Wireless energy harvesting based relaying : a diversity multiplexing tradeoff perspective

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**WIRELESS ENERGY HARVESTING
BASED RELAYING: A DIVERSITY
MULTIPLEXING TRADEOFF
PERSPECTIVE**

**YEPURI SUDHAKARA RAO
SCHOOL OF COMPUTER SCIENCE AND ENGINEERING**

2019

Wireless Energy Harvesting Based Relaying: A Diversity Multiplexing Tradeoff Perspective

YEPURI SUDHAKARA RAO

School of Computer Science and Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

To my mother

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

11 Jul 2019

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

12 Jul 2019

Date

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Authorship Attribution

Statement

This thesis contains material from seven papers published in the following peer-reviewed journals / from papers accepted at conferences in which I am listed as an author.

Chapter 3 is published as the following two papers.

- **Rao, Yepuri Sudhakara**, Rajendra Prasad Sirigina, and A. S. Madhukumar. “On the DMT of RF Energy Harvesting-Based Dynamic Decode-and-Forward Relaying.” *IEEE Communications Letters* 21.1 (2017): 200-203.
- **Rao, Yepuri Sudhakara**, A. S. Madhukumar, and Rajendra Prasad Sirigina. “RF energy harvesting based relays: Non-orthogonal AF Vs dynamic DF.” 20th International Symposium on Wireless Personal Multimedia Communications (WPMC), IEEE, 2017.

The contributions of co-authors are as follows:

- A/Prof AS Madhukumar and Dr. Rajendra Prasad Sirigina provided the initial direction by introducing me to the study of diversity-multiplexing trade-off.
- I analyzed and solved the problem for energy harvesting based systems. The intermediate analysis is validated by Dr. Rajendra Prasad Sirigina.
- I prepared the manuscript drafts. The manuscript was revised based on the

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The contributions of the co-authors are as follows:

- A/Prof AS Madhukumar and Dr. Rajendra Prasad Sirigina are involved in numerous discussions while solving the problem.
- I prepared the manuscript drafts. The manuscript was revised by A/Prof AS Madhukumar and Dr. Rajendra Prasad Sirigina

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- I prepared the manuscript drafts. The manuscript was revised by A/Prof AS Madhukumar.

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Abstract

This thesis presents a radio frequency (RF)-based energy harvesting (EH) coupled with relaying-based communication as a solution to address the end-to-end quality-of-service (QoS) requirements of future wireless communication systems. Typically, an increase in data rate leads to a rise in error probability. Conversely, to improve reliability, the system must sacrifice the achievable data rate. Thus, there is an inherent tradeoff between these two metrics. For quasi-static fading channels, Zheng and Tse proposed a fundamental performance metric, diversity-multiplexing tradeoff (DMT), to formalize the relationship between rate and reliability at asymptotically high signal-to-noise ratios. A direct characterization of the DMT for RF-EH-based relay channels is in general difficult because the transmission power of RF-EH-based relay is a function of source-to-relay channel gain. In this thesis, the DMT framework has been adapted to suit this class of channels.

The essence of this work is in deriving the closed-form expressions for the DMT in the high-SNR regime. Specifically, the focus is on the time-switching-based scheme in which the intermediate relay switches between energy harvesting (EH), information decoding (ID), and the information retransmission (IR). In the single-relay case, the DMT has been characterized for dynamic decode-and-forward (DDF) and non-orthogonal amplify-and-forward (NAF) protocols. An investigation of these RF-EH-based protocols yields a detailed characterization of the limitations of energy harvesting concerning optimal performance. In particular,

Abstract

an interesting conceptual relation between the diversity gain and the energy-harvesting interval has been found. It is observed that the achievable diversity gain improves with the reduction in energy-harvesting interval. Moreover, a comparison with various benchmarking schemes has established the supremacy of RF-EH-based DDF among all the proposed relaying protocols.

Next, a multiple-access relay system (MARS), where the relay node powered by RF-EH, is analyzed. For this system, the DMT is characterized for two variants of EH-based DDF protocols: without feedback (EH-DDF) and with limited feedback (EH-DDF-LF). Analysis of these protocols reveals that the diversity gain of EH-DDF scheme is inferior to that of traditional non-EH-based DDF protocol. On the other hand, EH-DDF-LF achieves optimal diversity gain in the high-multiplexing-gain regime. Subsequently, the DMT study has been extended to an interference-limited relay-aided communication system in the moderate-interference regime.

