array loading of 150 Ω. The block diagram of this DRLA travelling wave rectenna is illustrated in Figure 2-27.

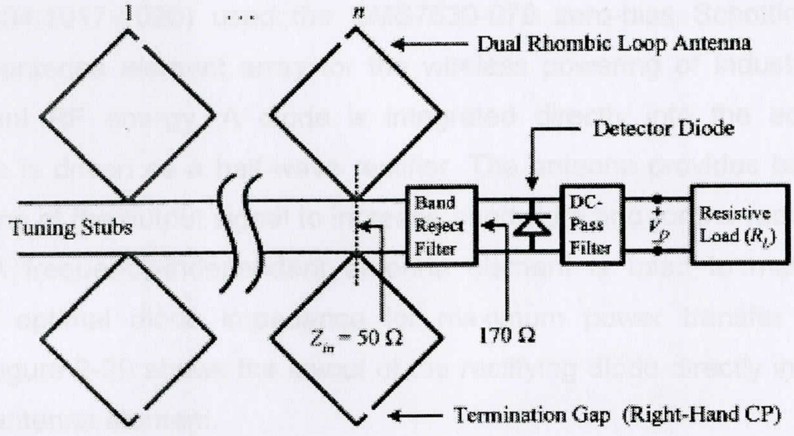

Figure 2-27 : DRLA travelling-wave rectenna (Strassner & Chang 2003:1549)

A rectenna design with a harmonic-rejecting circular-sector antenna at 2.4 GHz is proposed by Park *et al.* (2004:52-54). The circular sector antenna suppresses radiation of the second and third harmonics. A low-pass filter between the diode and the antenna that has additional insertion loss at the fundamental frequency can be eliminated to produce higher efficiency. The low-pass filter is only included on the dc output side of the diode. The rectenna is fabricated on RT/Duroid 5870 substrate with a dielectric constant of 2.33 and a thickness of 31 mils. A circularly polarised antenna offers power reception with less polarisation mismatch. The Agilent surface-mount HSMS-2820 RF Schottky barrier diode is used in the rectenna design. A maximum efficiency of 77.8% is achieved with a 150 Ω load resistor for an input power of 10 dBm. A circularly polarised circular sector rectenna design is illustrated Figure 2-28.

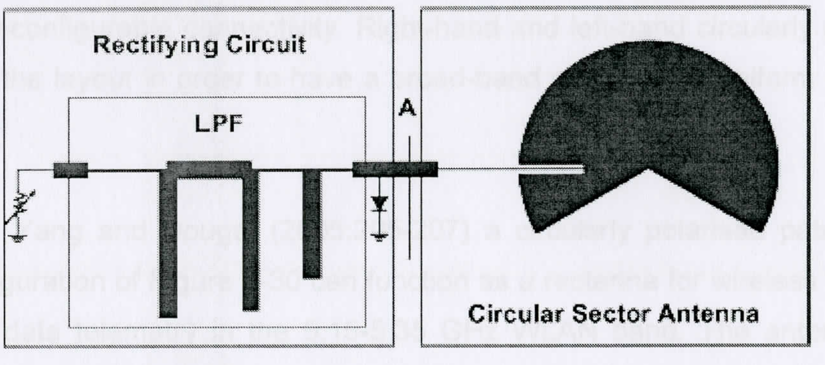

Figure 2-28 : Rectenna with a circular sector antenna (Park et al. 2004:52)

Hagerty *et al.* (2004:1017-1020) used the SMS7630-079 zero-bias Schottky diode and an equiangular spiral antenna element array for the wireless powering of industrial sensors and recycling of ambient RF energy. A diode is integrated directly into the equiangular spiral antenna. The diode is driven as a half-wave rectifier. The antenna provides both the matching and filtering functions of the output signal to increase bandwidth and for the reduction of the size of the rectenna. A frequency-independent antenna element is used to match the antenna impedance to the optimal diode impedance for maximum power transfer for the desired frequency range. Figure 2-29 shows the layout of the rectifying diode directly integrated into the equiangular spiral antenna element.

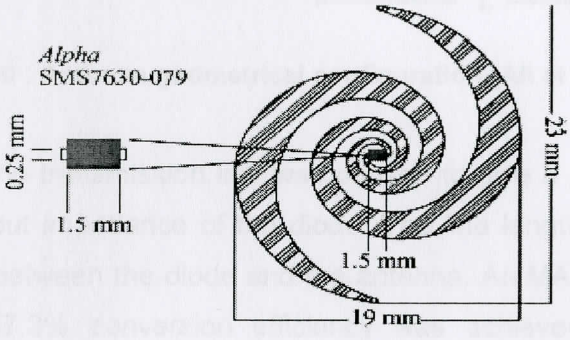

Figure 2-29 : Integrated rectenna (Hagerty *et al.* 2004:1018)

RF powers received independently by each element of a 64-element array are summed upon rectification as dc currents or voltages. The 64-element array is connected using 2×1 parallel pairs connected in series to form 2×2 subarrays. Four of these subarrays are connected in parallel to create a 4×4 subarray. Four more of these subarrays are left as units to comprise the 8×8 array with reconfigurable connectivity. Right-hand and left-hand circularly polarised spirals are alternated in the layout in order to have a broad-band array with a uniform pattern in space and polarisation.

According to Ali, Yang and Dougal (2005:205-207) a circularly polarised patch antenna with geometrical configuration of Figure 2-30 can function as a rectenna for wireless battery charging at 5.5 GHz and data telemetry in the 5.15-5.35 GHz WLAN band. The antenna was initially designed and developed on a 3.15-mm thick Duroid substrate and fed by a coaxial probe. The antenna characteristics were optimised for wide return loss and circular polarisation by a parametric study using Ansoft HFSS. The two slots positioned along the left diagonal of the patch generate right-hand circular polarisation and positioning the slots along the right diagonal generates left-hand circular polarisation.

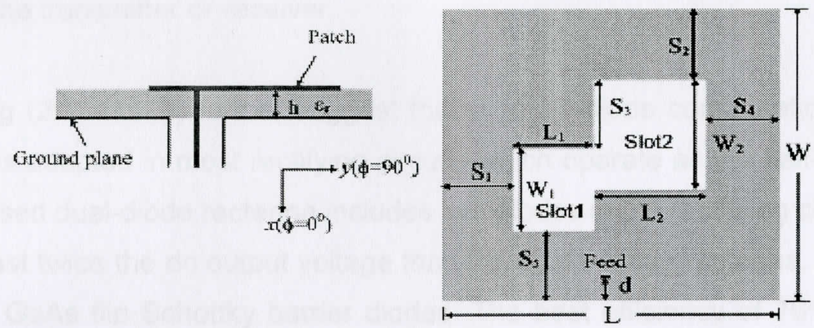

Figure 2-30 : Antenna geometrical configuration (Ali et al. 2005:205)

The width of the microstrip transmission line was chosen to give a characteristic impedance of 172 Ω, based on the input impedance of the diode. The line length was chosen to achieve a good impedance match between the diode and the antenna. An MA4E1317 detector diode was used for rectification. 57.3% conversion efficiency was achieved at 5.5 GHz for a load impedance of 300 Ω (Ali *et al.* 2005:205). The geometry and the circuit diagram of the rectenna are illustrated in Figure 2-31.

