ENERGY HARVESTING ENABLED COOPERATIVE NETWORKS: RESOURCE ALLOCATION TECHNIQUES, PROTOCOL DESIGN AND PERFORMANCE ANALYSIS

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TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS ii

TABLE OF CONTENTS iv

LISTS OF TABLES viii

LIST OF FIGURES ix

LIST OF ABBREVIATIONS xi

LIST OF SYSMBOLS xiii

ABSTRAK xv

ABSTRACT xvii

CHAPTER ONE: INTRODUCTION

1.1 Problem Statement 3

1.2 Research Objectives 5

1.3 Scope of Work 5

1.4 Organization of the Thesis 6

CHAPTER TWO: BACKGROUND AND RELATED WORKS

2.1 Fundamentals of EH-enabled Cooperative Networks 8

  2.1.1 Cooperative Communication Networks 8

    2.1.1(a) Amplify-and-Forward (AF) Relaying 11

    2.1.1(b) Decode-and-Forward (DF) Relaying 11

    2.1.1(c) Selection Relaying 11

    2.1.1(d) Incremental Relaying 12

2.1.2 Wireless Energy Harvesting and Information Transfer 12
2.1.3 Energy Harvesting Receiver Architecture 14
2.1.4 SWIPT Techniques 17
2.1.4(a) Power Splitting (PS) Technique 17
2.1.4(b) Time Switching (TS) Technique 19
2.1.4(c) Antenna Switching (AS) Technique 20
2.1.5 Application Areas of SWIPT 22
2.2 Review of Related Works 24
2.2.1 SWIPT in HD Wireless Relaying Networks 24
2.2.2 SWIPT in FD Wireless Relaying Networks 30
2.3 Summary 38

CHAPTER THREE: METHODOLOGY

3.1 The Proposed ES Resource Allocation Technique 40
3.1.1 System Model 42
3.1.2 Results and Discussion 44
3.2 The Proposed HPTSR Protocol 44
3.2.1 System Model 1 46
3.2.2 Results and Discussion 47

CHAPTER FOUR: ENERGY EFFICIENCY OPTIMIZATION BASED ON THE PROPOSED ENERGY SAVING RESOURCE ALLOCATION TECHNIQUE

4.1 Analysis of the Proposed System Energy Efficiency 49
4.1.1 The Proposed ES-TSR Protocol 50
4.1.1(a) System Transmission Model for the Proposed ES-TSR Protocol 50

4.1.1(b) Problem Formulation with the Proposed ES-TSR Protocol 53

4.1.2 The Proposed ES-PSR Protocol 54

4.1.2(a) System transmission Model for the Proposed ES-PSR Protocol 55

4.1.2(b) Problem Formulation with the Proposed ES-PSR Protocol 57

4.2 Solution to the Proposed Optimization Problems 59

4.3 EH-enabled Cooperative Network with an Interfering Transmitter 65

4.3.1 RF-EH from the Source Transmission only 66

4.3.2 RF-EH from the Source and IT Transmissions 71

4.4 Results and Discussion 76

4.5 Summary 88

CHAPTER FIVE: PROPOSITION AND PERFORMANCE ANALYSIS OF A HYBRIDIZED POWER-TIME SPLITTING BASED RELAYING PROTOCOL

5.1 The Proposed HPTSR Protocol for SWIPT 90

5.2 Throughput Analysis of the Proposed HPTSR Protocol 91

5.2.1 Energy Harvesting 91

5.2.2 Information Transmission 92

5.2.2(a) AF HPTSR 92

5.2.2(b) DF HPTSR 98

5.3 Results and Discussion 101

5.4 Summary 110

CHAPTER SIX: CONCLUSION AND FUTURE WORKS

6.1 Conclusion 112

6.2 Future Work 114

REFERENCES 116

APPENDICES

Appendix A: Proof of Outage Probability of the Proposed AF HPTSR Protocol

Appendix B: Proof of Outage Probability of the Proposed DF HPTSR Protocol

LIST OF PUBLICATIONS

LIST OF TABLES

Page

Table 2.1 Characteristics of wireless energy transfer techniques 16

Table 2.2 Advantages and disadvantages of various SWIPT techniques 22

Table 2.3 Summary for some of the related works on SWIPT reported in the literature 34

Table 4.1 Simulation parameters for the ES resource allocation technique 77

Table 5.1 Simulation parameters for the throughput performance of the system 102

LIST OF FIGURES

		Pages
Figure 2.1	Cooperative communication networks: (a) A two-hop transmission model without cooperative diversity, and (b) A two-hop transmission model with cooperative diversity	10
Figure 2.2	Topology of WEHIT	13
Figure 2.3	EH receiver architecture for energizing a communication transceiver	15
Figure 2.4	Block diagram of PS technique	18
Figure 2.5	Block diagram of TS technique	20
Figure 2.6	Block diagram of AS technique	21
Figure 3.1	An organization of the research methodology	41
Figure 3.2	A schematic diagram of the system model for the EH-enabled cooperative network	42
Figure 3.3	Architecture of the relay receiver for the proposed HPTSR protocol	45
Figure 3.4	The diagram of the proposed HPTSR protocol	46
Figure 4.1	The transmission block structure of the proposed ES-TSR protocol	50
Figure 4.2	The transmission block structure of the proposed ES-PSR protocol	55
Figure 4.3	Iterative ES algorithm	65
Figure 4.4	The system model of the EH-enabled cooperative network with IT	66
Figure 4.5	The system model of the EH-enabled cooperative network with IT, where R harvests the RF energy from both S and IT transmissions	72
Figure 4.6	System energy efficiency against number of transmission blocks (L) for different protocols	79

Figure 4.7 System energy efficiency against number of transmission blocks (L) for different values of σ^2 80

Figure 4.8 System energy efficiency against energy conversion efficiency η for the proposed ES-TSR and ES-PSR protocols 81

Figure 4.9 System energy efficiency against source-relay distance d_{SR} (m) 82

Figure 4.10 System energy efficiency against the path loss exponent β with $d_{SR} = d_{RD} = 1.5$ m 83

Figure 4.11 System energy efficiency against $P_S^{\max}$ (dBm) 84

Figure 4.12 System energy efficiency of the EH-enabled cooperative network with and without IT against number of transmission blocks (L) 85

Figure 4.13 System energy efficiency of the EH-enabled cooperative network with IT against number of transmission blocks (L) 86

Figure 4.14 System energy efficiency of the EH-enabled cooperative network with IT against number of transmission blocks for different values of P_T (dBm) 87

Figure 5.1 Algorithm for the throughput performance of the proposed HPTSR protocol 101

Figure 5.2 Throughput performance of the proposed HPTSR protocol against TS factor 104

Figure 5.3 Throughput performance against source transmitted power 105

Figure 5.4 Throughput performance against transmission rate R_t 107

Figure 5.5 Throughput performance against source to relay distance d_{SR} 108

Figure 5.6 Throughput performance against different values of noise variance σ^2 109

Figure 5.7 Throughput performance against different values of energy conversion efficiency η 110