Unfortunately, the asymptotic (high-SNR) DMT does not reveal the tradeoff between diversity and multiplexing gains at low to moderate SNRs. Thus, there is a need to characterize the DMT for finite SNR regimes to assess the complete picture on the effects of various design parameters. In this work, an analytical framework to derive closed-form expressions for finite SNR DMT (f-DMT) for RF-EH-based amplify-and-forward (AF) and decode-and-forward (DF) protocols is also proposed. The results of this investigation suggest that the DF offers superior performance in the low-SNR regime, whereas AF performs better in high-SNR scenarios. Furthermore, an analytical study is presented to evaluate the effect of the fraction of time devoted to RF-EH (time-sharing parameter, ϵ) on the f-DMT. For both AF and DF, it is shown that the optimum ϵ depends on the operating SNR. However, it is observed that the influence of ϵ is nominal in the high-SNR regime. As a result, it is concluded that the asymptotic DMT has its relevance, even though it hides a few finer details.

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List of Abbreviations

AF	Amplify-and-forward
ARQ	Automatic repeat request
AWGN	Additive white Gaussian noise
BP	Battery-powered
BPCU	Bits per channel use
CAGR	Compound annual growth rate
CCI	Co-channel interference
CF	Compress and Forward
CSI	Channel state information
DDF	Dynamic decode-and-forward
DF	Decode-and-forward
DMT	Diversity-multiplexing tradeoff
DoF	Degree(s) of freedom
DPS	Dynamic power splitting
EE	Energy efficiency
EH	Energy harvesting
FD	Full-duplex
f-DMT	Finite-SNR DMT
GSC	Generalized selection combiner
HD	Half-duplex
i.i.d.	independent and identically distributed

List of Abbreviations

ICR	Interference channel with a relay
ICT	Information and communication technology
II	Interference ignorant
JD	Joint-decoder
LF	Limited feedback
MAC	Media access control
MAF	Multiple-access amplify-forward
MARC	Multiple access relay channel
MARS	Multiple access relay system
MIMO	Multi-input-multi-output
MISO	Multi-input-single-output
MRC	Maximal ratio combiner
NAF	Non-orthogonal amplify-and-forward
NOMA	Non-orthogonal multiple access
OAF	Orthogonal amplify-and-forward
ODF	Orthogonal decode-and-forward
OEH	Opportunistic energy harvesting
P2P	Point-to-point
PLNC	Physical layer network coding
PS	Power splitting
QoS	Quality of service
RF	Radio frequency
SE	Spectral Efficiency
SI	Self-interference
SIC	Successive interference cancellation
SINR	Signal-to-interference-plus-noise ratio
SISO	Single-input-single-output
SNR	Signal-to-noise-ratio

List of Abbreviations

SWIPT	Simultaneous wireless information and power transfer
TS	Time switching
WEH	Wireless energy harvesting
WPT	Wireless power transfer

List of Symbols

$\mathbb{C}$	set of complex numbers
$\mathbb{R}$	set of real numbers
$\mathbb{N}$	set of natural numbers
$\mathbf{X}$	matrix
$\mathbf{x}$	vector
x	scalar
$ x $	absolute value of $x \in \mathbb{R}$
$\inf.$	infimum operator
$\min.$	minimum operator
$\max.$	maximum operator
(x, y)	Cartesian coordinates
R_n^+	set of real n-vectors with non-negative elements
A^+	$A \cap R_n^+$
$\mathbf{X}^{-1}$	inverse of the square matrix $\mathbf{X}$
$(\cdot)^T$	transpose of a matrix or vector
$\sim$	distributed as
$\mathcal{N}(\mu, \sigma^2)$	Gaussian distribution with mean μ and variance σ^2
$\ \mathbf{x}\ $ or $\ \mathbf{x}\ _2$	two-norm of the vector $\mathbf{x}$
$\mathbb{E}\{\cdot\}$	expectation operator
$\mathbf{I}_N$	identity matrix of dimension N
$\Gamma(t)$	Gamma function defined as $\int_0^\infty x^{t-1} \exp^{-x} dx$

Chapter 1

Introduction

1.1 Background

Future wireless systems must address the fundamental challenges of supporting exponential growth in the number of wireless devices, the rapid increase in data traffic (at an estimated 50 – 60% compound annual growth rate [CAGR]), and heterogeneous mix of networks, while achieving up to 90% energy savings [8].