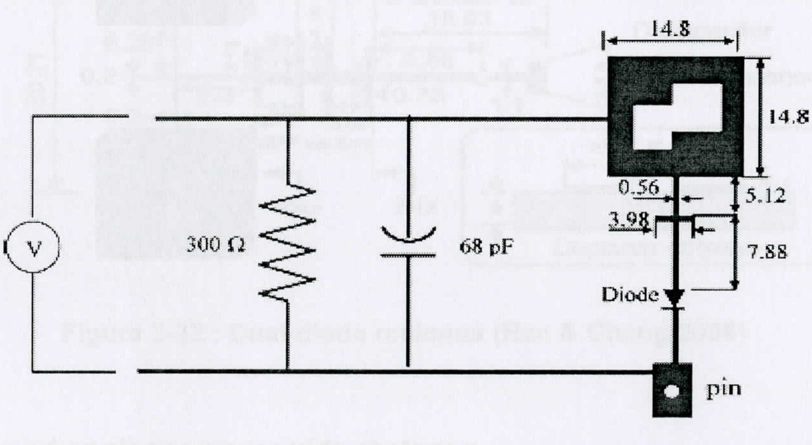

Figure 2-31 : Geometry and Circuit diagram of circularly polarised patch antenna (Ali *et al.* 2005:205)

Ren and Chang (2006:1495-1498) proposed a circularly polarised dual-diode rectenna at 5.8 GHz for microwave power reception. The microwave rectenna consists of a pair of circularly polarised truncated patch antennas, a harmonic-rejecting band pass filter to suppress harmonic signals, two detector diodes for RF-to-dc conversion and a dc pass filter. The patch antenna has characteristics comparable to that of a two element array that allows the rectenna to receive more power and to be compact. Circular polarisation avoids changes in the output voltage due to the rotation of the transmitter or receiver.

Ren and Chang (2006:1495) further suggest that a single-diode configuration in past rectenna developments is adopted in most rectifying circuits which operate as the half-wave rectifier. The circularly polarised dual-diode rectenna includes two diodes in the rectifying circuit. The rectenna produces at least twice the dc output voltage than the single diode rectenna. The rectenna uses an MA4E1317 GaAs flip Schottky barrier diodes. The best efficiency of 76% occurs at 100 Ω loading while the output dc output voltage is 6.22 V. The rectenna is printed on Rogers Duroid 5880 substrate with the dielectric constant of 2.2 and 20 mil (0.508 mm) thickness. Figure 2-32 shows the layout of the dual-diode rectenna.

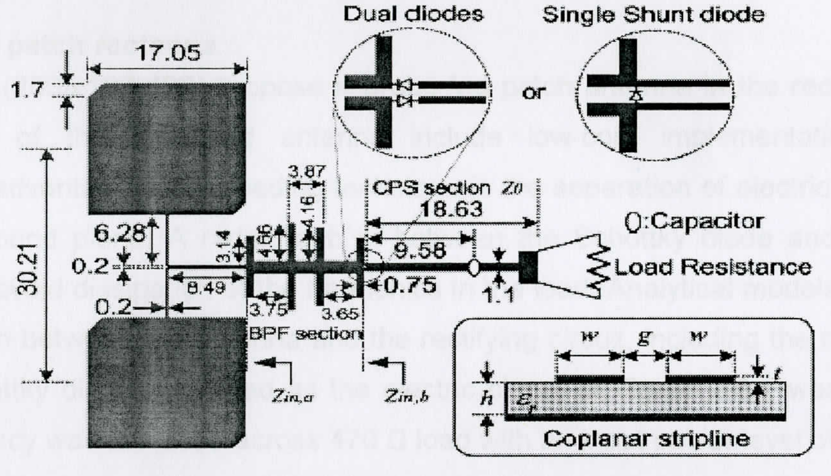

Figure 2-32 : Dual-diode rectenna (Ren & Chang 2006)

2.9.6 Finite ground coplanar waveguide rectenna

Chin *et al.* (2005:175) suggest the finite ground coplanar waveguide (FG-CPW) rectenna fabricated on a 0.7572-mm-thick RT/Duroid 6002 substrate with a dielectric constant of 2.94. A full-wave electromagnetic simulator is used in this rectenna design to design the antenna and the coplanar waveguide resonant cell filter. The measured gain of the antenna is 9 dBi. The rectenna has a conversion efficiency of 68.5% at 5.8 GHz frequency with an input power of 18 dBm. An HSMS-8202 Schottky barrier diode is used for rectification. The circuit configuration of the proposed finite ground coplanar waveguide rectenna is illustrated in Figure 2-33.

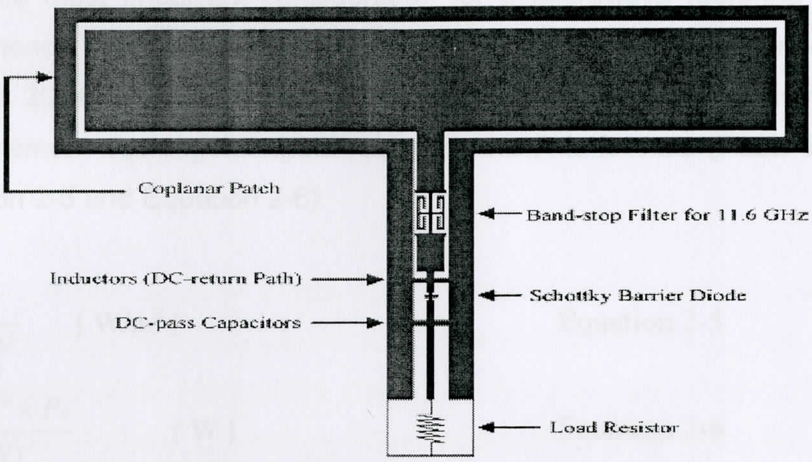

Figure 2-33 : FG-CPW rectenna (Chin *et al.* 2005:175)

2.9.7 Probe-fed patch rectenna

Akkermans *et al.* (2005:187-190) propose a probe-fed patch antenna in the rectenna designs. The advantages of the proposed antenna include low-cost implementation and small dimensions. The advantage of the feeding technique is the separation of electric circuit and the antenna via a ground plane. A radial stub in between the Schottky diode and the load is a bandstop filter to avoid dissipation of the harmonics in the load. Analytical models are employed to acquire a match between the antenna and the rectifying circuit, including the radial stubs. An HSMS-2852 Schottky diode, modelled as the electric circuit of Figure 2-34, was used. A 40% conversion efficiency was achieved across 470 Ω load with an input power level of 0 dBm.

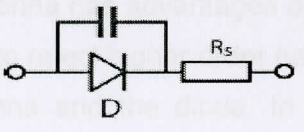

Figure 2-34 : Electric circuit model of rectifying diode (Akkermans *et al.* 2005:187)

2.9.8 Choice of a microwave rectenna design

According to Green (1982:57-58), many instances occur in electronic and telecommunication engineering where a source of e.m.f. is to be connected to the load and maximum power must be transferred to the load from the source. For maximum power to be transferred from the source to the load, the resistance of the load must be equal to the resistance of the source.

In conclusion, the most important consideration for a microwave rectenna design is how to obtain high efficiency, as maximum power should be collected and delivered to the rectifying diode (Park *et al.* 2004:52). In calculating the expected radiated power density and input power for the sixteen-element equiangular spiral rectenna, the Friis formula (Pozar 2005:647-648) will be used (Equation 2-5 and Equation 2-6):

$$Savg = \frac{Gt \times Pt}{4 \times \pi \times R^2} \quad [\mathbf{W/m^2}] \qquad \text{Equation 2-5}$$

$$\Pr = \frac{Gt \times Gr \times \lambda^2 \times Pt}{(4 \times \pi \times R)^2} \quad [\mathbf{W}] \qquad \text{Equation 2-6}$$

where *Savg* is the radiated power density, *Gt* is the transmitting antenna gain, *Pt* is the transmitted power and *R* is the distance between the transmitting and the receiving antenna. *Pr* is the received power, *Gr* is the receiving antenna gain and λ is the operating wavelength.