LIST OF ABBREVIATIONS

AF	Amplify-and-Forward
AS	Antenna Switching
AWGN	Additive White Gaussian Noise
BS	Base Station
CSI	Channel State Information
DF	Decode-and-Forward
EH	Energy Harvesting
ES	Energy Saving
ES-PSR	Energy Saving Power Splitting Relaying
ES-TSR	Energy Saving Time Switching Relaying
FD	Full duplex
HD	Half duplex
HPTSR	Hybridized Power-Time Splitting Relaying
HTC	Harvest-Then-Cooperate
IoT	Internet of Things
IT	Interfering Transmitter
KKT	Karush Kuhn Tucker
MIMO	Multiple-Input-Multiple-Output
MISO	Multiple-Input-Single-Output
MRC	Maximum Ratio Combining
PS	Power Splilitting
PSR	Power Splitting Relaying
QoS	Quality of Service

RF	Radio Frequency
RF-EH	Radio Frequency Energy Harvesting
RF-DC	Radio Frequency to Direct Current
SC	Selection Combining
SINR	Signal-to-Interference-plus-Noise-Ratio
SNR	Signal-to-Noise-Ratio
SWIPT	Simultaneous Wireless Information and Power Transfer
TS	Time Switching
TSR	Time Switching Relaying
WEHIT	Wireless Energy Harvesting and Information Transfer

LIST OF SYMBOLS

α	Time switching factor
β	Path loss exponent
ρ	Power splitting factor
η	RF-DC energy conversion efficiency
ω	The energy fraction consumed
$\vert . \vert$	Absolute value operation
$\varepsilon\{.\}$	Expectation operation
$K_n(.)$	The modified Bessel function of the second kind with order n
f	Channel gain coefficient between interfering transmitter and relay
g	Channel gain coefficient between interfering transmitter and destination
L	Number of transmission blocks
T	The time duration of each transmission block
d_{ij}	Distance between nodes i and j
h_{ij}	Channel gain coefficient from node i to node j
σ_{ij}^2	Noise variance from node i to node j
$C_{\min}$	The minimum required channel capacity to meet QoS criterion
$\min(A,B)$	The minimum between A and B
$\max(A,B)$	The maximum between A and B
P_R	Transmission power of the relay
P_S	The transmit power at the source
P_T	Transmission power of the interfering transmitter

P^{av}	The power available at the relay
$P_S^{\max}$	The maximum transmitted power constraint at the source
$P_r(\Delta)$	The probability of the event Δ happens
$P_r(\Delta^o, \Delta_o)$	The probability of the events Δ^o and Δ_o happen simultaneously
R_t	The source transmission rate
S_t	Normalized transmitted signal from the source
S_x	Normalized interference signal

PENUAIAN TENAGA RANGKAIAN KERJASAMA YANG DIAKTIFKAN: TEKNIK-TEKNIK PEMBAHAGIAN SUMBER, REKA BENTUK PROTOKOL DAN ANALISIS PRESTASI

ABSTRAK

Dalam rangkaian perhubungan kerjasama tanpa wayar, teknik kerjasama geganti boleh digunakan untuk mengurangkan masalah pelunturan dan pengecilan dengan meletakkan nod geganti diantara penghantar dan penerima. Oleh itu, prestasi rangkaian seperti kecekapan, celusan, dan kebolehpercayaan boleh ditingkatkan. Walau bagaimanapun, nod kerjasama geganti tanpa wayar yang dikekang tenaga mempunyai jangka hayat boleh jaya yang terhad, yang tidak dapat mengekalkan sambungan rangkaian yang mantap, sehingga menjadikan perhubungan boleh dipercayai sukar. Baru-baru ini, penuaian tenaga (EH) melalui isyarat frekuensi radio (RF) nampaknya menjadi satu penyelesaian untuk mengekalkan jangka hayat nod kerjasama geganti tanpa wayar. Pada tahun-tahun yang lalu, penyelidik telah mencadangkan beberapa teknik peruntukan sumber dan protokol untuk maklumat tanpa wayar dan pemindahan kuasa (SWIPT) serentak dalam rangkaian komunikasi kerjasama tanpa wayar. Walau bagaimanapun, masih terdapat banyak cabaran yang dihadapi oleh para penyelidik untuk mencapai SWIPT yang cekap dalam rangkaian sedemikian. Dalam kerja ini, teknik peruntukan sumber penjimatan tenaga (ES) baharu dicadangkan untuk pemboleh RF-EH rangkaian kerjasama dengan mengguna pakai protokol geganti pensuisan masa (TSR) dan geganti pemecahan kuasa (PSR). Ini adalah berdasarkan andaian bahawa nod geganti menggunakan bahagian tertentu daripada kuasa yang dituai dalam blok penghantaran semasa dan kemudian menyimpan baki bahagian untuk blok penghantaran seterusnya. Tidak seperti kerja sebelumnya, dengan teknik peruntukan sumber dalam pemboleh RF-EH rangkaian kerjasama telah dipertimbangkan dengan anggapan bahawa geganti dikekang tenaga mesti menggunakan semua kuasa yang dituai di setiap blok penghantaran. Teknik ES yang dicadangkan kemudian dioptimumkan dengan mempertimbangkan masalah pengoptimuman. Kemudian senario rangkaian kerjasama pemboleh EH yang terletak berdekatan dengan gangguan penghantar dipertimbangkan. Satu protokol kacukan geganti berasaskan pemecahan kuasa-masa (HPTSR) juga dicadangkan bersama teknik penggegantian dibesarkan-dan-kehadapan (AF) dan nyahkod-dan-kehadapan (DF) dengan memperkenalkan pembahagi berasaskan saluran dan kuasa-masa dalam seni bina penerima geganti telah dianalisis. Keputusan berangka mendedahkan bahawa protokol ES-TSR dan ES-PSR yang dicadangkan telah mengatasi protokol TSR dan PSR sedia ada dengan peningkatan kecekapan tenaga masing-masing sebanyak 13.87% dan 8.31%, terutamanya apabila bilangan blok penghantaran $L = 10$. Hasil ini menunjukkan bahawa teknik peruntukan sumber ES yang dicadangkan adalah lebih cekap tenaga daripada yang sedia ada. Pada nilai celusan optimum, protokol AF HPTSR yang dicadangkan telah mengatasi prestasi AF PSR, TSR dan protokol berasaskan kepada penggegantian pensuisan kuasa masa (TPSR) yang sedia ada dengan peningkatan celusan masing-masing sebanyak 54.18%, 72.31% dan 10.47%. Protokol DF HPTSR yang dicadangkan menunjukkan peningkatan prestasi sebanyak 2.81% mengatasi protokol AF HPTSR yang dicadangkan. Keputusan ini menunjukkan bahawa protokol AF atau DF HPTSR yang dicadangkan boleh mencapai prestasi celusan yang lebih baik melalui protokol sedia ada, terutamanya pada nisbah isyarat-hingar yang tinggi.

