DYNAMIC POWER ALLOCATION AND DISCRETE WAVELET TRANSFORM TECHNIQUES IN 5G WIRELESS SENSOR NETWORK SYSTEMS WITH ENERGY HARVESTING

BY

AMAR ESSE AHMED

A thesis submitted in fulfilment of the requirement for the
degree of Doctor of Philosophy (Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

AUGUST 2022

ABSTRACT

Energy harvesting wireless networks are one of the most researched topics in this decade. With a radio frequency (RF) energy harvester (EH) embedded, the sensors can operate for extended periods. Thus, providing sustainable solutions for managing massive numbers of sensor nodes (SN). There are different scheduling methods for information decoding (ID) and energy harvesting (EH) in the literature. These scheduling techniques can be classified into time switching (TS) and power splitting (PS). TS alternates between EH and ID on a temporal basis, receiving data just half of the time. In contrast, PS splits the received signal in theory between ID and EH circuitries without regard for the power requirement differences of the two circuitries. This thesis aims to develop an energy harvesting system with a dynamic power allocation transmitter and dynamic power splitting receiver between information decoding and energy harvesting circuitries for WSN to increase the energy harvester output. The presented receiver architecture integrates input signals from several RF sources and divides them between the EH and ID circuits. In addition, by moving the ID load into a separate circuit, the split design enhances the harvestable power at the RF energy harvester. DPA-SWIPT is implemented at the transmitter, where the ES is transmitted using an unmodulated high-power CW signal centred on the carrier frequency, while the IS is transmitted using a low-power signal around the carrier frequency. In TS and PS, the ES is conveyed on a modulated wave, resulting in increased interference with external networks. In contrast, in DPA-SWIPT, the high-power ES is constrained to a narrow band at the carrier frequency, resulting in less interference with bordering networks. Various system parameters were discussed, including the EH circuit's voltage multiplier output and ID data rates. As a result, the split receiver design demonstrated a considerable increase of more than 15 dBm in harvestable power level compared to the combined receiver. Moreover, this thesis also aims to improve the peak to average power ratio (PAPR). Hence, the PAPR of several wavelet methods are investigated, with the wavelet-based modulation technique outperforming fast Fourier transform (FFT) orthogonal frequency division multiplexing (OFDM) substantially where Haar wavelet scored a gain of almost 5dBm. As a result, it is stated that wavelet modulation is an excellent contender for implementation at the SN, where energy efficiency is critical. Ultimately, the increase in the input power level of the EH circuitry coupled with enhancing the energy efficiency of the WSN nodes marks an important milestone toward achieving fully autonomous WSNs.

ملخص البحث

تعد الشبكات اللاسلكية الخاصة بحصاد الطاقة واحدة من أكثر الموضوعات التي تم بحثها في هذا العقد. مع جهاز حصاد طاقة التردد اللاسلكي (RF) مدمج ، يمكن لأجهزة الاستشعار أن تعمل لفترات طويلة. وبالتالي ، بهذه الطريقة ، من الممكن توفير حلول مستدامة لإدارة أعداد هائلة من عقد الاستشعار (SN). توجد طرق جدولة مختلفة لفك تشفير المعلومات (ID) وجمع الطاقة (EH). يمكن تصنيف تقنيات الجدولة هذه إلى تقنيات تبديل الوقت (TS) وتقنيات تقسيم الطاقة (PS). في حالة تقنية تبديل الوقت ، يتناوب جهاز الاستقبال بين EH و ID على أساس زمني ، ويستقبل البيانات نصف الوقت فقط. بينما ، في تقنية تقسيم الطاقة ، يقسم المستقبل الإشارة المستقبلة نظريًا بين دارات ID و EH دون أي اعتبار لاختلافات متطلبات الطاقة بين الدائرتين. تقدم هذه الأطروحة وحدة فك ترميز معلومات متعددة المدخلات والمخرجات (MIMO) مع حاصدة للطاقة. مع دعم تخصيص الطاقة الديناميكي (DPA). علاوة على ذلك ، يتيح النظام للعقد اللاسلكية تلقي المعلومات والطاقة بشكل متزامن. بالإضافة إلى ذلك ، تقدم الأطروحة تصميم جهاز استقبال مقسم لـ RF EH مع نسبة PS قابلة للتعديل. تدمج بنية المستقبل المقدمة إشارات الإدخال من عدة مصادر RF وتقسمها بين دوائر EH و ID. بالإضافة إلى ذلك ، من خلال نقل حمل المعرف إلى دائرة منفصلة ، فإن التصميم المنفصل يعزز القدرة القابلة للحصاد في جهاز حصاد الطاقة. يتم تنفيذ DPA-SWIPT في جهاز الإرسال ، حيث يتم إرسال ES باستخدام إشارة CW عالية الطاقة غير مشكلة مركزها على تردد الموجة الحاملة ، بينما يتم إرسال IS باستخدام إشارات منخفضة الطاقة حول تردد

