



**Ambient Radio Frequency Energy Harvesting
Featuring Antenna with Multistage Rectifier**

by

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LIST OF ABBREVIATIONS

ADS	Advanced Design System
AUT	Antenna under test
CST	Computer Simulation Tool
DC	Direct current
DUT	Device under test
EM	Electromagnetic
GPS	Global Positioning System
GSM	Global System Mobile Communication
LTE	Long Term Evolution
PNA	Performance Network Analyzer
RF	Radio Frequency
Wi-Fi	Wireless Fidelity
WiMAX	Wireless Interoperability for Microwave Access

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LIST OF SYMBOLS

λ	Wavelength
ϵ_r	Dielectric constant
h	Substrate height
t	Conductor thickness
f	Frequency
Z_{in}	Input impedance
Z_L	Load impedance
S_{11}	Reflection coefficient
L	Inductor
C	Capacitor

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Penuaian Tenaga Gelombang Radio Ambien Mengaplikasikan Antena dan penerus pelbagai peringkat

ABSTRAK

Kajian yang dibentangkan dalam tesis ini memberi tumpuan kepada pendekatan penuaian tenaga frekuensi radio (RF) dengan mengumpulkan tenaga daripada radiasi elektromagnet RF untuk menghasilkan isyarat elektrik dalam persekitaran yang sebenar. Berbanding dengan sumber tenaga alternatif lain, seperti solar dan angin, tenaga RF adalah satu-satunya yang dapat menyediakan tenaga berterusan tanpa mengira siang atau malam dan tidak terjejas dengan keadaan cuaca yang buruk. Salah satu masalah yang dihadapi oleh penuaian tenaga RF ialah kepadatan kuasa yang rendah yang dihasilkan daripada tenaga ambien RF. Oleh itu, sangat penting untuk merekabentuk pengendali penuaian yang sangat cekap pada penggunaan spektrum RF yang meluas. Salah satu kebaruan dalam tesis ini adalah penyiasatan kebolehan penuaian tenaga RF di Malaysia, yang dijalankan sebelum penuai direka bentuk. Sebelum merekabentuk penuai, kajian keupayaan penuaian tenaga RF di kawasan pengukuran yang dipilih di Malaysia disiasat. Melalui pengukuran ketumpatan kuasa ini, sumber RF ambien dengan tahap kuasa yang boleh dituai dikenalpasti. Sistem komunikasi tanpa wayar GSM 900 (860 - 960 MHz), GSM 1800 (1730 - 1866 MHz) dan UMTS (2100 - 2200 MHz) menyediakan sumber yang optimum untuk penuaian tenaga di kedua-dua lokasi bandar dan separa bandar. Litar antena dan penerus kemudiannya direka secara berasingan sebelum digabungkan dan pengukuran prestasi dilaksanakan. Beroperasi daripada 1800 MHz sehingga 2.5 GHz, penuaian tenaga RF yang dicadangkan mempunyai antena jalur lebar dan penerus pelbagai peringkat dalam satu litar bersepadu. Tambahan pula, sensitiviti penuai dioptimumkan antara -30 hingga -20 dBm, berdasarkan kuasa yang telah diukur yang terdapat di persekitaran. Prestasi penuai disiasat oleh enam kombinasi dua penerus dan tiga antena yang berbeza, diuji dalam persekitaran dalaman dan luaran untuk sumber tenaga RF tertuju khas dan tidak khas. Untuk memperlihatkan lagi hubungan antara pengutuban *rectenna* dengan keupayaan untuk menuai tenaga RF, kajian pengutuban dijalankan. Bagi merealisasikan pengukuran ini, antena terkutub bulat yang ringkas dan mempunyai jalur lebar dicadangkan. Hasil pengukuran yang diperolehi adalah konsisten dengan kepadatan kuasa yang diukur dalam pengukuran kepadatan kuasa, dimana lebih banyak output dc diperolehi di kawasan bandar berbanding dengan kawasan separa bandar. Di kawasan bandar, hasil pengukuran menunjukkan bahawa sistem ini mampu menuai sehingga keluaran 1.8 V dc dari sumber tenaga RF yang tidak khusus. Dc yang dihasilkan dalam penuaian tenaga RF mungkin kurang daripada yang dijanakan oleh teknik solar dan angin, namun ia adalah bermakna jika tidak ada sumber tenaga lain.