ENERGY HARVESTING ENABLED COOPERATIVE NETWORKS: RESOURCE ALLOCATION TECHNIQUES, PROTOCOL DESIGN AND PERFORMANCE ANALYSIS

ABSTRACT

In In wireless cooperative communication networks, cooperative relaying techniques can be employed to mitigate fading and attenuation problems by positioning relay nodes between a transmitter and a receiver. Therefore, network performance such as efficiency, throughput, and reliability can be improved. However, energy-constrained wireless cooperative relay nodes have a limited viable lifetime, which cannot sustain steady network connectivity, thereby making reliable communication difficult. Recently, energy harvesting (EH) via radio frequency (RF) signals appears to be a solution for sustaining the lifetime of the wireless cooperative relay nodes. In the past years, researchers have proposed some resource allocation techniques and protocols for simultaneous wireless information and power transfer (SWIPT) in the wireless cooperative communication networks. Nevertheless, there are still a lot of challenges being faced by the researchers to achieve an efficient SWIPT in such network. In this work, a new energy saving (ES) resource allocation technique is proposed for RF-EH enabled cooperative networks by adopting time switching relaying (TSR) and power splitting relaying (PSR) protocols. This is based on the assumption that the relay node uses a certain proportion of the harvested power in the current transmission block and then save the remaining portion for the next transmission block. Unlike the previous works, in that the resource allocation techniques in RF-EH enabled cooperative networks have been considered under the assumption that the energy-constrained relay must utilize all of its harvested power in each transmission block. The proposed ES technique is then optimized by considering the optimization problems. Then, the scenario of EH-enabled cooperative network with the presence of an interfering transmitter is considered. A hybridized power-time splitting based relaying (HPTSR) protocol is also proposed with amplified-and-forward (AF) and decode-and-forward (DF) relaying techniques by introducing a channel-based and power-time splitter into the relay receiver architecture are analyzed. Numerical results revealed that the proposed ES-TSR and ES-PSR protocols outperformed the existing TSR and PSR protocols with an energy efficiency gain of 13.87 % and 8.31 %, respectively, particularly, when the number of transmission block $L = 10$. These results show that the proposed ES resource allocation technique is more energy efficient than the existing ones. At the optimal throughput value, the proposed AF HPTSR protocol outperformed the existing AF PSR, TSR, and time power switching relaying (TPSR) based protocols with a throughput gain of 54.18 %, 72.31 %, and 10.47 %, respectively. The proposed DF HPTSR protocol showed a performance gain of 2.81 % over the proposed AF HPTSR protocol. These results show that the proposed AF or DF HPTSR protocol can achieve a better throughput performance over the existing protocols, especially at high signal-to-noise ratio.

CHAPTER ONE

INTRODUCTION

The ever increasing demands for wireless services over the past decades have led to the recent advancements in wireless cooperative communication systems. Cooperative communications allow resource-sharing among multiple nodes in a single communication network due to the broadcast nature of wireless networks. This can improve the network connectivity, reliability, energy efficiency, and average throughput (Hong et al., 2007; Li et al., 2012). In comparison to other emerging communication techniques that could proffer similar advantages, such as multiple-input-multiple-output (MIMO) technique, cooperative communication is preferable in implementation adaptability and hardware feasibility. These benefits of the cooperative communication make it one of the favorable techniques for future wireless communication systems.

However, since one of the factors that make a wireless communication network operational and reliable is the availability of energy, energy-constrained communication nodes have a limited viable lifetime. As a result, energy-constrained cooperative communication nodes have a limited viable lifetime and these cooperative nodes cannot sustain constant network connectivity, thereby making reliable communication demanding. Furthermore, recharging or replacing the batteries that powered such nodes of the wireless cooperative communication network results in high cost, difficulty, risk, or highly adverse effects, specifically in sensors placed inside the human body and in building structures (Nasir et al., 2013; Zhang & Ho, 2013; Zhai & Liu, 2015). This has created some fundamental research problems which require solutions. Taking into consideration the earlier mentioned cases, collecting energy from renewable energy sources in the surroundings is a safe and convenient choice.

Energy harvesting (EH) emerges to be a quick fix for sustaining the lifetime of the energy-constrained wireless cooperative communication networks. In recent years, EH has gained considerable attention among researchers (Chalise et al., 2012; Fouladgar & Simeone, 2012; Luo et al., 2013; Nasir et al., 2013; Xu & Zhang, 2014; Nguyen et al., 2017; Ye et al., 2018) and the advances made in EH technology have made self-sustaining wireless nodes achievable, thereby creating a promising and convenient technique to charge batteries in 5G wireless cooperative communication networks in the future (Liu et al., 2013a; Do, 2015; Nguyen et al., 2017).

Sequel to the advances made in EH technologies, a new emerging solution to switch energy constrained nodes on by using radio frequency (RF) signals has been proposed recently, the rationale of which is that RF signals can concurrently transfer wireless energy and information (Varshney, 2008; Nasir et al., 2013; Di, et al., 2017; Chu, et al., 2017). Thus, communication nodes with limited energy in wireless cooperative networks can harvest energy via RF signals broadcast from the energetic nodes, which will be used in the simultaneous processing and transmission of information (Varshney, 2008; Nasir et al., 2013; Zhang & Ho, 2013; Ye et al., 2018). This EH technique is termed simultaneous wireless information and power transfer (SWIPT). To achieve SWIPT in cooperative communication networks, different protocols have been proposed in the literature (Nasir et al., 2013; Krikidis et al., 2014b; Zhao et al., 2018), which are now widely adopted.

Furthermore, radio signals radiated by neighboring transmitters can be a close alternative source for wireless EH. As reported by (Zungeru et al., 2012; Ju & Zhang, 2014b), using a power-cast RF energy harvester operating at 915 MHz, the wireless energy of 3.5 mJ and 1 uJ can be scavenged from RF signals at the equivalent ranges of 0.6 and 11 m, respectively. Advances in the design of energy-saving rectifying antennas can pave the way for an efficient wireless EH via RF signals in the near future (Vullers et al., 2009).

This thesis presents resource allocation techniques, protocol design and performance analysis of a RF EH-enabled cooperative network that comprises a source node, an energy-constrained cooperative relay node and a destination node. The source node sends RF signals to the destination node with the assistance of the energy-constrained cooperative relay node. Since the relay node has no embedded energy supply, it harvests energy from the RF signals broadcast by the source node, which can be stored in a rechargeable battery and concurrently process the received signals. The relay can then utilize the harvested energy to deliver the information signal at the destination node. However, wireless communication networks are prone to interference due to their broadcasting feature. This condition can result in the degradation in system performance. Therefore, the effects of the presence of an interfering transmitter in the neighbourhood of the RF EH-enabled cooperative network is also investigated. This is done in order to show the benefit of interference in the SWIPT systems.

1.1 Problem Statement

In wireless communications, researchers have investigated conventional renewable energy resources (e.g., solar, mechanical vibration, and wind) and studied a number of resource allocation techniques for different goals and network topologies (Krikidis et al., 2014b). However, the unpredictable and periodic character of these energy sources cannot promise good quality of service (QoS), thereby motivating the use of EH via RF signals. This drawback can be overcome in a wireless network with the use of RF signals by using SWIPT. The energy-constrained nodes can renew their energy from RF signals that come from more energetic nodes (Lu et al., 2015). Specifically, the demand for RF–EH can be predictable, thereby making it suitable for QoS-based application support (Mishra et al., 2015).