This challenge can be split into two main problems. First, keeping the massive number of devices alive requires astronomical amounts of energy. Notably, as shown in Figure 1.1, the annual energy demand for the information and communication technology (ICT) industry is projected to reach 8,265 terawatt-hours (TWh) by 2030 [1]. This enormous increase in energy consumption not only escalates the operating cost of wireless communication systems but also exacerbates harmful-carbon emission levels. Second, conventional wireless networks are typically powered by fixed energy supplies, such as batteries, with limited storage capacity. While the operating lives of such networks can be extended by recharging or replacing the drained batteries, it becomes truly challenging if a large portion of the devices are hidden (e.g., in the building structures, appliances, human body, and so on) or deployed in remote or

Figure 1.1: Electricity footprint of information and communication technology (in terawatt-hours [TWh]). [1]

hazardous environments (e.g., in radioactive areas or pressurized pipes). Even in systems in which the battery replacement is practical, it may not be economical to do so. Moreover, the disposal of a huge number of exhausted batteries results in environmental damage. Therefore, a more elegant and greener solution for supplying energy to future wireless nodes is deemed necessary. In this pursuit, researchers have focused on two important aspects: enhancing *energy efficiency* (EE) and incorporating *energy harvesting* (EH). Extensive research has been carried out to improve the EE in wireless devices in recent years. In particular, there has been a trend in designing energy-efficient media access control (MAC) and routing protocols to keep the nodes operative for more extended periods [9–16]. However, most of the energy conservation protocols rely on lazy scheduling algorithms [6, 17], in which the energy consumption is traded for the transmit duration. Such implementations lead to a degradation in the quality of service (QoS). In spite of the compromises, even the most energy-efficient devices eventually run out of battery life. On the other hand, EH offers a more elegant solution, which enables the wireless devices to recharge their batteries from

Figure 1.2: Energy-harvesting technologies [2]

external energy sources, thus promising perpetual operation.

Wireless devices can harvest the energy from ambient sources such as solar [18], wind [19], mechanical vibrations [20], thermal [21], and so on (please refer to Figure 1.2 and Table 1.1 for details). As detailed in Table 1.1, apart from the radio frequency based EH, intermittent energy availability from ambient sources poses new challenges related to energy storage and power management. To counter these concerns, more recently, radio frequency (RF)-based energy harvesting (RF-EH) has emerged as a leading solution, owing to its suitability for supporting applications with strict QoS requirements [3]. RF waveforms for wireless communications carry both information and energy. Therefore, the energy needed to power the communication nodes can be harvested from the transmitted RF signal itself (refer to the electromagnetic radiation section of

Table 1.1: Comparison: Energy harvesting methods [7]

Energy Source	Power density	Advantages	Disadvantages
Solar	15 mW/cm^3	Sufficient energy during the day	Not available at night
Vibration (piezoelectric)	200 uW/cm^3	Absence of voltage source	Brittle materials
Thermoelectric	40 uW/cm^2	Long life, reliable with low maintenance	Low energy conversion efficiency
Radio frequency	1 uW/cm^2	Sufficient in urban areas	Few opportunities in suburban and rural areas

Figure 1.2). This feature opens up many fascinating and unprecedented possibilities in the realm of green communications [22–26].

1.2 Need for Relay-Based Wireless Communication

In addition to addressing the energy requirements and associated challenges, future wireless networks must meet the envisaged exponential traffic growth. In fact, one of the significant aims of 5G networks is a thousand-fold increase in capacity compared to 4G networks. This daunting mission is proposed to be accomplished by three major themes: higher spectral efficiency, network densification, and more spectrum usage [8]. Multiple-input multiple-output (MIMO) is one of the significant developments; it exploits the space dimension to improve the performance of wireless networks in terms of enhancing the capacity, reducing the detrimental effects of interference (which emanates out of the increase in cell density), and combating fading. Information-theoretic results have demonstrated the efficacy of MIMO systems in simultaneously enhancing the capacity and the reliability in wireless fading links [27–29]. MIMO has become a mature and reliable technology, which finds applications even in complex

networks such as multiple-access and broadcast channels [30–34]. However, the straightforward implementation of MIMO may not be feasible in space-constrained applications such as sensor networks and internet of things (IoT) due to the smaller size of the wireless nodes. As a result, relay-aided communication has gained prominence to realize the benefits of MIMO in such scenarios.

Relay-Aided communication, as in MIMO, takes advantage of spatial diversity to improve the overall system performance in terms of throughput and reliability. In effect, the relay acts as a virtual distributed antenna to achieve performance gains similar to MIMO systems. The concept of relaying was first proposed by Van der Meulen [35], and subsequent developments introduced different implementation strategies [36–38]. In the last two decades, research on this topic has matured to the point that it has become a common practice to utilize relay-assisted communication in providing extended coverage or increased capacity. Moreover, the relay-aided system significantly outperforms the comparable conventional peer-to-peer communication system in offering better reliability and higher data rates while doing so in a more economical manner [39, 40]. There are many promising results reported in the research related to the extensions of relay channel to multiple access [34], broadcast [32], multiple relay [41], MIMO systems [42], relay-assisted Z-channel [43], and limited-feedback-based relay channel [44]. Motivated by these results, in this thesis, we explore whether these gains can be realized with RF-EH-based relaying.