Ambient Radio Frequency Energy Harvesting Featuring Antenna with Multistage Rectifier

ABSTRACT

The work presented in this thesis focuses on a radio frequency (RF) energy harvesting approach which scavenging energy from RF electromagnetic radiation to generate electrical signal in a real environments. Compared to other alternative energy sources, such as solar and wind, RF energy is the only one that can provide continuous supply of energy regardless days or nights and not affected by bad weather conditions. One of the challenging problems of RF energy harvesting is the low power densities yielded from ambient RF energy. Thus, it is very crucial to design a highly efficient harvester operating at widespread use of RF spectrums. One of the novelty of this thesis is contributes by the investigation of the feasibility of RF energy harvesting in Malaysia, in advance of the harvester design. Through this power density measurements, the scavengeable ambient frequency sources with their associated available RF power level were identified. It is demonstrated that wireless communication systems of GSM 900 (860 – 960 MHz), GSM 1800 (1730 – 1866 MHz) and UMTS (2100 – 2200 MHz) bands provide optimal sources for power harvesting at both measured urban and semi-urban location in Malaysia. The antenna and rectifier circuit are then designed separately prior to their combination and performance assessment. Operated from 1800 MHz up to 2.5 GHz, the proposed RF energy harvester features a broadband antenna and a multistage rectifier in one integrated circuit. Furthermore, the harvester sensitivities are optimized between -30 to -20 dBm, based on the measured available power in the surroundings. The performance of the harvester is investigated by six combination of two rectifiers and three different antennas, tested in both indoor and outdoor environment for dedicated and non-dedicated RF power sources. To further demonstrate the relation between the rectenna polarizations with the capability to harvest the RF energy, a polarization study is conducted. To realize this measurement, a novel simple and broadband circular polarized antenna is proposed. The obtained measurement results are consistent with the power densities measured in power density measurement, where more dc output are obtained in urban areas compared to semi-urban areas. In an urban area, the measurement results indicate the system is capable of harvesting up to 1.8 V dc output from non-dedicated ambient RF energy sources. The dc generated in RF energy harvesting may be less than generated by solar and wind techniques, however it can be significant in the absence of other energy sources.

CHAPTER 1 : INTRODUCTION

1.1 Background

Energy harvesting has been a phenomenon in such areas especially in solar and wind energy, where else it have been widely deployed in a large scale in many countries such as Germany, China and United State (International Energy Agency IEA, 2013, 2014). In addition there are increasing interest in research and development of photovoltaic (PV) and wind power technologies which can provide up to 150 GW (International Energy Agency IEA, 2014) and 2.5% (International Energy Agency IEA, 2013) of global electricity demand in 2013.

Although solar energy harvesting has been extensively used for years to power remote devices, several other types of energy-harvesting methods have also emerged for micropower applications including vibration, thermal, mechanical, and radio frequency (RF). Among these technologies, RF energy is the only one that can provide either intentional or ambient power source for battery-less appliances (Olgun, 2012). Moreover, ambient RF energy is ubiquitous, thanks to the communication networks such as TV broadcasting, mobile and Wi-Fi. It is also noticeable that there are more than a million smartphones phones are activated every day, expressive a large source of transmitters for RF energy harvesting.

Many researchers (Alam, Ullah, & Moury, 2013; Barcak, Partal, & Member, 2012; Bouchouicha, Latrach, Dupont, & Ventura, 2010; Gudan, Shao, Hull, Ensworth, & Reynolds, 2015; Gudan, Shao, Hull, Hoang, et al., 2015; J. A. Hagerty, Helmbrecht, McCalpin, Zane, & Popović, 2004; Harouni, Osman, & Gharsallah, 2010; Jabbar, Song, & Jeong, 2010; B. S. Kim et al., 2014; Kuhn, Lahuec, Seguin, & Person, 2015) have proved that this electromagnetic energy can be harvested and turned it into useable electrical energy. Numerous reliable electromagnetic resources such as signal transmission from television and radio broadcasting, wireless LAN, and mobile phone signal are widely available in the atmosphere and have been triggered significant interest in radio frequency (RF) energy harvesting (Alam et al., 2013; Barroca et al., 2013; J. A. Hagerty et al., 2004; B. S. Kim et al., 2014; Marian, Allard, Vollaire, & Verdier, 2012; Piñuela, Mitcheson, & Lucyszyn, 2013; Song et al., 2015). Moreover, with the development of Wireless Power Transfer (WPT) technologies that allow maintenance-free and mobile electronic devices to operate without batteries has become the driving force for RF energy harvesting.