Typical wireless access point antenna gain is 2.2 dBi and the maximum power level in the regulatory domain is 100mW for the IEEE 802.11b in America (Cisco Systems 2003:A-4). Using a typical wireless access point on the 2.4 GHz frequency, the calculated radiated power density is 10.57 nW/cm^2 for a radius (*R*) of 10 m.

The second consideration is the suppression of harmonics generated by the diode (Park *et al.* 2004:52). A circular broad-band rectenna design approach is chosen for the research study because the circular broad-band rectenna has advantages of receiving from all directions over a broad frequency range and its ability to reject higher order harmonics without the need to employ a low pass filter between the antenna and the diode. In particular, the circular broad-band rectenna design by Hagerty *et al.* (2005:1014-1024) will be used as the basis for the development of the microwave rectenna as it is able to achieve rectification with low input power levels ranging from tens of nW/cm^2 to 0.1 mW/cm^2 in a wide frequency band from 2 GHz to 18 GHz. The Hagerty *et al.* (2005:1014-1024) microwave rectenna design provides the most viable choice as the expected maximum radiated power density for the research study is 10.57 nW/cm^2, as discussed above. The expected minimum radiated power density is a few magnitudes below the threshold Hargety *et al.* (2004:1020) used to determine the usefulness of low power rectification. The choice of the rectenna design concludes the discussion on the rectenna. One of the key challenges with electromagnetic power harvesting is that the ambient power densities in the microwave frequency range cannot generate powers sufficient for continuous operation of the microsensors. Power conditioning is required and will now be examined.

2.10 Power conditioning

Power conditioning is the process where the harvested electromagnetic power can be stored efficiently in capacitors or micro-batteries and functions of the microsensor performed in discrete time intervals (Hagerty *et al.* 2004:1022). Capacitors have virtually infinite recharge cycles and are ideal for frequent pulsing applications. Super-capacitors have improved capacity but have higher leakage current, larger size and cost. Leakage of super-capacitors is lowered by connecting two capacitors in series (Jiang, Polastre & Culler 2005:2). Excess capacitance is undesirable as it necessitates longer charging periods between microsensors functions (Leland *et al.* 2004:3). This concludes the literature survey. The research methodology followed will now be discussed.

3 CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction and Background

The objective of this research study is to develop a power harvesting technique to facilitate energy conversion in low-cost and low-power indoor DWSNs to reduce the user involvement in the power management process, and thus reduce maintenance and administrative costs. In this chapter, the research method and research design are stipulated. This is followed by a discussion of how the researcher will ensure both internal and external validity as well as research relevance and vigour. In conclusion, the chapter highlights how the data will be collected and analysed.

Mouton (2001:56) states that the research methodology focuses on the research process and the kinds of tools and procedures to be used to collect data. In Chapter 2 the sixteen-element equiangular spiral rectenna was selected as the most viable rectenna to harvest the ambient microwave energy indoors. A suitable research methodology needs to be selected for developing and testing the viability of this rectenna to supply a low-cost and low-power indoor DWSN microsensor with 5 mW of power for a 6 ms sensing and transmission operation.

3.2 Research Method

Leedy & Ormrod (2001:102) state that a quantitative approach is a more suitable approach to explain, predict, validate or test theory with known variables, established guidelines and when findings are to be communicated in numbers. In this research study a quantitative research approach will be adopted as the study is aimed at testing the theory of the viability of collecting ambient indoor microwave energy with the sixteen-element equiangular spiral antenna array and rectifying it to supply low-cost and low-power indoor DWSNs. The sixteen-element equiangular spiral rectenna model will be developed and its viability tested by measuring the rectenna output voltage.

3.3 Research Design

Mouton (2001:163) states that the purpose of computer simulation research designs is to develop and validate accurate representations of models of the real world. The model is used to generate expected values that are compared with actual data by statistical techniques. Banks

(1998:10-11) adds that simulation enables designers to test every aspect of a proposed change or addition without committing resources to their acquisition, and aid in providing an understanding about how a system works, rather than indicating someone's predictions about how a system will operate. In this research, a computer simulation research design will be adopted and the sixteen-element equiangular spiral rectenna model will be developed.

3.4 Sampling

Cooper and Schindler (2003:201) state that judgement sampling occurs when a researcher selects sample members to conform to some criterion. Judgement sampling is chosen because a maximum radius of 7 m and a minimum radius of 1 m are required for this research study, since using several short intermediate hops to send a bit are more energy-efficient than using one longer hop (Rabaey *et al.* 2000:44). It is anticipated that the sensors will typically be within 7m from the energy sources, such as wireless access points.

3.5 Internal research validity

The internal validity refers to the degree to which the measurement correctly attributes changes in the dependent variable to the independent variable instead of to any irrelevant factors (Welman *et al.* 2001:98). The rectenna will be characterised under the controlled conditions of the anechoic chamber at the Department of Electrical Engineering, University of Stellenbosch. These measurements yield accurate efficiency characterisation of the rectenna.

3.6 External research validity

The external validity of the research is the extent to which its results apply to situations beyond the study itself (Leedy & Ormrod 2001:105). The results of this study will be applicable to low-cost and low-power indoor DWSNs that are in the vicinity of microwave radiators such as wireless access points, mobile phones or microwave ovens. For this purpose, the rectenna's performance will be tested and measured in a real-life environment of a typical indoor space (e.g. a classroom or laboratory).

3.7 Research relevance and rigour

The research study should demonstrate relevance and rigour when the research investigates current organisational challenges and dilemmas as well as providing suggestions on how findings can be implemented in practice (Benbasat & Zmud, 1999:4-5). In this research study, relevance and rigour will be provided for by making recommendations on how the sixteen-element equiangular spiral rectenna model may be optimised to address the power challenges in low-cost and low-power indoor DWSNs, whilst reducing costs and sharing the results of the research study with other academics and practitioners by publishing a journal article.

3.8 Simulation

The equiangular spiral antenna will be designed and characterised in FEKO. FEKO uses a full-wave formulation which enables accurate predictions of the far fields, radiation patterns, current distributions and impedance (EM Software & Systems-SA 2001:Application note G.A Planarant 2).

In order for the maximum power to be transferred from the equiangular spiral antenna to the rectifying circuit consisting of an Alpha Industries SMS7630-079 zero bias detector diode, a load pull simulation with the Microwave Office/Analog Load Pull Wizard will be performed on the rectenna model to determine the optimum impedance match.

3.9 Data analysis

Cooper and Schindler (2003:87) state that data analysis involves reducing accumulated data to a manageable size and developing summaries. In this research study, the collected data (dc output power) will be assessed to determine the adequacy of the output power at various distances from the electromagnetic source to power low-cost and low-power indoor DWSN microsensors.

4 CHAPTER FOUR: RESEARCH RESULTS

4.1 Introduction

This chapter presents the simulation, implementation and testing of the 16-element spiral rectenna. In the first section, the impedance matching between the rectenna and rectifying diode is investigated through simulation to determine whether a matching circuit is indeed required. In addition to this, the radiation pattern of the spiral antenna is simulated to verify its desired omni-directionality. The antenna simulation is followed by a discussion on its implementation.

The chapter concludes with the experimental verification of the rectenna. The testing of the rectenna is twofold. In the first instance the internal validity of the implementation is verified through a rigorous characterisation of the rectenna in the controlled environment of an anechoic chamber. This is followed by the external verification of the rectenna whereby its power harvesting capabilities are tested in a real-life, indoor environment with various appliances serving as microwaves sources.