الموجة الحاملة. في TS و PS ، يتم نقل ES على موجة مشكلة ، مما يؤدي إلى زيادة التداخل مع الشبكات الخارجية. في المقابل ، في DPA-SWIPT ، يتم تقييد ES عالي الطاقة في نطاق ضيق عند تردد الموجة الحاملة ، مما يؤدي إلى تداخل أقل مع الشبكات المجاورة. تمت مناقشة عوامل النظام المختلفة ، بما في ذلك خرج مضاعف الجهد لدائرة EH ومعدلات بيانات المعرف. ونتيجة لذلك ، أظهر تصميم المستقبل المنفصل زيادة كبيرة حوالي 15 ديسيبل في مستوى الطاقة القابلة للحصاد مقارنة بالمستقبل المدمج. علاوة على ذلك ، تم التحقق من نسبة الذروة إلى متوسط القدرة (PAPR) للعديد من أنواع المويجات ، حيث تفوقت تقنية تعديل المويجات بشكل كبير على تقنية تعديل الموجة على تحويل فورييه السريع (FFT) بتقسيم التردد المتعامد (OFDM). حيث حققت موجات هار مكاسب تقارب 5 ديسيبل. ونتيجة لذلك ، تم التأكيد على أن تعديل المويجات هو بديل ممتاز للتنفيذ في SN ، حيث تكون كفاءة الطاقة أمرًا بالغ الأهمية. في النهاية ، تمثل الزيادة في مستوى طاقة الإدخال لدائرة EH جنبًا إلى جنب مع تعزيز كفاءة الطاقة لعقد WSN معلمًا مهمًا نحو تحقيق شبكات WSN المستقلة بالكامل.

APPROVAL PAGE

The thesis of Amar Esse Ahmed has been approved by the following:

Khaizuran Bin Abdullah
Supervisor

Mohamed Hadi Habaebi
Co-supervisor

Huda Adibah Mohd Ramli
Co-supervisor

Ani Liza Asnawi
Co-supervisor

Md. Rafiqul Islam
Internal Examiner

Jafri bin Din
External Examiner

Ismaiel Hassanien Ahmed
Chairman

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Amar Esse Ahmed

Signature... Date ....

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

DYNAMIC POWER ALLOCATION AND DISCRETE WAVELET TRANSFORM TECHNIQUES IN 5G WIRELESS SENSOR NETWORK SYSTEMS WITH ENERGY HARVESTING

I declare that the copyright holders of this thesis are jointly owned by the student and IIUM.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below

1. Any material contained in or derived from this unpublished research may be used by others in their writing with due acknowledgement.

2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purposes.

3. The IIUM library will have the right to make, store in a retrieved system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Amar Esse Ahmed

……………………………… Signature

………………….. Date

This thesis is dedicated to my father, who passed away during my PhD journey

ACKNOWLEDGMENTS

First and foremost, I praise and thank Allah glory be to him for guiding me and giving me the strength to complete this work. Then, my mother and father who supported and encouraged me through my life. Special thanks to my father, who always gave unconditional support to me and who is no longer with us today. May the Almighty bestow his mercy upon him. I want to extend my utmost gratitude to my supervisor and mentor, Assoc. Prof. Ir. Dr Khaizuran Bin Abdullah for his guidance and continuous support throughout my study. I also want to express my gratefulness to my co-supervisors, Prof. Dr Mohamed Hadi Habaebi and Assoc. Prof. Dr Huda Adibah Bt. Mohd. Ramli for their valuable insights and suggestions.