1.3 RF-EH-Based Relay-Assisted Networks

The RF-EH has emerged as the most promising technology to achieve one of the critical objectives of upcoming wireless systems (i.e., perpetual autonomous operation of terminal devices). Similarly, relay-aided communication has gained prominence in addressing the stringent QoS demands of future wireless networks.

Figure 1.3: System models with RF-EH-based relay(s)

To exploit the synergy between RF-EH and relay-assisted communication, a composite framework has been presented in this section. In view of this, four different RF-EH-based relay-aided communication system models are provided in Figure 1.3. The first two models (refer to Figure 1.3(a) and Figure 1.3(b)) capture the typical single-user relay systems. The third model (refer to Figure 1.3(c)) depicts a cooperative uplink, and finally the fourth system (refer to Figure 1.3(d)) models the cell-edge scenario, in which the intended user suffers from interference. Note that in all these models, the intermediate relay nodes $T_1, T_2, \dots, T_N$ are entirely powered by the RF transmission that emanates from hybrid-source nodes (refer to Figure 1.4).

In the first case, as shown in Figure 1.3(a), the hybrid source S_1 transmits its data to the user U_1 with the help of an EH-based relay node T_1 . Here, there are two possible variants of relaying protocols: orthogonal and non-orthogonal.

Figure 1.4: RF energy-harvesting system [3]

In orthogonal protocols, the source and relay use exclusive (either in frequency or time) channels to transmit a symbol. On the other hand, in non-orthogonal protocols, the source and relay utilize the same channel. In this work, we consider both orthogonal and non-orthogonal relaying for single-relay-based systems. The second model illustrated in Figure 1.3(b) extends the analysis to multiple EH-based-relay systems.

In a typical uplink wireless communication system, multiple users transmit their information to the same destination (e.g., a base station). In general, this is achieved through multiple access techniques, in which each user is allocated with dedicated resources such as time slot, frequency band, and so on. While these orthogonal multiple-access techniques offer low receiver complexity, they suffer from poor spectral efficiency. To counter this deficiency, non-orthogonal multiple-access (NOMA) protocols have been proposed in the literature [45]. In NOMA, all users utilize resources simultaneously, thus leading to interference. As a consequence, more complicated multi-user-detection techniques — such as joint-decoding (JD) — are required to retrieve the individual user’s data. Furthermore, it is found that significant diversity gains can be achieved by sharing a single relay among multiple source nodes in slow-fading environments [46, 47]. In this work, motivated by these results, we investigate a multiple access relay channel (MARC) where the intermediate relay is powered by RF-EH. As illustrated in Figure 1.3(c),

MARC can be viewed as a combination of multiple access channel (MAC) and a relay channel. Thus, in the absence of a relay, a MARC degenerates into a MAC channel. Furthermore, it is well established in the literature that the optimum diversity performance is achieved when all the users have the perfect knowledge of channel state information (CSI). However, the process of acquiring CSI results in additional costs regarding complexity and bandwidth. One elegant method to substantially reduce this penalty is the usage of a low-rate feedback channel [44, 48, 49]. Owing to these observations, in this work, a limited-feedback option is also explored to further improve the diversity performance of RF-EH-based MARC.

The ever-increasing demand for consistently high data rates over a large coverage area has spurred the aggressive reuse of communication resources, such as frequency spectrum. However, frequency reuse introduces interference among users. Thus, maximizing the interference-limited user's throughput while meeting the QoS requirement is an essential issue in the design of wireless systems. This problem can be addressed by utilizing other available nodes in the network as relays to support the affected interference-limited user [50]. In the proposed work, the interference-limited relay-aided system shown in Figure 1.3(d) has been considered under the purview of RF-EH.

1.4 Problem Statement and the Objectives

As detailed in the earlier section, relays can be used to increase either the achievable data rate or to improve the reliability of the system. Traditionally, these effects are captured by spatial multiplexing gain and the diversity gain, respectively. Most of the existing literature related to EH-based relaying [51–53] deals with either the maximum achievable rate or the outage probability. However, the closed-form evaluation of such traditional performance metrics is challenging because of the mathematical intractability inherent in such system models. For this reason, these studies invariably employ approximations using probability bounds.

A more elegant metric is therefore needed to capture the tradeoff between the multiplexing gain and the diversity gain. In a landmark paper, Zheng and Tse [29] proposed a fundamental performance measure— namely, diversity-multiplexing tradeoff (DMT), which sufficiently addresses the interplay between these two gains in the high-SNR regime. Note that the DMT originally proposed by Zheng and Tse is an asymptotic result computed as the SNR approaches infinity. To bridge this gap, the DMT framework has been extended to non-asymptotic finite SNRs by Narasimhan [54]. Because of these considerations, we have chosen DMT as a suitable metric to evaluate the proposed RF-EH-based relay-assisted systems.