4.2 Rectenna simulations

4.2.1 Impedance Matching

For optimal transfer of power from the spiral antenna to the rectifying circuit, the antenna must be impedance-matched to the diode. The matching conditions are investigated through simulation. This is done in two phases. In the first instance, the optimal source impedance that has to be presented to the rectifying diode at different frequencies and input power levels is determined with the use of a load pull analysis in Microwave Office. This is followed by a simulation of the input impedance of the spiral antenna in FEKO as a function of frequency. By plotting these respective impedance curves (the optimal source impedance presented to the diode, and the input impedance of the antenna) on the same Smith chart, the matching between the antenna and diode can be evaluated visually. Overlap, or proximity, of these curves on the Smith chart would indicate a match at the appropriate frequency and power.

A load pull analysis was carried out on the rectifying circuit (see Figure 4-1) in Microwave Office (Applied Wave Research, Inc 2005:12-22-27). An Alpha SMS7630-079 Schottky diode was chosen in accordance to Hagerty *et al.* (2004:1015-10176) because of its low threshold, low cost and availability. The purpose of the load pull exercise is to obtain optimum impedances that must be presented to the rectifying circuit for maximum output (dc) power.

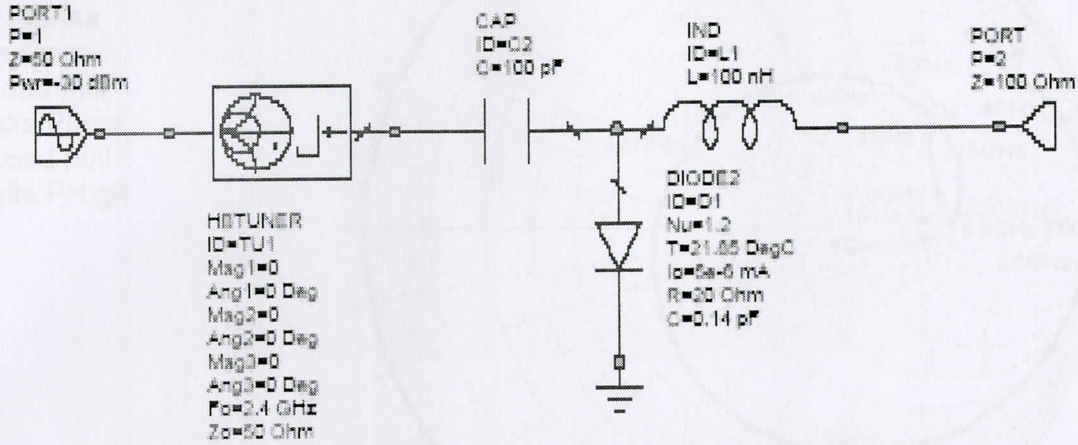

Figure 4-1 : Circuit schematic for source-pull analysis of the diode in Microwave Office

The variable tuner in the Microwave Office/Analog Load Pull Wizard was used to vary the frequency and impedance presented to the diode. The input power was initially fixed at -30 dBm (PLow) and the frequency varied from 1 GHz to 6 GHz in 1 GHz increments to observe the behaviour of the rectifying circuit with the change in frequency at low input power. The input power at PORT1 was then changed to 10 dBm (PHigh) and the frequency was again varied from 1 GHz to 6 GHz in 1 GHz increments to observe the behaviour of the rectifying circuit with the change in frequency at high input power.

The load pull simulations then plot optimum impedance values that the rectifying diode should see for optimum output power at each frequency. This is shown graphically in Figure 4-2. The antenna impedance simulation results from FEKO are plotted on the same Smith chart to determine the region of optimum impedance-match for maximum power transfer.

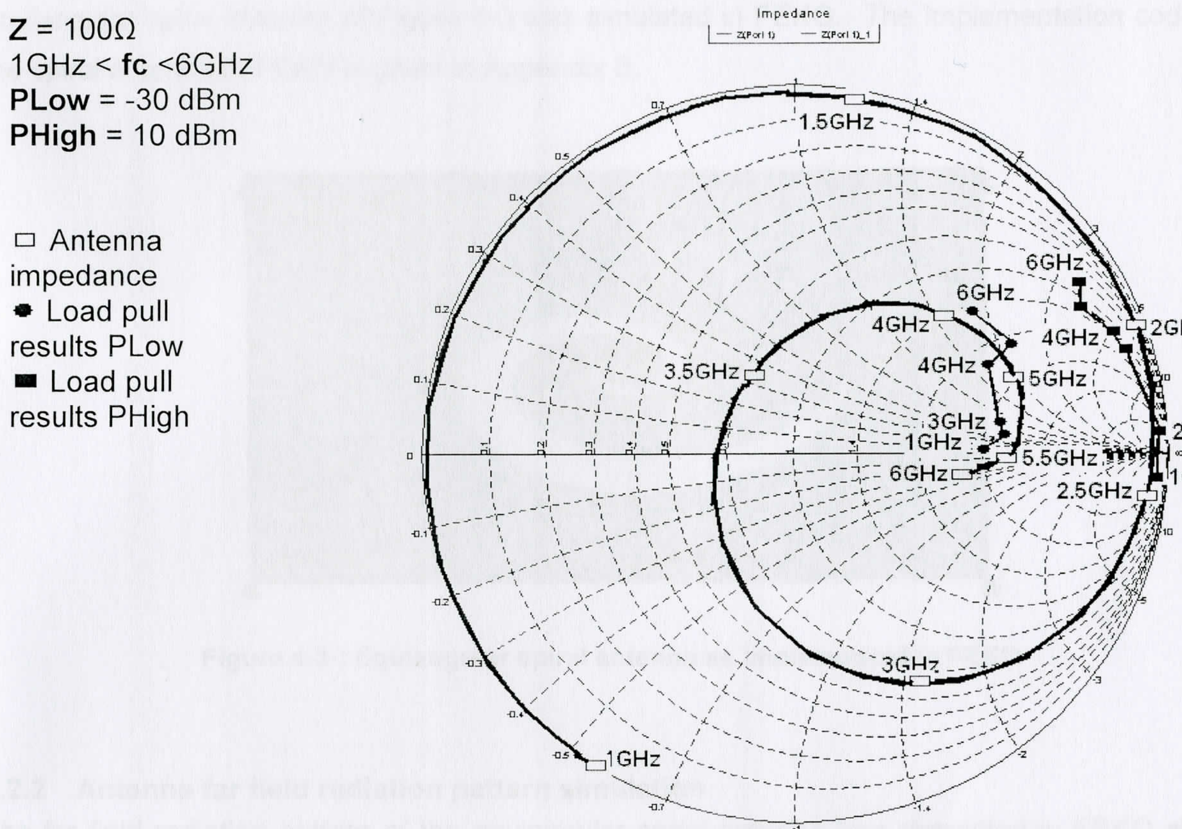

Figure 4-2 : Impedance matching simulation results

In Figure 4-2, the solid squares indicate the optimum source impedance that must be presented to the diode at different frequencies at high power levels. The solid circles indicate this for low input power levels.

The results illustrated on the Smith chart indicate that the optimum input impedance for the Alpha SMS7630-079 Schottky diode moves counter-clockwise with an increase in frequency, whilst the diode impedance moves from the edge of the Smith chart towards the centre with an increase in input power. A good impedance match occurs in the region around 2 GHz for high input powers and around 4 -6 GHz for low input powers. Broadly speaking, adequate matching is obtained in the frequency range 2 – 6 GHz with the exception of the frequency range 3 – 3.5 GHz.

Having determined the region of the optimum impedance for maximum power transfer between the antenna and the Schottky diode in Microwave Office, the far field radiation pattern of the equiangular spiral antenna of Figure 4-3 was simulated in FEKO. The implementation code for the spiral antenna in FEKO is given in Appendix B.