I wish to extend my appreciation to the Institute of telecommunications at technical university Wien for sharing simulation projects with me. Finally, I want to acknowledge all those who supported me throughout this journey. I want to specifically thank my sister Aisha and my friend Yasin for being there for me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A_C	Capacitive Reactance
E_D	Dissipated Energy
E_H	Harvested Energy
$I_d(t)$	The Current Across the Diode
$P_A(t)$	Normalized Power Wave
$P_H(t)$	The Harvested Power
$P_R(t)$	The Received Energy Signal
$S_R(t)$	The Received Signal
$V_{d_b}(t)$	Baseband Voltage
$V_{d_{rf}}(t)$	RF Voltage
V_A	Antenna Voltage
$V_{Rout}(t)$	Output Voltage of the Rectifier.
$V_d(t)$	The Voltage Across the Diode
$n_A(t)$	Antenna Noise
$y_R(t)$	The Received Signal
y_k	Transferred Energy from The Base Station to The Sensor Node.
$\mathcal{C}_{(E-R)}$	The Energy to Rate Ratio (E-R)
β_{sc}	Subcarrier
L	Wavelet Scale
P	The Average Received Power

$S(t)$	Transmitted Signal
$r(t)$	Data Rate.
ψ	Wavelet Function
ω	Angular Frequency
$\phi(t)$	Translation Function
$\boldsymbol{\delta}$	Dilation Function

LIST OF ABBREVIATIONS

AM	Amplitude Modulation
AP	Access Point
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
CDF	Comulative Distripution Function
CMOS	Complementary Metal-Oxide-Semiconductor
CSP	Concentrated Solar Planet
CW	Continuous Wave
DAC	Digital To Analoge Converter
DC	Discrete Current
DFT	Discrete Fourier Transform
DN	Destination Node
DPA	Dynamic Power Allocation
DSP	Digital Signal Processing
DTFT	Discrete Time Fourier Transform
DWT	Discrete Wavelet Transform
EH	Energy Harvesting
ES	Energy Signal

FCC	Federal Communications Commission
FSPL	Free Space Path Loss
FT	Fourier Transform
HPA	High Power Amplifier
ID	Information Decoding
ID	Information Decoder
IDWT	Inverse Discrete Wavelet Transform
IFT	Inverse Fourier Transform
IS	Information Signal
IS	Information Signal
LED	Light Emitting Diode
LNA	Low Noise Amplifier
LO	Local Oscillator
LoS	Line of Sight
MC	Multicarrier
MCU	Microcontroller Unit
MIMO	Multiple Input Multiple Output
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
OFDM	Orthogonal Frequency Division Multiplexing
PAN	Personal Area Network
PAPR	Peake To Average Power Ratio
PS	Power Splitting
PV	Photovoltaic
QAM	Quadratic Amplitude Modulation

RF	Radio Frequency
RFPT	Radio Frequency Power Transfer
SN	Sensor Node
SWIPT	Simultaneous Wireless Information And Power Transfer
TS	Time Switching
VS	Versus
WFT	Windowed Fourier Transform
WIPT	Wireless Information And Power Transfer
WSN	Wireless Sensor Network
WT	Wavelet Transform

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

The exponential growth in the Internet-of-Things (IoT) field and the related applications led to the introduction of low-energy wireless sensor networks (WSN) (Amato & Coronato, 2017), where small sensing nodes collect various types of data from the environment (Elappila, Chinara, & Parhi, 2020), ranging from temperature to radiation levels at the nuclear plants. The most significant predicament against any efficient implementation of such WSN is energy sourcing, as these sensors can accommodate a limited-size battery. Once that battery is depleted, the battery replacement cost for thousands of such nodes is even more expensive than the cost of the node itself. Not to mention the environmental cost of producing and discarding millions, if not billions, of batteries and Sensor Nodes (SNs). One solution to the energy constraint is to power SNs wirelessly by harvesting RF energy (M. Alfaqawi et al., 2020; Lu, Wang, Niyato, Kim, & Han, 2015).

The energy Harvesting notion in wireless communication refers to the process of collecting and storing the ambient RF energy from the environment in order to achieve self-sustaining nodes that can operate for extended lifetimes without the need to recharge them in conventional ways (Cansiz, Altinel, & Kurt, 2019a; Li et al., 2016).

The energy harvesting field has gone through enormous research, leading to the emergence of energy harnessing nodes that can harvest energy from the environment. Energy harvesting wireless nodes are capable of harvesting and storing RF energy from the surroundings. This RF energy could be ambient or interference, in other words, a signal not intended for the harvesting node, which can be categorized as green communication. Whereas, when a dedicated transmitter is used to send energy to a harvesting node, this could be more categorized as a convenience rather than a green solution due to the excessive loss of energy in the wireless medium as a result of fading (Chen, 2019).