In the past, several protocols have been proposed to virtually realize SWIPT, namely, time switching relaying (TSR), power splitting relaying (PSR) and antenna switching (AS) protocols and these protocols have been widely adopted (Nasir et al., 2013; Liu et al., 2013a; Hu et al., 2015; Wang et al., 2017b). Previous works on SWIPT have considered a number of resource allocation techniques for different objective orientations (e.g. throughput and energy efficiency enhancement) in EH-enabled cooperative networks under the assumption that the energy-constrained relay must utilize all of its harvested power in each transmission block. Hence, the relay's power causality was neglected. However, the ability to find the most efficient technique to utilize the harvested power optimally and satisfy certain requirements for the system QoS is still a critical issue for the researchers.

According to (Nasir et al., 2013), in PSR protocol utilization, the time switching (TS) factor is set to remain constant for throughput optimization, while the power splitting (PS) factor is not considered in TSR protocol. Thus, optimal throughput based on a single constraint (i.e. time or power) is regarded as a local optimization parameter. To tackle this challenge, (Do, 2016) proposed time-power switching relaying (TPSR) protocol for determining both the TS factor and the PS factor subject to maximizing throughput performance. However, the optimal TS or PS factor is affected by the channel statistics of the channel state information (CSI), thereby results in rapid changes of received signal strengths over a short period of transmission time and distances traveled.

1.2 Research Objectives

This research focuses on RF-EH as a means of sustaining the lifetime of energy-constrained wireless cooperative networks. The major objectives of this research include:

i. To propose a new and efficient energy saving (ES) resource (e.g. power) allocation technique for EH-enabled cooperative networks on the basis of the TSR and the PSR protocols.
ii. To propose a hybridized power-time splitting based relaying (HPTSR) protocol for an efficient SWIPT in EH-enabled cooperative networks.
iii. To determine the optimal system parameters that maximize the system energy efficiency in (i) and the throughput performance of the proposed HPTSR protocol in (ii) for the considered EH-enabled cooperative network.

1.3 Scope of Work

This thesis centers on exploitation of the RF-EH in wireless cooperative networks. The main targets are to propose an ES technique and an efficient SWIPT protocol for power allocation in EH-enabled cooperative networks. The cooperative network being used is a single-source node, a single-relay node, and a single-destination node. Furthermore, the ES resource allocation problem being addressed in this thesis is based on the TSR and PSR protocols, which are widely adopted in the literature (Nasir et al., 2013; Puniran et al., 2017; Ye et al., 2018), with decode-and-forward cooperative relaying scheme. The relay architecture design and analysis of the proposed HPTSR protocol are based on amplify-and-forward (AF) and decode-and-forward (DF) cooperative relaying schemes for the purpose of performance comparison.

Generally, this work involves the analysis of an EH-enabled cooperative network rather than the traditional one. The performance metrics being employed are system energy efficiency and throughput performance. The implementation of the proposed ES resource allocation technique and HPTSR protocol is based on MATLAB simulations. Lastly, this thesis does not intend to include the analysis of multi-relay scenario of the ES resource allocation technique and the HPTSR protocol being proposed. The reasons for this non-inclusion of the analysis of multi-relay scenario are that the basic concepts of EH and cooperative communication are based on single relay, the analysis for the multi-relay scenario is complex, and the availability of sufficient analytical results for the proposed ES resource allocation technique and the HPTSR protocol which are enough for their validation.

1.4 Organization of the Thesis

This thesis is structured into six chapters as follows. Chapter 1 presents an overall introduction of the cooperative communication networks, energy harvesting technology and its challenges; the problem statement, objectives of this research, and scope of the work.

Chapter 2 presents the background of this research and a thorough review of the related works. This chapter highlights the issues related to the previous works reported in the literature and also provides the motivation to conduct this research.

Chapter 3 discusses the methodology used to achieve the research objectives. At first, the proposed ES resource allocation technique is presented and later the HPTSR protocol.

Chapter 4 presents the energy efficiency optimization in EH-enabled cooperative network with energy saving (ES) resource allocation technique on the basis of the PSR and the TSR protocols . The proposed technique is then followed by the optimization problems and a corresponding solution. Later the results are discussed for the proposed technique.

Chapter 5 presents the proposed hybridized power-time splitting based relaying (HPTSR) protocol and the performance analysis in EH-enabled cooperative networks. In this chapter, the focus is on the throughput performance analysis. The results and discussion for the analysis are also provided.

Lastly, Chapter 6 gives a summary of the thesis. The chapter gives a comprehensive conclusion of the entire work and also beams light on the future direction of SWIPT-related researches in wireless cooperative communication networks.

CHAPTER TWO

BACKGROUND AND RELATED WORKS

This chapter is dedicated for a clear understanding of the fundamental theoretical concept and the review of related works on the EH-enabled cooperative networks reported in the literature. The overall summary which comprises the gap analysis and the proposed solutions is also presented in this Chapter.

2.1 Fundamentals of EH-enabled Cooperative Networks

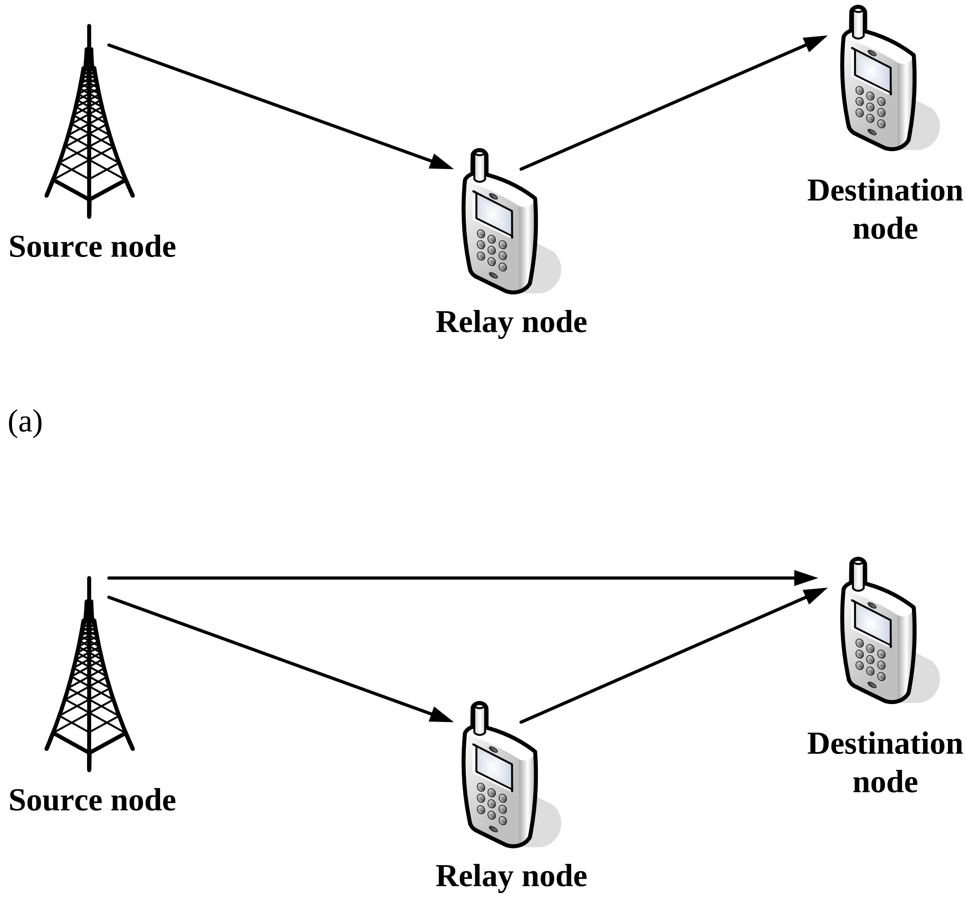
In this section, the basics and the theoretical structure of this research are presented. Firstly, cooperative communication network is described in relation to various cooperative relaying techniques. The concept of wireless information and power transfer is then discussed, followed by a brief discussion of EH receiver architecture which leads on to the various techniques in achieving SWIPT in cooperative communication networks. Finally, the application areas of SWIPT in wireless communication are briefly discussed.