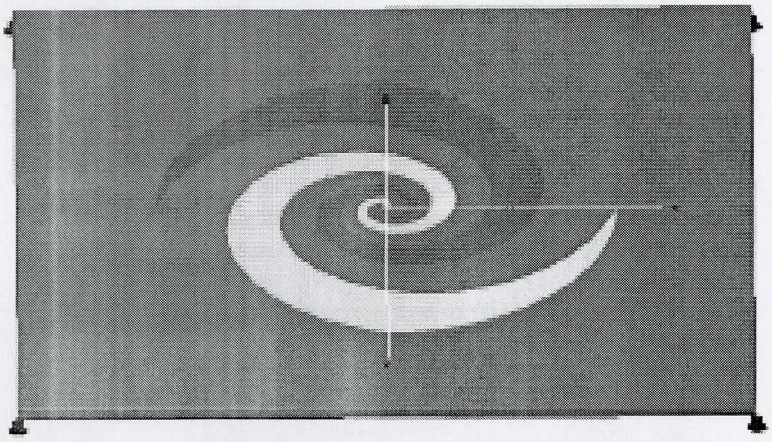

Figure 4-3 : Equiangular spiral antenna as implemented in FEKO

4.2.2 Antenna far field radiation pattern simulation

The far field radiation pattern of the equiangular spiral antenna was simulated in FEKO at 2.4 GHz. The simulated antenna far field radiation pattern polar plot is shown in Figure 4-4. It is also illustrated in the three-dimensional view of Figure 4-5.

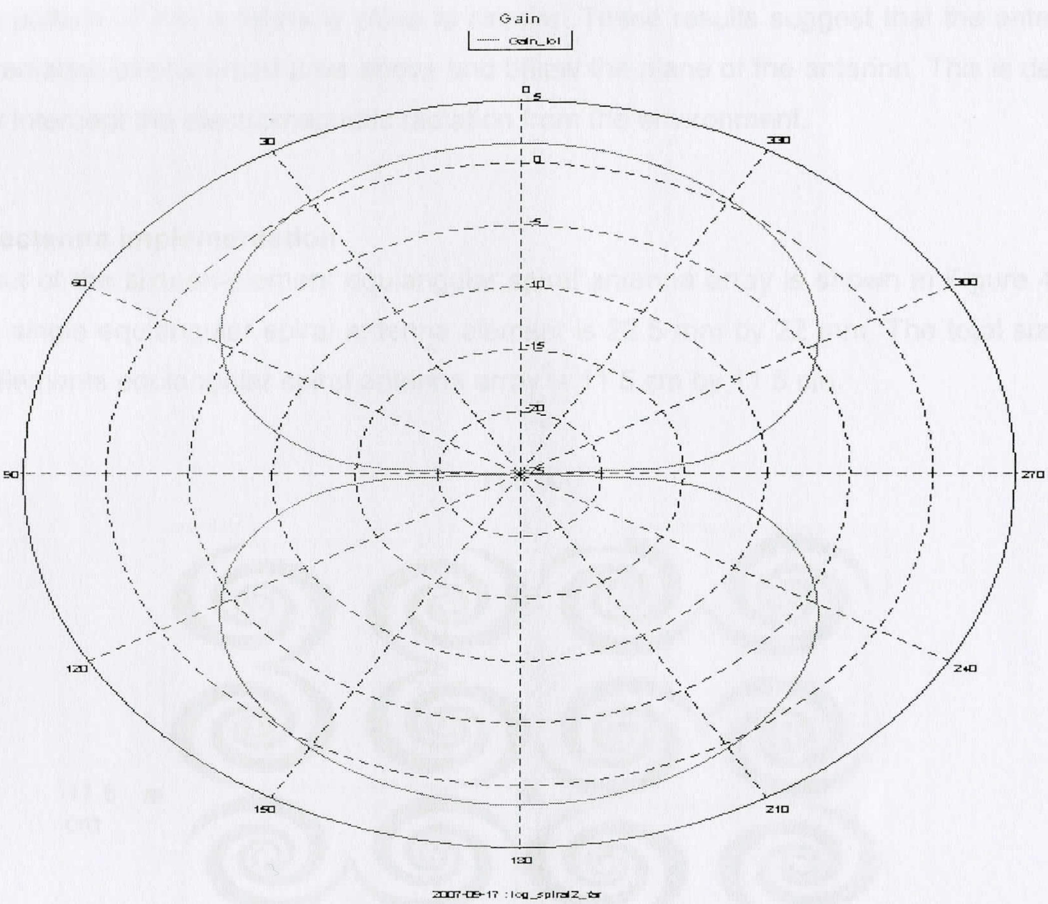

Figure 4-4 : Polar plot of the antenna radiation pattern

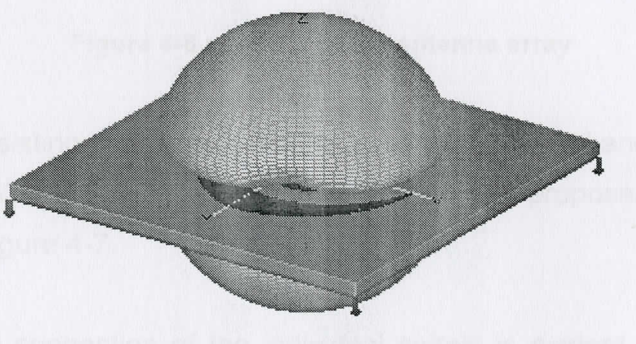

Figure 4-5 : Three-dimensional view of the radiation pattern

Both the two- and three-dimensional views of the far field radiation pattern indicate that the antenna has two broad beams above and below the plane of the antenna. Furthermore, the radiation pattern of this antenna is close to circular. These results suggest that the antenna will receive radiation over a broad area above and below the plane of the antenna. This is desired to optimally intercept the electromagnetic radiation from the environment.

4.3 Rectenna implementation

The layout of the sixteen-element equiangular spiral antenna array is shown in Figure 4-6. The size of a single equiangular spiral antenna element is 22.5 mm by 22 mm. The total size of the sixteen elements equiangular spiral antenna array is 11.5 cm by 11.5 cm.

Figure 4-6 : Layout of the antenna array

The antenna array, consisting of sixteen elements, was implemented and each antenna element attached to an SMS7630-079 Schottky diode to realise the proposed rectenna model. The prototype is shown in Figure 4-7.

The series and parallel connection of the individual spirals is evident from Figure 4-6 above. Two series-connected equiangular spiral antennas are each attached to an SMS7630-079 rectifying diode and connected in parallel with another pair of two series-connected spirals to form a 2×2 subarray. Four of these 2×2 subarrays are connected in parallel to comprise the sixteen-element equiangular spiral rectenna. This is in accordance with the work by Hagerty *et al.* (2004:1014-1024).

The output voltage is simply tapped at the terminals (squares).

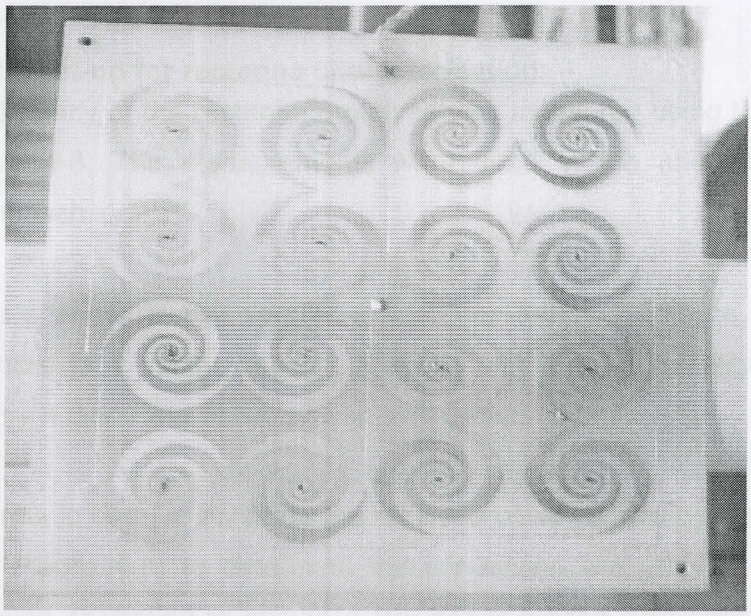

Figure 4-7 Sixteen elements equiangular spiral rectenna model

4.4 Experimental results

4.4.1 Experimental characterisation of rectenna

Rectenna characterisation primarily relates to the experimental measurement of its power conversion efficiency, since this is the important parameter in the harvesting of very low ambient power levels. To a lesser degree, the radiation pattern of the antenna is also important since this indicates the antenna's ability to harvest power from a broad physical angle. Due to time constraints, the radiation pattern has not been measured in the anechoic chamber, and the reader is referred back to the simulation results presented earlier. These simulations clearly verify the spiral rectenna's ability to receive power over a wide angle.