RF energy harvesting represents a genuine opportunity for replacing huge batteries (M. Alfaqawi et al., 2020; M. I. M. Alfaqawi et al., 2015), which are not just expensive to produce and discard but also limit the lifetime of a sensor node (Haijun Yu et al., 2020). Furthermore, when a sensor is operating in harsh environments, the battery life could be very much less than the expected lifetime due to the limited linear operating range of such batteries(C. M. Yu, Tala’T, Chiu, & Huang, 2019)(Mathieu & Taylor, 2016). RF power transfer (RFPT) enables an AP to send energy wirelessly to an SN. An AP has unbounded power, for example, connected to the grid, or has massive, stored energy, for example, harvests energy from the sun or other high-power sources.

RFPT is not a new concept, as Nicola Tesla conducted experiments on the earliest wireless energy transfer system almost a century ago (Dana, Sardhara, Sanghani, & Mehta, 2019), with an ambition of realizing global energy to replace the traditional power lines. However, due to the safety concerns of the high transmission power adopted by Tesla, the RFPT field had lost interest for quite some time. In the 1960s, William developed the first rectifying antenna, where he conducted several successful trials to transmit microwave power(Brown, George, …, & 1969, n.d.). The rectifying antenna or “Rectenna” consists of an antenna element, impedance matching network, RF to DC converter, and an energy reservoir, as shown in Figure 1.1

The field of RF-EH has recently gained attention again as a consequence of the development in microcontroller units (MCU)s. Such developments make it possible to produce MCUs with high computing power, low energy consumption, and very small size, which enables them to be embedded in almost anything.

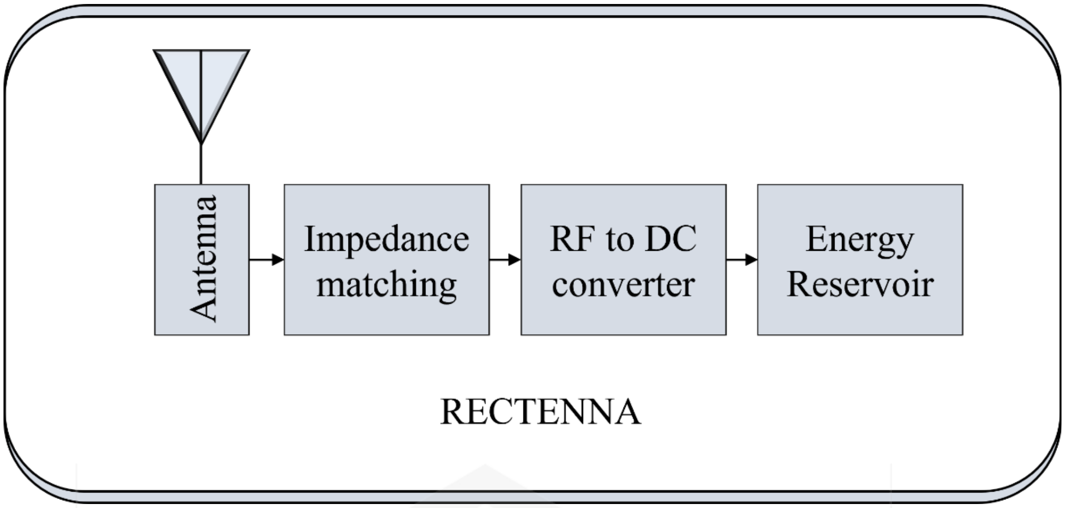

Figure 1.1 Block Diagram of a rectenna

In wireless communications, both information and energy are transmitted on the same signal. However, traditional wireless systems only extract the data from the received signal. Whereas in an RF energy harvesting system, the receiver partially exploits the energy carried by the RF signal for the purpose of electricity generation (Mouapi, Hakem, & Delisle, 2018), such a system can extract energy and information from RF signals (Tutuncuoglu & Yener, 2013). Furthermore, simultaneous wireless information and power transfer (SWIPT) was proposed to realize a system where energy and information are communicated.

In SWIPT, the transmitter transfers information and energy over the same frequency band. SWIPT can be classified into three categories. The first category assumes that the receiver can simultaneously harvest and extract information from the received signal(Grover & Sahai, 2010) using the same circuit. However, the feasibility of this category is in question, as there is no practical hardware implementation that can extract information and energy at the same time (Zhou, Zhang, & Ho, 2013a). In the second and third categories, which are the more practical ones, the receiver performs time switching (TS) or power splitting (PS). In PS, the receiver splits the received signal between energy harvesting and information decoding circuitries. While in TS, the receiver switches periodically between energy harvester and information decoder circuits. However, information is usually sent in low