2.1.1 Cooperative Communication Networks

In wireless communications, providing high QoS and maximum end-to-end throughput to the participating users is a great challenge. One of the techniques to overcoming this challenge is the application of relay sometimes called relaying or cooperative communication (Nosratinia et al., 2004; Touati et al., 2015). The basic concept of cooperative communication is to allow single-antenna devices to share their antennas and transmit cooperatively such that a virtual MIMO can be established in order to achieve transmit diversity. Cooperative communication is a solution for energy constraint and multipath fading problems associated with wireless communication in addition to enhancing the performance and diversity capacity (Laneman et al., 2004; Alouane & Hamdi, 2015; Nguyen & Kong, 2016). Cooperative communication network comprises three nodes, the source, relay and destination, which are all within each other's communication range as shown in Figure 2.1. The signal transmission between the source and the destination with the assistance of the relay takes place in two time slots.

Cooperative communication increases coverage area and QoS by dividing a transmission over a long distance from the source to the destination into two shorter transmission hops as shown in Figure 2.1a. The first hop is called source-to-relay hop while the second hop is referred to as relay-to-destination hop (Liang et al., 2013; Jangsher et al., 2015). Moreover, cooperative communication or relaying is an energy saving technology; relay is placed closer to the user node terminal so it saves energy through application of low power multi-hop transmissions instead of traditional high power one-hop transmission (Fantini et al., 2011; Lee & Hwang, 2010; Ming et al., 2015).

In Figure 2b, additional hop is added, this is called source-to-destination hop. The source node transmits RF signals to the destination in the first phase, i.e., direct transmission, and due to the broadcast nature of wireless networks, the relay may overhear the information. In the second phase, the relay transmits the received signals to the destination. Therefore, two copies of the original signals are received at the destination, which are transmitted over the two independent paths (direct path and cooperative path) and experience different channel degradation (fading and shadowing). These signals may be combined at the destination by applying one of the combining techniques, e.g. maximum-ratio-combining (MRC) for efficient packet decoding, or selection combining (SC), i.e. easily select the signal with a higher signal-to-noise-ratio (SNR) and then decode it (Brennan, 2003; Liang et al., 2013). Hence, the cooperative diversity gain can be achieved. It means that a signal transmission breakdown only occurs when both paths experience deep channel fading or shadowing at the same period of time.



(a)

(b)

Figure 2.1: Cooperative communication networks: (a) A two-hop transmission model without cooperative diversity, and (b) A two-hop transmission model with cooperative diversity

To achieve diversity gain and channel efficiency, different relaying techniques have been proposed and are briefly discussed as follows:

2.1.1(a) Amplify-and-Forward (AF) Relaying

In the AF relaying technique, the relay node amplifies the signal received from the source node by a gain with noise in the first time slot and then forwards the amplified signal to the destination node in the second time slot (Yang et al., 2012). This technique permits noise enhancement as a result of amplification characteristics of the signals with noise but simpler than decode-and-forward technique in implementing cooperation (Laneman et al., 2001; Son et al., 2016).

2.1.1(b) Decode-and-Forward (DF) Relaying

In the DF relaying technique, the relay node restores, decodes and recodes the received signals transmitted by the source node in the first time slot and then forwards the recoded signals to the destination node in the second time slot (Yang et al., 2012). A major advantage of this technique is in its simplicity and adaptability to channel conditions, and the fact that the noise observable in the AF technique can be eliminated by the relay. However, this technique would likely fail if the detection by the relay is unsuccessful.

2.1.1(c) Selection Relaying

Apart from the AF and the DF relaying techniques, another cooperative relaying technique is the selection relaying technique. In this technique, multiple relays are located within the transmission range of the source node and the destination node. All the relays are ready to assist the source node forwarding its message to the destination node but only the best relay is selected for cooperation. The selection of the best relay requires knowledge of order statistics of CSI. The first step in this technique is to obtain the weaker channel between the first hop and second hop of each relay node. These weak channels are ordered and the one with the highest SNR is selected. Then, the best relay forwards the received message to the destination. The advantages of this technique are that it allows efficient bandwidth utilization and provides full diversity (Bletsas et al., 2006; Beres & Adve, 2008; Adinoyi et al., 2009). However, the selection criterion can create unfairness among the cooperative partners in the network.

2.1.1(d) Incremental Relaying

Incremental relaying technique is another technique for achieving cooperative diversity. This technique attempts to save the channel resources by limiting the relaying process to the required conditions (Laneman et al., 2004). In this technique, the cooperation process is dependent on the limited feedback from the destination node. If the feedback shows that the source-destination transmission (direct transmission) is successful, the relay node remains idle (Laneman et al., 2004; Ikki & Ahmed, 2008). Otherwise, the feedback requests that the relay forwards the overheard signal from the source to the destination by employing either the AF or DF relaying technique.

2.1.2 Wireless Energy Harvesting and Information Transfer

Wireless energy harvesting and information transfer (WEHIT) in wireless communication networks have attracted many researchers both in the academe and industry. The work introduced by (Varshney, 2008) on WEHIT assumed the extraction of power and information from one and self-same signal. This finding has opened the way for the emergence of SWIPT techniques. With the introduction of WEHIT, harvesting energy from ambient RF signals enables energy-constrained nodes in wireless cooperative communication networks to renew their energy and consequently sustain their lifetime, thereby making SWIPT a promising supportive technology for wireless cooperative communication networks (Zhang & Ho, 2013; Xu & Zhang, 2014; Lu et al., 2015).

For WEHIT, energy can be scavenged strategically from the signal in the environs or from a well-managed and dedicated source, such as a grid-powered base station (BS) as depicted in Figure 2.2, or BS which uses conventional forms of renewable energy. By the signal in the environs, it refers to the transmitters (e.g., television towers) that are not dedicated or designed for RF–EH. This type of RF energy is absolutely for free. By contrast, the dedicated RF sources are not for free (i.e., they have been commercialized). Therefore, these sources are employed to deliver power to network nodes when reliable power supply is required. Thus, a high price is needed in order for the network to be deployed (Lu et al., 2015). Various dedicated RF energy transfer strategies for mobile power transmitter to renew energy in wireless sensor networks were also explored (Erol-kantarci & Mouftah, 2012a; Erol-Kantarci & Mouftah, 2012b; Erol-Kantarci & Mouftah, 2012c).