1.4.1 Objectives

The primary focus of this work is to elucidate the benefits of adding EH-based relay(s) to the traditional wireless networks using the system models detailed in Section 1.3. For this purpose, DMT has been chosen as a performance metric, owing to its merit of capturing both multiplexing gain and diversity gain in a single curve. In summary, the objectives of this thesis are as follows:

- Single-user (RF-EH-based) relay systems: Although some of these networks have been investigated in recent literature, there are some critical questions that have been left unanswered. Most of the state-of-the-art research in this area has focused either on outage-error probability or on the maximum-achievable throughput. Therefore, it is time to consider a tradeoff between these two performance figures. Moreover, EH-based relays rely exclusively on the harvested energy for their operation, so the impact of harvested energy on the overall performance needs to be quantified. In view of the practical design considerations of these systems, the system performance at finite SNRs must be investigated. Finally, the optimal placement of the relay nodes depends on the chosen relay strategy (decode-and-forward [DF], amplify-and-forward [AF]), and dynamic decode-and-forward [DDF]). Therefore, it is critical to

evaluate the system performance considering the relay position.

- Multiple access (RF-EH-based) relay system (MARS): Sharing one relay to assist multiple users in improving the overall performance of the system is a well-established theme. However, the RF-EH-based MARC systems are still in their relative infancy. Therefore, it is appropriate to investigate whether similar performance gains can also be achieved with RF-EH-based relaying. Similarly, the knowledge of CSI at the transmitter terminals (transmit-CSI) significantly improves the performance of traditional non-EH-based relay systems. It is vital to explore the impact of transmit-CSI on diversity performance for RF-EH-based relay systems.
- Interference limited (RF-EH-based) relay system: The deleterious consequences of interference and the solutions to counteract such effects have been thoroughly investigated for traditional non-EH-based systems in previous studies. Thus, it is equally important to perform such investigations under the purview of RF-EH-based relay networks.
- The media access control (MAC) layer tradeoffs between transmission delay and the expended energy have been well investigated for traditional battery-powered systems. Therefore, it is critical to explore such MAC layer scheduling issues for energy-harvesting-based networks.

1.5 Contributions

In this work, RF-EH-based relaying protocols are proposed to achieve higher throughput and better reliability. Subsequently, the performance of these systems is quantified either by closed-form expressions or through a semi-analytic study. To accomplish the aforementioned objectives, we have chosen DMT as a characteristic performance parameter. To that end, the main contributions are summarized as follows:

- The present research starts with investigating the DMT of RF

energy-harvesting-based relay channel using non-orthogonal amplify-and-forward (EH-NAF) and dynamic decode-and-forward (EH-DDF) protocols in single-antenna single EH-based-relay networks. As part of this study, first, the impact of RF-EH on the resultant channel behavior has been analyzed. Subsequently, the fraction of energy harvest duration (ϵ) has been identified as a critical factor, which captures the influence of RF-EH on DMT performance. As a result of this exercise, the following conclusions are drawn:

- The DMT performance of EH-NAF scheme approaches that of non-EH-based counterpart for smaller ϵ values.
- The EH-DDF protocol outperforms EH-NAF protocol for lower ϵ values.
- The diversity performance of EH-DDF protocol improves with the reduction of ϵ value. However, the performance difference between non-EH-based DDF and EH-DDF persists even for infinitesimal ϵ value.
- The EH-DDF establishes its supremacy among the proposed RF-EH-based relaying protocols.

Based on the abovementioned concluding remarks, EH-DDF protocol has been chosen as a candidate for all the subsequent studies in this thesis. Finally, for the sake of completeness, the DMT analysis of single-relay single-user networks has been extended for multiple EH-based relays.

- A multiple access relay system (MARS) with an RF-EH-based intermediate relay is proposed. For this system, two variants of EH-DDF protocols have been analyzed. First, the DMT has been derived for the system with no transmit CSI. As in the case of single-user systems, it is observed that the incorporation of RF-EH negatively affects the DMT. To remedy this performance difference, a limited feedback based EH-DDF protocol has been proposed. Finally, it is shown that the system with limited feedback

achieves substantially better diversity compared to the one without feedback information.