Early work of Heinrich Hertz in the 1958 (Brown, 1984) triggered the idea of radio wave can be used for power transmission. He had demonstrated a complete system with a spark gap to generate high frequency power on electromagnetic wave propagation in free space using parabolic reflectors at both end.

The concept of harvesting DC power from RF signals is obtained from a combination of receiving antenna and rectifier circuit. An antenna captures the RF energy, which then rectifier converts the energy into DC power. Thus, the RF energy

harvesting circuit or rectenna (rectifying antenna) is made up of antenna, matching circuit, rectifying circuit and a load. A lot researches have been done in RF energy harvesting, where the rectenna was first introduced by W. C. Brown (Alam et al., 2013; Brown, 1984). Issues such as low incident power and matching between antenna and rectifier has been addressed in ambient RF energy harvesting (Gudan, Shao, Hull, Hoang, et al., 2015; Song et al., 2015; Volakis, 2012) among researchers. On the other hand, one trade-off in rectenna design is the need to choose either good DC output level or RF-DC efficiency.

Strong growing interest in the number of researches in RF energy harvesting demonstrates that there is a bright future in this field. The first commercial appliance patented under brand Freevolt, which harvests ambient RF energy from existing wireless data and broadcast networks (Drayson Technologies, 2015). In addition, the internet of thing (IOT) technology is actively in research and development (Buriot, 1999; MIMOS Berhad, 2014), where there will be access point everywhere and the connections always ON and all things can be done wirelessly. With the increasing wireless energy in the environment, there is high possibility to utilize this energy by converting into useful electrical power instead of only used it for transferring data.

For an effective RF energy harvesting system, a feasibility study is one of important step to identify the available RF energy in selected area. A number of researchers have reported on this study, for example by (Pinuela, Mitcheson, & Lucyszyn, 2013) in London city, (N. Shariati, Rowe, & Ghorbani, 2012) in Australia, (Barroca et al., 2013) in Portugal and (Beng Lim, Lee, & Poh, 2013) in Singapore.

However, in Malaysia none have been reported yet, thus the data collected in this thesis is the first one. This data is useful prior in developing an energy harvester module as it provides a review of which frequency range suitable to harvest.

Until recently, there has been several researches concerning on circular polarization in RF energy harvesting (Agarwal et al., 2013; Ghosh, 2016; Harouni, Cirio, Osman, Gharsallah, & Picon, 2011; Ong, Karim, Ong, Chiam, & Alphones, 2010; Song et al., 2016) but none of the previous works implement the idea of the CP in RF energy harvesting either in indoor or ambient scenario. By considering the advantages offered by CP antenna, here in this thesis a CP antenna were designed and implemented in the rectenna system. In addition, the author also conducted the polarization study of the rectenna system with dedicated and ambient RF measurement.

In Malaysia, at present the research in RF energy harvesting is still in its infancy. Most of the works focused on developing the rectenna system rather than implementing the rectenna in real harvesting scenario. For example works done by (Din, Chakrabarty, Ismail, Devi, & Chen, 2012; N. Abdullah, 2016; R. A. Rahim, Hassan, Malek, Junita, & Jamlos, 2012; Yaldi, Rahim, & Ramli, 2016; Zainuddin et al., 2013; Zakaria, Zainuddin, Abd Aziz, Husain, & Mutalib, 2013). To the best of author knowledge, only Din et al., (2012) reported on a complete RF harvester circuit with the measurement of ambient GSM 900 energy harvesting in Malaysia. Therefore, the works on an ambient RF measurement of a complete RF energy harvesting in Malaysia is the first reported in this thesis.