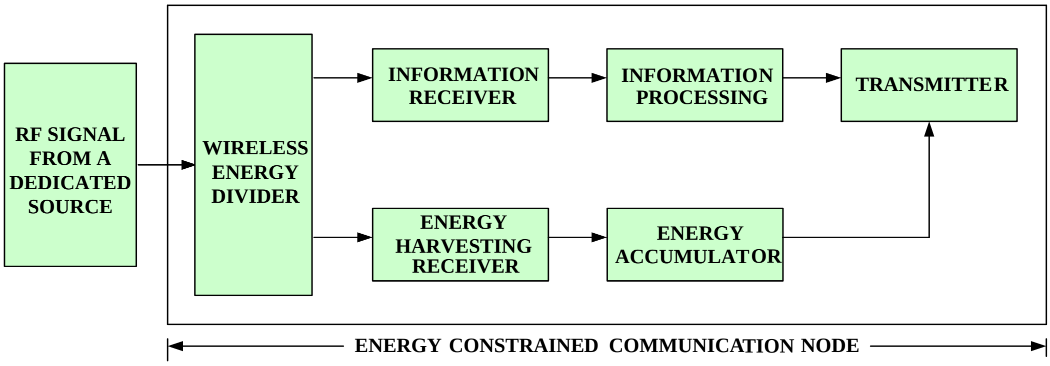


Figure 2.2 : Topology of WEHIT

The SWIPT technology recognizes effective utilizations of RF signals radiated by both ambient and dedicated transmitters and thus, offers great benefit to mobile users (Zhou et. al, 2013). Moreover, RF-EH can be predictable on demand, thus makes it suitable for supporting QoS-based applications (Mishra et al., 2015). Among other notable benefits of SWIPT are significant gains in terms of energy consumption, time delay, spectral efficiency, and interference management by superimposing information and power transfer are possible (Krikidis et al., 2014b).

Moreover, RF signals can simultaneously deliver controllable and efficient wireless information and energy when required, thereby providing an economical possibility for the maintainable operations of wireless systems without any alteration to the hardware at the transmitter end (Lu et al., 2015). Nevertheless, contemporary research on SWIPT has identified that optimizing wireless information and energy transmission simultaneously introduces a tradeoff to the design of a wireless communication system (Varshney, 2008). In this case, the amount of information and energy transferred cannot be maximized simultaneously. This issue remains an open question in the implementation of SWIPT, especially in cooperative networks.

2.1.3 Energy Harvesting Receiver Architecture

Generally, an EH receiver consists of two major sections, namely, rectenna and energy sections (Popovic, 2013; Krikidis et al., 2014b), each of which contains different components, as shown in Figure 2.3. A rectenna consists of an RF power receiver antenna, a matching circuit, and an RF to direct current (RF-DC) rectifier or converter. The matching circuit consists of inductive and capacitive elements. It ensures maximum energy delivery from the RF power antenna to the RF-DC converter (Nintanavongsa et al., 2012). Power management and energy storage units are the major units in the energy section. After successful charging of the energy storage unit (sometimes a rechargeable battery) by the DC signal from the converter, the storage unit ensures smooth power transmission to the loads (sensors, central processing unit, and communication transceiver). It also serves as a backlog for a period of time when external energy is unavailable (Nintanavongsa et al., 2012; Krikidis et al., 2014b).

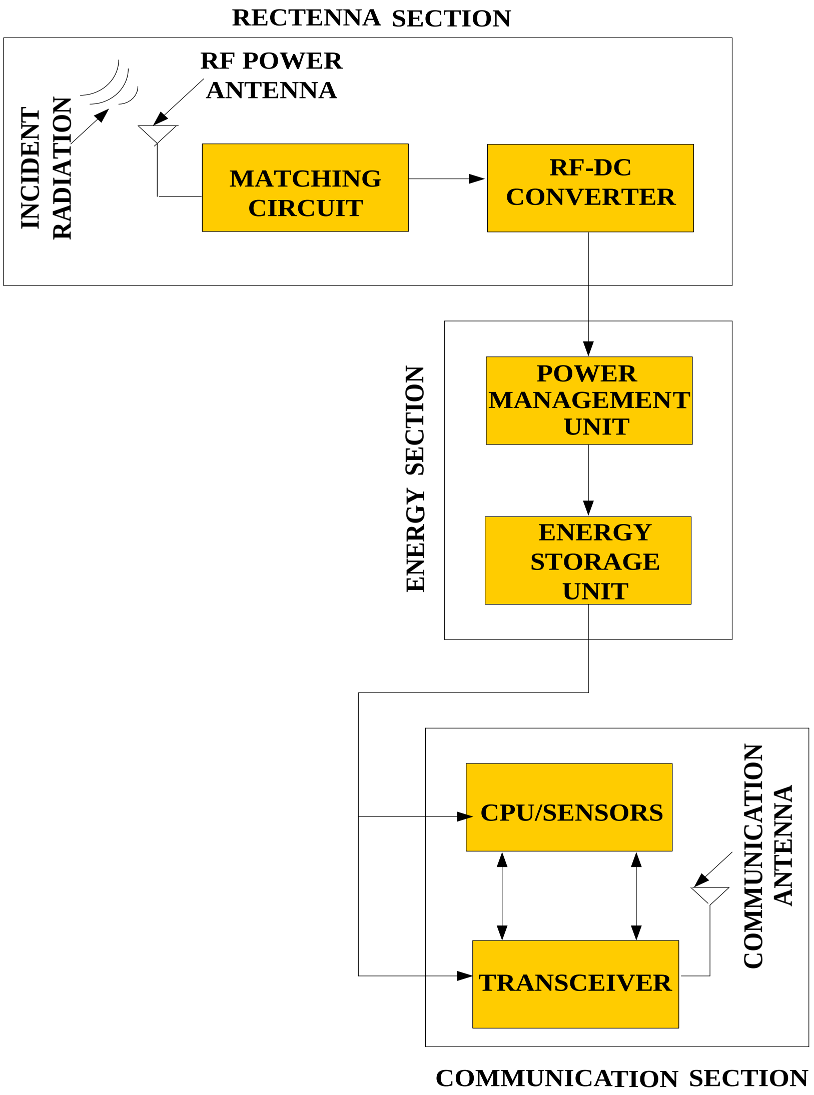


Figure 2.3: EH receiver architecture for energizing a communication transceiver (Krikidis et al., 2014b)

The wireless EH system (charging system) involves other two major techniques aside from the RF energy transfer technique, namely, inductive coupling and magnetic resonance techniques (Park et al., 2016). The inductive coupling technique is used for a small distance of about 0.5 cm with a frequency transfer range of 85 to 375 kHz. In-band communication is employed for transmission and reception of packets (Azad et al., 2012; Park et al., 2016). The standards for this technique are wireless power consortium (WPC) and power matter alliance (PMA). The magnetic resonance technique is applied for transmission over distances greater than 1.0 cm, and its transmission frequency is 6.78 MHz ISM band (Kurs et al., 2007; Park et al., 2016). Furthermore, it is used in 2.4 GHz low-energy Bluetooth (LEB) communication according to the standard of the alliance for wireless power (A4WP) (Park et al., 2016). The characteristics of each of the wireless energy transfer techniques are shown in Table 2.1.