- An RF-EH-based relay-aided interference limited system where the intended user is affected by the interference has been considered. For this system, the closed-form solutions for DMTs of traditional non-EH-based DDF and RF-EH-based DDF protocols have been derived. It is shown that incorporating a relay improves the DMT of the interference-limited user. Moreover, it is also proven that the proposed RF-EH-based relay system performs almost as well as a non-EH-based counterpart. Finally, it is concluded that the diversity gain drops to zero in the higher multiplexing gain regime due to the dominant effect of interference.
- An extensive finite SNR-based DMT (f-DMT) analysis has been made for single-antenna single RF-EH-based relay networks. Consequently, closed-form expressions for f-DMT have been derived for EH-based AF and DF protocols. Next, the impact of the quantum of energy harvested on diversity performance has been investigated. As part of this study, the optimum energy-harvest duration for low-SNR, medium-SNR, and high-SNR regimes has been ascertained. Furthermore, the effect of relay location on achievable diversity gain has been thoroughly investigated. It has been shown that at higher SNRs, the finite-SNR DMT agrees with the asymptotic DMT. In contrast, at low SNRs, the finite-SNR DMT deviates from the asymptotic counterpart. Finally, it is concluded that the asymptotic DMT analysis has its relevance, even though it hides a few minor details.
- MAC layer scheduling aspects for deterministic energy and data-arrival scenarios have been investigated. First, a traditional battery-powered system is considered. For this model, in the presence of nonzero circuit overheads, the optimum critical power required to maximize the energy efficiency has been evaluated. Subsequently, critical power characterization

has been adapted to formulate optimum scheduling algorithms for EH-based systems.

1.6 Thesis Organization

The remainder of the thesis is organized as follows.

Chapter 2 provides a survey of the related literature in the areas of relay-based networks, RF-based energy harvesting, and various performance metrics used to evaluate wireless communication networks. Chapter 2 also discusses some of the limitations of existing research in relation to performance evaluation and reveals the rationale in choosing the DMT as a key performance metric for the considered RF-EH-based system models.

Chapter 3 considers a single user EH-based-relay network. The DMT analysis is presented for non-orthogonal amplify-and-forward (EH-NAF) and dynamic decode-and-forward protocols (EH-DDF). Furthermore, the EH-DDF protocol extension for the multiple EH-based relays is also investigated. Results of this chapter establish the superiority of EH-DDF protocol over other EH-based relaying protocols.

Chapter 4 deals with a multiple-access relay system in which the single EH-based-relay aids multiple source nodes in transmitting their data to the destination user. For such a system model, DMT is analyzed using EH-DDF protocol. Furthermore, to improve the diversity performance, EH-DDF protocol has been extended considering limited feedback.

Chapter 5 evaluates the DMT for the interference-limited (IL) user using EH-DDF protocol. It shows that the incorporation of an EH-based-relay significantly improves the diversity performance of an IL user.

Chapter 6 investigates the DMT in the finite SNR regime using EH-based AF and DF protocols. Using numerical studies, the practical design insights related to

optimum energy-harvesting intervals and the relay placement at various SNRs are also presented.

Chapter 7 focuses on the MAC layer scheduling aspects for deterministic energy and data-arrival scenarios. In addition, state-of-the-art scheduling algorithms are optimized for EH-based systems considering various processing costs.

Chapter 8 provides a summary of the contributions, promising directions of the future work, and conclusions. Finally, the appendices provide detailed mathematical proofs for the theoretical results presented in this thesis.

Chapter 2

Relay-Assisted Communications Systems with RF-Based Energy Harvesting: A Review

2.1 Introduction

The main focus of this work is the performance analysis of RF energy-harvesting (RF-EH)-based relay-assisted communications systems using diversity-multiplexing tradeoff (DMT) as a performance metric. The relevant aspects of this research— such as typical relay-assisted communication systems, state-of-the-art relaying protocols, traditional performance metrics, the role of DMT as a performance measure, wireless-energy-harvesting techniques, and RF-EH-based receiver architectures — are introduced in this chapter.

The rest of the chapter is organized as follows. Section 2.2 presents a brief description of a relay-assisted communication system and various state-of-the-art relaying protocols. Section 2.2 also reviews suitable performance metrics to evaluate the proposed systems, with a particular emphasis on DMT. Section 2.3 discusses wireless energy harvesting and practical receiver architectures for RF-EH-

based relays. Section 2.3 also presents a literature review on the relevant topics and provides the basis to pursue this work. Finally, section 2.4 concludes the chapter with a summary.

2.2 Relay-Assisted Communication Systems

A simple point-to-point (P2P) wireless communication system is composed of two terminals that wish to exchange their messages through a wireless radio link. However, signals transmitted through wireless media experience serious impairments, such as path loss, shadowing, and fading [55], which in turn leads to breaks in radio links. This problem can be addressed by deploying intermediate communication nodes whose only purpose is to relay the information between terminals. These intermediate nodes are called as relays, and the resultant system is referred to as a relay-assisted communication system.