Suh and Chang (2002:1787) state that the conversion efficiency of the rectenna can be represented as in Equation 4-1. According to Equation 4-1, efficiency is the measure of merit of the rectenna's ability to convert the received electromagnetic energy into dc output power.

$$efficiency = \frac{P_{DC}}{P_{in}} \times 100(\%) \quad \text{Equation 4-1}$$

4.4.2 Experimental set-up for rectenna characterisation

In this study, the efficiency of the rectenna prototype was measured using the experimental set-up shown in Figure 4-8. The measurements were done in the anechoic chamber of the University of Stellenbosch.

The set-up consists of a microwave source, a reference antenna and the rectenna prototype. The source used here is a vector network analyzer with the source signal swept over the frequency range 0.8 – 4 GHz, and at two power levels, low and high.

The reference antenna is used to calibrate the received power at the input to the rectenna (the reference plane in Figure 4-8) to determine the conversion efficiency of the rectenna. The microwave source was controlled to ensure a low power setting (-30 dBm) and a high power setting (0 dBm for frequencies below 2 GHz, and -6 dBm for frequencies above 2GHz) at the reference plane. The reference plane was placed 2.5 m away from the source to ensure far-field operation across the frequency range.

Two sets of experiments were carried out: the first with the load resistance R = 1000 Ω, and then with a load resistance R = 2700 Ω. This was done to investigate the effect of a variance in load resistance on the efficiency of the rectenna.

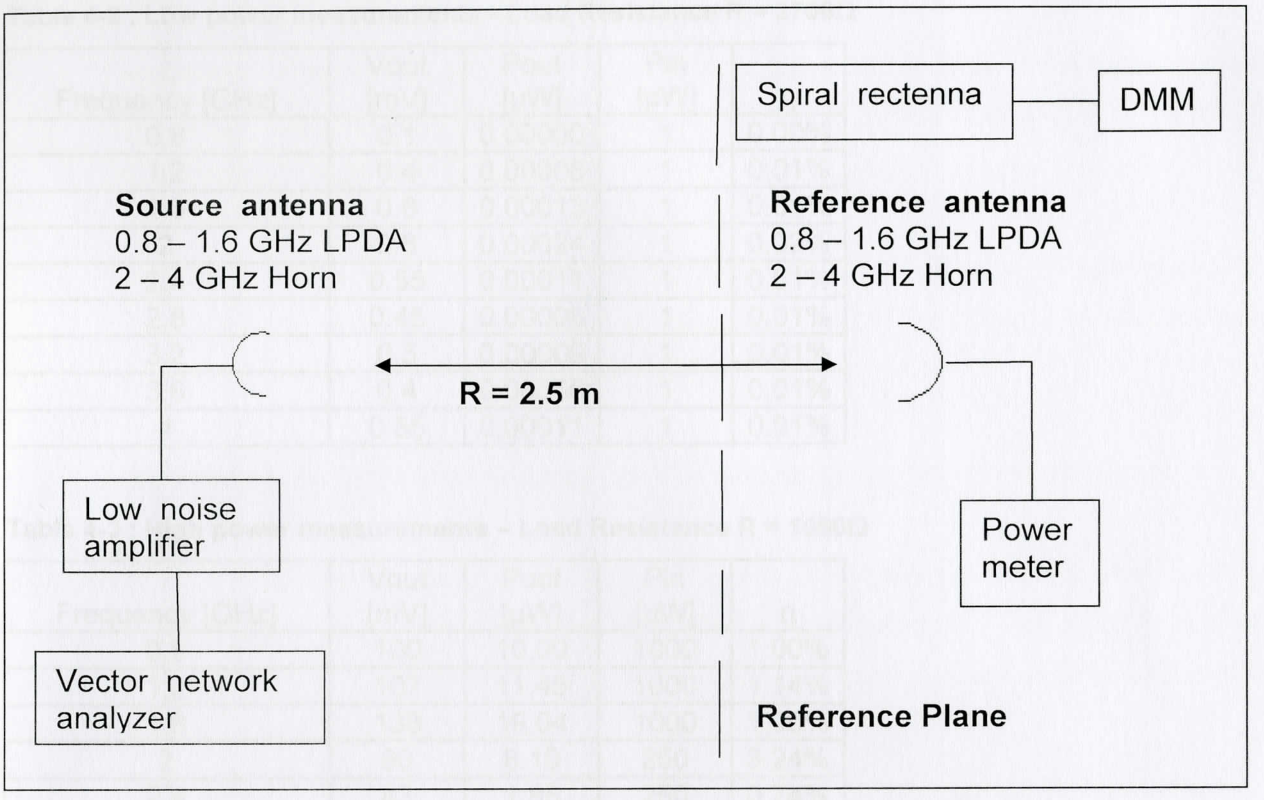

Figure 4-8 : Rectenna characterisation experimental set-up

4.4.3 Rectenna efficiency measurements

The experimental results are tabulated in Tables 4.1 through 4.4 below. Tables 4.1 and 4.2 tabulate the low power measurements, with the two load resistance values respectively. Tables 4.3 and 4.4 tabulate the high power measurements.

Table 4-1 : Low power measurements - Load resistance R = 1000Ω

Frequency [GHz]	Vout [mV]	Pout [μW]	Pin [μW]	η
0.8	0.1	0.00001	1	0.00%
1.2	0.4	0.00016	1	0.02%
1.6	0.6	0.00036	1	0.04%
2	0.6	0.00036	1	0.04%
2.4	0.4	0.00016	1	0.02%
2.8	0.3	0.00009	1	0.01%
3.2	0.3	0.00009	1	0.01%
3.6	0.35	0.00012	1	0.01%
4	0.4	0.00016	1	0.02%

Table 4-2 : Low power measurements - Load Resistance R = 2700Ω

Frequency [GHz]	Vout [mV]	Pout [μW]	Pin [μW]	η
0.8	0.1	0.00000	1	0.00%
1.2	0.4	0.00006	1	0.01%
1.6	0.6	0.00013	1	0.01%
2	0.8	0.00024	1	0.02%
2.4	0.55	0.00011	1	0.01%
2.8	0.45	0.00008	1	0.01%
3.2	0.5	0.00009	1	0.01%
3.6	0.4	0.00006	1	0.01%
4	0.55	0.00011	1	0.01%

Table 4-3 : High power measurements – Load Resistance R = 1000Ω

Frequency [GHz]	Vout [mV]	Pout [μW]	Pin [μW]	η
0.8	100	10.00	1000	1.00%
1.2	107	11.45	1000	1.14%
1.6	138	19.04	1000	1.90%
2	90	8.10	250	3.24%
2.4	43	1.85	250	0.74%
2.8	31	0.96	250	0.38%
3.2	30	0.90	250	0.36%
3.6	29	0.84	250	0.34%
4	37	1.37	250	0.55%

Table 4-4 : High power measurements – Load Resistance R = 2700Ω

Frequency [GHz]	Vout [mV]	Pout [μW]	Pin [μW]	η
0.8	98	3.56	1000	0.36%
1.2	128	6.07	1000	0.61%
1.6	160	9.48	1000	0.95%
2	115	4.90	250	1.96%
2.4	56	1.16	250	0.46%
2.8	40	0.59	250	0.24%
3.2	41	0.62	250	0.25%
3.6	42	0.65	250	0.26%
4	52	1.00	250	0.40%

From the above, it is clear that the following parameters play a role in the efficiency of the rectenna: frequency, input power level and load resistance. The following broad tendencies may be identified:

- Frequency: The highest efficiency is obtained round about 2 GHz, irrespective of load resistance. This may be attributed to the antenna being closely matched to the diode in this frequency range (see Figure 4-2).