Table 2.1: Characteristics of wireless energy transfer techniques

Wireless Energy Transfer Technique/ Characteristic	**RF Energy Transfer**	**Inductive Coupling**	**Magnetic Resonance**
Power Transfer Distance	From several meters to several kilometers	< 0.5 cm	>1.0 cm
Power Transfer Frequency	3 kHz – 300 GHz (Lu et al., 2015)	85-357 kHz	6.78 MHz
Field Region	Far-field	Near-field	Near-field
Propagation	Radiative	Non-radiative	Non-radiative
Communication Scheme	Not limited to specific bands (Omairi et al., 2017)	In-band Communication	2.4 GHz LEB
Standard	No international standard yet (To the best of our knowledge)	WPC, PMA	A4WP

2.1.4 SWIPT Techniques

In the past, researchers provided information on SWIPT technology in their theoretical studies with the assumption that one signal can carry both power and information in the absence of any loss, thereby conceding a basic compromise between information and power transfer (Varshney, 2008; Grover & Sahai, 2010; Krikidis et al., 2014b). Nevertheless, this assumption of simultaneous transfer turns out to be untrue in real life (Zhou et al., 2013) because the practical circuits for harvesting energy from RF signals in the environs lack the capacity to instantly detect the carried information. Furthermore, the EH operation carried out in the RF domain can destroy the content of the information (Krikidis et al., 2014b). As a result, to virtually realize SWIPT, a receiver designed to separate the received signal into two segments, namely, for EH and information decoding, is needed. This method has been widely adopted (Xiang & Tao, 2012; Nasir et al., 2013; Zhang & Ho, 2013; Zhou et al., 2013; Liu et al., 2013b). The various techniques on signal separation in different domains proposed in the literature are discussed as follows:

2.1.4(a) Power Splitting (PS) Technique

The PS technique is one of the remarkable techniques for achieving SWIPT in wireless cooperative networks. In this technique, the signal power P at the receiver is split into two fractions, $\rho:(1-\rho)$ with $0 \le \rho \le 1$. The fractional ρ is called the PS factor, which represents the proportion of energy to be scavenged at the EH receiver. This energy is then used for transmitting the signal processed by the information receiver. The remaining fraction, $(1-\rho)$ represents the proportion of energy for the information decoding at the information receiver (Nasir et al., 2013; Nasir et al., 2014; Lai et al., 2017). The block diagram of the PS technique is shown in Figure 2.4.

For instance, given a source l, if $\rho \in (0,1)$ denotes the PS factor for a receiver k, (i.e. ρ is the ratio of the RF signals used for EH), the harvested energy by the receiver k, $E_{l,k}^{PS}$ from the source l can be expressed as in (2.1). And the achievable channel capacity at the receiver k, $C_{l,k}^{PS}$ is expressed as in (2.2).

$$E_{l,k}^{PS} = \frac{\eta \rho P \left| h_{l,k} \right|^2}{d_{l,k}^{\beta}} T/2, \tag{2.1}$$

$$C_{l,k}^{PS} = \frac{T}{2} \log_2 \left(1 + \frac{(1-\rho) P \left| h_{l,k} \right|^2}{d_{l,k}^{\beta} \sigma_{l,k}^2} \right), \tag{2.2}$$

where η denotes the energy conversion efficiency, P denotes the transmit power at the source, T denotes the transmission block time; $h_{l,k}$ and $d_{l,k}$ denote the channel coefficient and the distance between the source l and the receiver k, respectively. Meanwhile, $\sigma_{l,k}^2$ denotes the noise variance between the source l and the receiver k and β is the path loss exponent (Nasir et al., 2013).

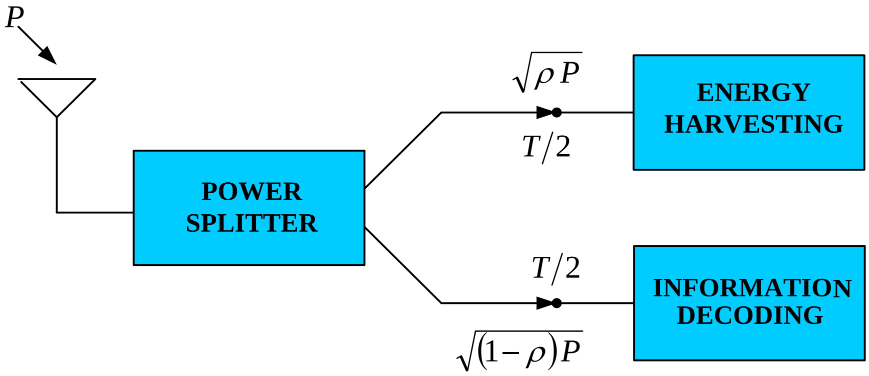


Figure 2.4: Block diagram of PS technique (Zhou et al., 2012; Nasir et al., 2013)

For the PS technique, the optimization of the PS factor (ρ) is required, thus, achieving higher receiver complexity. However, this technique attains spontaneous SWIPT, because the signal received in a time slot of one time block is used simultaneously for power transfer and information decoding. Therefore, it is more suitable for applications with delay constraints (Krikidis et al., 2014b).

2.1.4(b) Time Switching (TS) Technique

Another means of achieving SWIPT is by exploiting the TS technique. In this technique, the receiver is specially designed to actively switch in time for EH and information decoding using time fraction (α) (Nasir et al., 2013; Zhang & Ho, 2013). In this scenario, the switching of a signal is carried out based on the TS factor (α) with $0 \leq \alpha \leq 1$. Hence, the signal received during a one-time slot is utilized either for power transfer or information decoding. The entire signal power received is used for EH at the EH receiver as the information receiver is off. As the information receiver is turned on, information decoding uses all the signal power received (Zhou et al., 2013). The block diagram of the TS technique is shown in Figure 2.5.

Given a source l, if $\alpha \in (0,1)$ denotes the TS factor for a receiver k, (i.e. α is the fraction of time used for EH), the harvested energy by the receiver k, $E_{l,k}^{TS}$ from the source l can be expressed as in (2.3).

$$E_{l,k}^{TS} = \frac{\eta P \left|h_{l,k}\right|^2}{d_{l,k}^{\beta}} \alpha T \,, \tag{2.3}$$

And the achievable channel capacity at the receiver k, $C_{l,k}^{TS}$ is expressed as in (2.4).

$$C_{l,k}^{TS} = \frac{(1-\alpha)T}{2} \log_2\left(1 + \frac{P\left|h_{l,k}\right|^2}{d_{l,k}^{\beta}\,\sigma_{l,k}^2}\right), \tag{2.4}$$

According to the TS technique, the EH-enabled relay receiver uses $(1-\alpha)T/2$ for information reception and the remaining half, $(1-\alpha)T/2$ to forward the received signal to the final destination (Nasir et al., 2013; Srivantana & Maichalernnukul, 2017).