Broadly, the relay-assisted communications system offers the following advantages:

1. Offer higher spatial diversity (and/or multiplexing gain), which in turn improves the overall system reliability (and/or capacity) [56].
2. Multiple relays can use the same radio resources, such as spectrum and time slots, thus improving the spectral efficiency [57].
3. Highly adaptable to network conditions (e.g., energy and bandwidth can be opportunistically allocated as per the channel conditions) [58].
4. Deploying relays (instead of expensive base stations) can be economical [59].

2.2.1 System Model

Figure 2.1 illustrates a classic relay-assisted communication system. In this model, a source ($\mathcal{S}$) transmits its information to a destination ($\mathcal{D}$) with the help of a relay ($\mathcal{T}$). A relaying protocol typically has two phases: the broadcast phase

Figure 2.1: System model for a single-relay-assisted communication

and the retransmission phase. Note that these two phases need not be orthogonal in time or frequency. In non-orthogonal strategies, there is an overlap in the broadcast and cooperative phases. Intuitively, non-orthogonal schemes offer better spectrum utilization compared to their orthogonal counterparts. However, this improved performance comes at the cost of interference and additional system complexity. Furthermore, the relay can operate either in half-duplex mode or in full-duplex mode. In the half-duplex (HD) mode of operation, the relay transmits and receives on orthogonal subchannels. On the other hand, in the full-duplex (FD) mode, the relay receives and transmits on the same subchannel. Ideally, full-duplex implementation supports higher throughput. However, in practice, self-interference (SI) that emanates out of full-duplex operation deteriorates signal-to-interference-plus-noise (SINR) ratio, resulting in performance degradation. Moreover, the FD system demands more hardware resources, such as separate antennas for transmission and reception, circuitry to suppress the SI, and so on [60]. The half-duplex (HD) network significantly simplifies the implementation at the cost of spectral efficiency.

From the diversity-multiplexing tradeoff (DMT) perspective, Azarian *et al.* [46] provided the analysis for a HD-based dynamic decode-and-forward (DDF) for a single relay channel. It is shown that the performance of HD-based DDF approaches that of an ideal full-duplex-based decode-and-forward protocol. This

fact motivated us to investigate the DMT performance of HD-based protocols.

In the considered half-duplex-based relay system, the relay ($\mathcal{T}$) receives the signal from the source ($\mathcal{S}$) during the first phase and retransmits the processed data toward the destination ($\mathcal{D}$) during the second phase. $x_{\mathcal{S}}$ and $x_{\mathcal{T}}$ are the transmitted signals from source and relay with power constraints $E(|x_{\mathcal{S}}|^2) = P_{\mathcal{S}}$, the average transmission power at the source and $E(|x_{\mathcal{T}}|^2) = P_{\mathcal{T}}$, the average transmission power at the relay. The quasi-static fading gains are denoted by $h_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2)$, where $\sigma_{ij}^2 = \left(\frac{d_{\mathcal{SD}}}{d_{ij}}\right)^n$ is the variance of h_{ij} , d_{ij} is the distance between the terminals i and j , and n is the path loss exponent. Using this notation, the signal received at the terminal j due to signal from the terminal i is given by

$$y_{ij} = h_{ij}x_i + z_j, \quad (2.1)$$

where $z_j \sim \mathcal{CN}(0, N_j)$ is the additive white Gaussian noise at the terminal j , N_j is the variance of additive white Gaussian noise (AWGN) at the terminal j , and $(i, j) \in \{\mathcal{S}, \mathcal{T}, \mathcal{D}\}$. Thus, the instantaneous signal-to-noise ratio (SNR) of the received signal at terminal j due to the signal from the terminal i is given as:

$$\gamma_{ij} = |h_{ij}|^2 \frac{P_i}{N_j} \quad (2.2)$$

In other words, the average SNR of the corresponding link $\bar{\gamma}_{ij}$ is equal to $\sigma_{ij}^2 \frac{P_i}{N_j}$.

2.2.2 Preliminaries

Relaying can be used to increase either the achievable data rate or improve the reliability of the system. Traditionally, these effects are captured by capacity and outage probability, respectively [55, 61].

2.2.2.1 Capacity

The well-known Shannon's formula gives the capacity of an AWGN channel:

$$C = \log(1 + \gamma), \quad (2.3)$$

where γ is the SNR at the receiver, and the units of capacity C are bits per channel uses (bpcu).