- Power level: Efficiency is enhanced with higher power levels. This can be ascribed to the diode operating in its square-law state as apposed to operating close to its off-state with lower power levels.

- Load resistance: In general, lowering the load resistance increases the efficiency.

In conclusion, a maximum conversion efficiency of 3.24% is achieved at 2 GHz, with an input power level of 250 µW, and a load resistance of 1000Ω. It should also be noted that a maximum output voltage of 0.16 V may be expected from the rectenna operating at 1.6 GHz, in the high power region, with a high load resistance.

The rectenna model was also tested in a natural environment setting to investigate its power harvesting in real-life situations. The following sources (appliances) have been used: wireless access point, mobile phone, and a microwave oven. The results from these tests are presented. The load resistance for these measurements was maintained at 3.4 kΩ.

4.4.3.1 Harvesting power from the wireless access points

The WRT54G Linksys Wireless-G Broadband router is an all-in-one internet sharing router, 4-port switch, and a 802.11g wireless access point (Cisco Systems 2007: WRT54G Linksys Wireless-G Broadband Router). The WRT54G Linksys Wireless-G Broadband router has an RF power output of 18 dBm. This was used to test the viability of the sixteen-element equiangular rectenna model to harvest the ambient electromagnetic energy. The distance between the WRT54G Linksys Wireless-G Broadband router and the rectenna was varied from 1m to 5m due to space limitations in 1 m increments and each measurement repeated 5 times. The measured average load voltages (Vavg) are tabulated in Table 4-5.

Table 4-5 : WRT54G Linksys Wireless-G Broadband router

Distance (m)	Vavg (mV)
1	18.14
2	6.7
3	2.58
4	1.18
5	1.12

A peak instantaneous average output power of 0.097 mW was obtained at a distance of 1 m away from the router.

4.4.3.2 Harvesting power from a mobile phone

In addition to conducting tests on the wireless access points, the rectenna model was further tested with a mobile phone as this is a potential electromagnetic energy source available indoors. The distance between the mobile phone and the rectenna model was again varied from 1m to 7m in 1 m increments and each measurement repeated 5 times. These results are tabulated in Table 4-6.

Table 4-6 : Mobile phone

Distance (m)	Vavg (mV)
1	61.56
2	26
3	30.14
4	20.58
5	14.98
6	12.28
7	6.6

The peak instantaneous output power of 1.12 mW occurs at a distance of 1 m away from the mobile phone.

4.4.3.3 Harvesting power from the microwave oven

The microwave oven operates at 2450 MHz microwave frequency and has an output power of 850 W (contained inside oven chamber). On-time was set to 6 seconds for each measurement and the distance between the rectenna and the microwave oven varied from 1 m to 5 m due to space limitations in 1 m increments. The results of the microwave oven as a potential source of electromagnetic energy are shown in table 4-7.

Table 4-7 : Microwave oven

Distance (m)	Vavg (mV)
1	38.2
2	21.2
3	6.02
4	6.26
5	4.44

The highest output power of 0.429 mW is achieved at distance of 1 m away from the microwave oven.

Table 4-8 gives the summary of the average peak output (load) voltages and peak instantaneous average output power of the rectenna model from these three electromagnetic energy sources, located 1m from each of these sources.

Table 4-8 : V_{out} and P_{out} instantaneous peaks

Electromagnetic Sources	F_c Source (MHz)	V_{out} (mV)	P_{out} (mW)
Wireless Access Point	2400	18.14	0.097
Mobile phone	890 – 915 935 - 960	61.56	1.12
Microwave oven	2450	38.2	0.429

4.5 Summary

In summary, the rectenna model was optimised by matching the antenna impedance to the impedance of the rectifying diode and determining the far field radiation pattern. The rectenna model's capacity to harvest energy was tested taking into account electromagnetic safety, internal validity and output power relative to resistance. The efficiency of the rectenna model was determined and the rectenna model tested with a wireless access point, mobile phone and a microwave oven. In the next chapter a conclusion will be drawn as to the viability of the sixteen-element equiangular spiral rectenna to generate adequate power that enables long periods of operation of the DWSNs without human intervention in the power management process, thus reducing maintenance and administration costs.

5 CHAPTER FIVE: RESEARCH FINDINGS

5.1 Introduction and Background

In this chapter, the research findings are discussed and recommendations made. Reviewing the literature revealed that power limitations in DWSNs remains an open challenge. The research question investigated in the research study is how to develop a power harvesting technique to facilitate energy conversion in indoor DWSNs to reduce maintenance and administrative costs. Typical low-cost and low-power indoor DWSN microsensors require a maximum peak power of 5 mW for 6 ms sensing and transmission operation or 3.75 mW for 5 ms reception. Batteries are currently the predominant source of energy in DWSNs. Recharging or replacing batteries can significantly increase costs in DWSNs. Harvested energy presents a probable solution to this problem as harvested energy, unlike stored energy in batteries, represents an inexhaustible energy source that is continually replenished when consumed by an application. Sources for ambient energy harvesting include solar, vibrational, thermal, and electromagnetic energy. In this research study the focus is on electromagnetic energy harvesting from microwave radiation. Previous studies suggest that reception and rectification of electromagnetic radiation is a most viable option for powering of low-power indoor sensor networks. Analysing the literature indicated that electromagnetic energy can be collected for use by a rectenna, which is a receiving antenna attached to a rectifying circuit, that efficiently converts microwave energy into useful power. An analysis of several rectennas cited in the literature concluded by proposing the equiangular spiral rectenna for low-cost and low-power indoor DWSN microsensors. Such a rectenna has the potential to efficiently harvest electromagnetic energy to facilitate long periods of sensor network operation without human intervention in the power management process.

The impedance matching simulations have indicated that the antenna design is optimised to operate around the 2 – 2.5 GHz for low input powers and above 4 GHz for high input powers. In implementing the rectenna, two series connected equiangular spiral antennas are each attached to a SMS7630-079 rectifying diode and connected in parallel with another pair of two series connected equiangular spiral antennas attached to SMS7630-079 rectifying diodes to form a 2×2 subarray. Four of the 2×2 subarrays are connected in parallel to comprise the sixteen-element equiangular spiral rectenna. The rectenna model was tested taking into account issues of electromagnetic safety, internal validity and external validity. The rectenna displayed a maximum conversion efficiency of about 3 % at 2 GHz.

5.2 Research Findings

The energy requirements for DWSNs are a maximum peak of 5 mW of power for 6 ms sensing and transmission operation or 3.75 mW of power for 5 ms reception. Table 5-1 presents a comparison of the energy output recorded at a distance of 1 m and the requirements of the DWSNs.