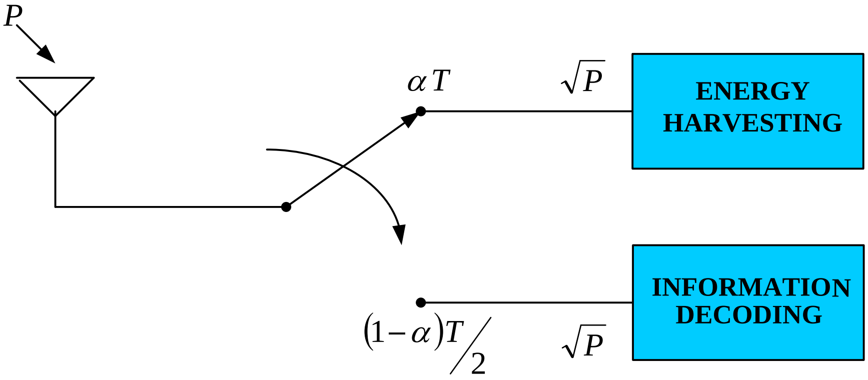


Figure 2.5: Block diagram of TS technique (Nasir et. Al., 2013)

For the TS technique, the hardware implementation at the receiver is not as complex as in the PS technique, but requires proper time synchronization and information/energy scheduling (Krikidis et al., 2014b).

2.1.4(c) Antenna Switching (AS) Technique

Apart from the PS and TS techniques, another basic SWIPT technique is the AS technique. The AS technique is employed in the MIMO broadcasting system. In this technique, the receiving antennae are classified into two groups. As shown in Figure 2.6, one group of receiving antennae is employed for information decoding and another group for EH (Zhang & Ho, 2013; Krikidis et al., 2014b). Therefore, this classification allows independent and simultaneous EH and information decoding. However, this technique results in an optimization problem, which requires a solution in each communication frame for deciding the optimal allocation of the antenna sets for EH and information decoding. Furthermore, the AS technique is highly complex. Therefore, in the literature, a low-complexity AS scheme was developed by combining the principles of generalized selection to facilitate SWIPT (Krikidis et al., 2014a; Perera et al., 2018). In Table 2.2, the advantages and disadvantages of the various techniques to achieving SWIPT in cooperative communication networks are presented.

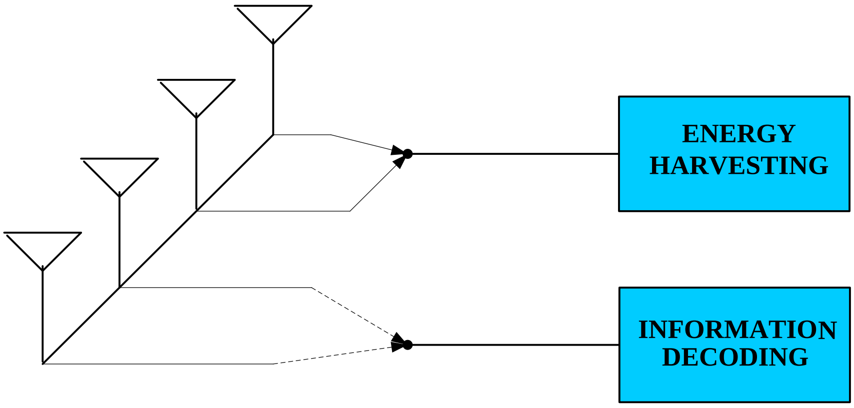


Figure 2.6: Block diagram of AS technique (Krikidis et al., 2014a)

Table 2.2: Advantages and disadvantages of various SWIPT techniques

SWIPT Technique	Advantages	Disadvantages
Power splitting (PS)	(i) It attains spontaneous SWIPT (ii) It is adequate for applications with delay constraints (iii) It achieves better tradeoffs between information rate and the amount of RF energy transfer as compared to other techniques (Perera et al., 2018).	(i) It requires optimization of the power factor (ii) Higher receiver complexity.
Time switching (TS)	(i) The receiver simply switches in time between EH and information decoding. (ii) TS factor and the transmit signal can be jointly optimized for different systems. (iii) Hardware implementation of the receiver is simple.	It requires proper time synchronization and information or energy scheduling (Krikidis, et al., 2014b; Perera et al., 2018).
Antenna switching (AS)	(i) It can acquire different tradeoffs between maximal information rate and RF energy transfer (Zhang & Ho, 2013). (ii) The antennas can observe different channels, thereby perform EH and information decoding independently and simultaneously.	(i) The optimization problem is complex (ii) It suffers from high receiver complexity. (iii) In case of hardware impairment, the system performance can be degraded.

2.1.5 Application Areas of SWIPT

As stated earlier, recent advancement in wireless communications have paved way for the SWIPT technology in both academe and industry, especially where wireless communication nodes use batteries as supply power. However, the energy limitation of battery constitutes a major issue to an efficient and a reliable communication between two or more communication nodes. Recognizing the effective utilization of the RF signals in such communication networks can be of great benefits to increasing the lifetime of the networks. The following are some of the application areas of SWIPT:

- **Wireless sensors and transceivers:** With wireless sensors and transceivers becoming smaller and more energy-efficient, electromagnetic radiations will not only become a major source of energy for operating these devices but simultaneous information and energy transfer will also be exploited. For example, healthcare monitoring using implantable biomedical sensors; and automation of building by adopting smart sensors that monitor and control different building processes (Krikidis et al., 2014b).
- **Internet of things (IoT)**: In the future generation networks, adopting SWIPT technologies in the IoT can be of significant importance for supplying energy and exchange of information with many ultra-low-power sensors, which support diverse sensing applications.
- **Cellular systems:** Cellular systems with small exchanges (cells), massive MIMO, and millimeter-wave technologies can overcome dominant path loss effects (Krikidis et al., 2014b); SWIPT can be employed as an efficient way to jointly support high throughput and energy sustainability in the system.

In addition, dedicated power transmitters are used to implement wireless energy transfer in an application like passive radio frequency identification (RFID) networks, (Yeager et al., 2010).

2.2 Review of Related Works

The major issues in wireless communication systems with EH capability include the decrease in energy transfer efficiency and signal fading over a long transmission range. The effects of these issues can be mitigated by using the cooperative relaying technique with SWIPT. An intermediate EH-enabled relay node(s) can be employed in transmitting a sourced information to a destination node, thereby resulting in reliable communication. The power allocation strategy, operation policy, selection scheme, and pre-coder optimization problem in the communication network should be considered in relay nodes.

Basically, most researchers studied on how to enhance performance gain on the power allocation strategies, relay operation policy as well as relay selection schemes by applying the AF and DF relaying techniques (Chalise et al., 2013; Moritz et al., 2014; Lu et al., 2015). In the last decade, researchers have considered SWIPT with other techniques in cooperative communication networks, and the recent advances are now classified into two categories, namely, SWIPT in half-duplex (HD) and SWIPT in full-duplex (FD) wireless relaying networks.

2.2.1 SWIPT in HD Wireless Relaying Networks

The SWIPT in HD wireless relaying or cooperative communication networks has been examined by many researchers and several techniques or schemes have been proposed under this category. In (Nasir et al., 2013), an optimal resource allocation between EH and data transmission using TS and PS relaying protocols in an AF wireless cooperative network was investigated. The goal was to maximize the system throughput. An energy-constrained relay node harvests power from the RF signal broadcast by an energetic source node. The relay utilizes the harvested power to deliver