Table 5-1 : Harvested power from typical appliances (1 m away from source)

Electromagnetic Sources	P_{out} (mW)
Wireless Access Point	0.097
Mobile phone	1.12
Microwave oven	0.429

Considering the results tabulated above, the instantaneous average output power generated by the appliances is below the peak power requirements. An energy storage device is therefore required to store the instantaneous power over time. This is viable in the context of DWSNs operating non-continuously.

The instantaneous output voltages can be stored in a capacitor over a period of time to meet the required 5 mW of power. Capacitors are the most appropriate energy storage devices as Jiang *et al.* (2005:2) state that the capacitors have infinite recharge cycles and are ideal for pulsing applications. An intelligent power conditioning circuit is further required to store the harvested power in the capacitor banks during the periods of ample ambient energy supply and power the low-power and low-cost indoor DWSNs when the energy storage capacitor banks have accumulated adequate power for typical sensing, transmission or reception.

The main finding from the research is that electromagnetic power harvesting with the sixteen-element equiangular spiral rectenna has the potential to provide a long-term source of energy to DWSNs, without human intervention in the power management process.

5.3 Future Research

The size of the rectenna model to be implemented is impractically large for indoor DWSNs. Further research may be required to reduce the size of the rectenna model.

Another challenge is to broaden the frequency range where optimal matching exits. This will ensure more power rectification in a broader spectrum.

Finally, a power conditioning circuit needs to be incorporated in the design for practical continuous operation of the microsensors.

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APPENDICES

Appendix A: Definition of terms

DWSN microsensor is a single device consisting of sensing unit, a transceiver, a power unit, low-power signal processing and computation that is connected to the DWSN and able to communicate with other devices in an untethered manner along multihop paths (Akyildiz *et al.* 2004:354; Roundy *et al.* 2003:1131 & Santi 2005:164).

EIRP is the effective isotropically radiated power, which is the product of the power supplied to the antenna and its antenna gain given relative to an isotropic antenna (Bensky 2004:251).

Image theory if an antenna carrying a current is placed adjacent to a conducting plane, the combined system has same fields above and below the plane as if the image of the antenna is present below the plane.

Polarisation of an antenna describes how the orientation of the electric field radiated by an antenna behaves as the function of time (Räisänen & Lehto 2003:211).

Radiation intensity is the power radiated from an antenna per unit solid angle (Kraus 1988:25).

Receiver accepts the signal that was sent by the transmitter (Bullock 2000:11).

Theorem of reciprocity states that, if a voltage is applied to the terminals of an antenna A and the current measured at the terminals of another antenna B, then an equal current will be obtained at the terminals of antenna A if the same voltage is applied to the terminals of antenna B (Saunders 1999:66).

Transceiver is a system that contains both a transmitter and a receiver (Bullock 2000:1).

Transmitter creates, modulates and transmits the signal through space to the receiver (Bullock 2000:5).

Appendix B: The code for generating the spiral model

(The Author is indebted to Prof R Lehmensiek for providing the code outlined below.)

```
function logspiral

% logspiral Creates logspiral prefeko file.
%         To be used together with log_spiral.pre
%         Author: R. Lehmensiek, 10/2006.

pth = 'c:\Data\Misc\Spiral\';
flnm = 'spiral1';

r0 = 10;
the = 3.5*pi;
freq = 6e9;

d = pi/2;
a = log(4)/2/pi;

w = 1*r0*(1-exp(-a*d));
R = r0*exp(a*(the-d));
lam = 1/sqrt(pi*4e-7*8.854187818e-12)./freq*1e3;
t_len = min([lam/20 w]);

th1 = th_1(t_len,the,r0,a,w,0); th1 = th1(1:end-1);
R1 = min([r0.*exp(a.*th1); R*ones(1,length(th1))]);
x1a = R1.*cos(th1);
y1a = R1.*sin(th1);
x1b = [0 r0-w];
y1b = [-w/2 -w/2];

th2 = th_1(t_len,the,r0,a,w,d);
R2 = r0.*exp(a.*(th2-d));
x2a = R2.*cos(th2);
y2a = R2.*sin(th2);
x2b = [0 0];
y2b = [-w/2 w/2];
plot([x1b x1a],[y1b y1a],'b.-',[x2b x2a],[y2b y2a],'r.-');

th = linspace(0,the,1000);
R3 = min([r0.*exp(a.*th); R*ones(1,length(th))]);
x3 = R3.*cos(th-pi);
y3 = R3.*sin(th-pi);
R4 = r0.*exp(a.*(th-d));
x4 = R4.*cos(th-pi);
y4 = R4.*sin(th-pi);
hold on
```

```
plot(x3,y3,'g-',x4,y4,'m-');
hold off
axis equal
grid on


% Write to pre file
fid = fopen([pth flnm '.pre'],'w');

s = sprintf('** Spiral model\n'); fwrite(fid,s);
s = sprintf('** Author: R. Lehmensiek\n\n'); fwrite(fid,s);

s = sprintf('#t_len = %g\n',t_len); fwrite(fid,s);
s = sprintf('IP                         #t_len\n\n'); fwrite(fid,s);
pos = [[x1b.'; x1a(1); x2a(1); x2b(2)] [y1b.'; y1a(1); y2a(1); y2b(2)] zeros(5,1)];
pm_(pos,fid)

[th,ind] = sort([th1 th2]);

cnt = 1; ad = 10;
while cnt
  in1 = find(ind(cnt:cnt+ad)<=length(th1)); in1 = ind(cnt+in1-1);
  in2 = find(ind(cnt:cnt+ad)>length(th1)); in2 = ind(cnt+in2-1)-length(th1);
  if cnt==1
    pos = [[x1a(in1).'; x2a(in2(end:-1:1)).'] [y1a(in1).'; y2a(in2(end:-1:1)).']
zeros(length(in1)+length(in2),1)];
  else
    pos = [[x1a([in1(1)-1 in1]).'; x2a([in2(end:-1:1) in2(1)-1]).'] ...
        [y1a([in1(1)-1 in1]).'; y2a([in2(end:-1:1) in2(1)-1]).'] zeros(2+length(in1)+length(in2),1)];
  end
  pm_(pos,fid)
  cnt = cnt+ad+1;
  if cnt>length(ind), cnt = 0;
  elseif cnt+ad>length(ind), ad = length(ind)-cnt;
  end
end

fclose(fid);


function th = th_1(t_len,the,r0,a,w,d)
  th = zeros(1,1000); cnt = 2;
%   th(1) = RootFd(@(th) r0*exp(a*(th-d)).*sin(th)-w/2,0,pi/4,[1 0 0],[0 28 1e-4 3 3 500]);
  th(1) = RFD(@(th) r0*exp(a*(th-d)).*sin(th)-w/2,0,pi/4,[1 0 0],[0 28 1e-4 3 3 500]);
  while cnt
    th(cnt) = log(t_len/(r0*sqrt(1+1/a^2))+exp(a*(th(cnt-1)-d)))/a + d;
    if th(cnt)>=the
      th = [th(1:cnt-3) linspace(th(cnt-2),the,3)];
      cnt = 0;
    else
```

```
    if cnt==length(th), th = [th zeros(1,1000)]; end
    cnt = cnt + 1;
  end
end


function pm_(pos,fid)
  st = 'PM'; nm = 'abcdefghijklm';
  for k = 1:size(pos,1)
    s = sprintf('#x = %g\n',pos(k,1)); fwrite(fid,s);
    s = sprintf('#y = %g\n',pos(k,2)); fwrite(fid,s);
    s = sprintf('#z = %g\n',pos(k,3)); fwrite(fid,s);
    s = sprintf(['DP: ' nm(k) ' : : : : : #x : #y : #z\n']); fwrite(fid,s);
    if k==5, st = [st ': ']; end
    st = [st ': ' nm(k) ' '];
  end
  s = sprintf([st '\n\n']); fwrite(fid,s);
```