Ergodic Capacity

Typically, wireless channels exhibit fading. Interestingly, the Shannon capacity can still be used as a performance metric, provided the process of fading is stationary (and ergodic). However, the capacity of such a fading channel depends on the availability of CSI at various terminals. The capacity of a fading channel with CSI at the receiver is given by

$$C = \mathbb{E}[\log(1 + |h|^2\gamma)], \quad (2.4)$$

where $\mathbb{E}$ is the expectation operator, which is in respect to the fading distribution. Note that, to achieve this capacity, the code must be sufficiently long so that every possible fading state influences the received codeword.

Outage Capacity

In the case of quasi-static fading, where the instantaneous SNR is constant over the entire codeword, there is no guarantee for reliable communication. In other words, Shannon's capacity is often zero and thus cannot be used as a performance metric. In such scenarios, outage capacity is a more appropriate performance metric. As the name implies, the outage capacity is related to outage probability. The definitions of outage probability and the outage capacity are given below:

Definition 2.1. *Outage probability $p_{out}(R)$ is the probability that the system is in outage for given transmission rate R (in bit/s/Hz), and is given by:*

$$P_{out}(R) = Pr \{ \log(1 + |h|^2\gamma) \leq R \} \quad (2.5)$$

Therefore, from (2.5), we can observe that the outage probability decreases with increase in SNR γ for the given target data rate R . Alternatively, for a given SNR γ , the outage probability decreases with the decrease in R . With this brief

introduction on outage probability, we can now define the outage capacity.

Definition 2.2. *For a given outage probability v , the outage capacity at the receiver is given by*

$$C_v = \max\{R : P_{out}(R) \leq v\} \quad (2.6)$$

Therefore, in the quasi-static fading, the protocols designed to achieve outage capacity should concede for channel errors. For a comprehensive summary of outage probability, ergodic capacity, and outage capacity in fading channels, please refer to [55, 61].

2.2.2.2 Diversity Multiplexing Tradeoff (DMT)

Before introducing the DMT, it is vital to define the terms "diversity gain" and "multiplexing gain" [29].

Definition 2.3. *A system achieves diversity gain d , if*

$$P_E(\gamma) \sim \gamma^{-d} \quad (2.7)$$

In essence, the diversity gain d is the slope of a curve that plots the error probability as a function of SNR on a log-log scale.

Definition 2.4. *A system achieves spatial multiplexing gain r , if*

$$R(\gamma) = r \log \gamma \quad (2.8)$$

Note that the multiplexing gain can be viewed as the normalized channel capacity. Owing to the logarithmic behavior of the functions with respect to SNR, in the high-SNR regime, the curvature of P_E or the slope of the aforementioned log-log plot becomes constant. This behavior can be precisely captured by DMT as follows:

$$d \triangleq -\lim_{\gamma \rightarrow \infty} \frac{\log(P_E(\gamma))}{\log(\gamma)} \text{ and } r \triangleq \lim_{\gamma \rightarrow \infty} \frac{R(\gamma)}{\log(\gamma)}, \quad (2.9)$$

Finally, an additional essential definition that is relevant to the subsequent discussion in this thesis is given below:

Definition 2.5. A function $f(\gamma)$ is said to be exponentially equal to b , denoted by $f(\gamma) \doteq \gamma^b$, if

$$\lim_{\gamma \rightarrow \infty} \frac{\log f(\gamma)}{\log(\gamma)} = b \quad (2.10)$$

Similarly, the exponential inequalities are defined as $\stackrel{\cdot}{\geq}$ and $\stackrel{\cdot}{\leq}$.

2.2.3 Achievable Rate Region

Relaying protocols can be broadly classified into three categories: Amplify-and-forward (AF) [62], decode-and-forward (DF) [37], and compress-and-forward (CF) [63]. In AF, the relay simply amplifies and retransmits the signal without decoding. In DF schemes, the relay decodes (and re-encodes) the source's data before transmitting it to the destination. Finally, in CF, the relay compresses and forwards the observed signal to the destination, and the destination decodes the message by utilizing both the compressed relayed version and its own direct path signal. This work considers AF, DF, and dynamic DF (DDF) relaying schemes. The respective achievable rate regions are presented below.

2.2.3.1 Amplify-and-Forward (AF) Protocol

In the AF protocol, the relay amplifies the signal received during the first slot and retransmits it to the destination in the second slot. By using the earlier defined notations, the signal transmitted by the relay can be represented as $x_{\mathcal{T}} = ay_{S\mathcal{T}}$, in which $a = \sqrt{\frac{P_{\mathcal{T}}}{|h_{S\mathcal{T}}|^2 P_S + N_{\mathcal{T}}}}$ is the amplification factor. Destination adds the signals received from source and relay using the maximal ratio combiner. The achievable instantaneous rate for the AF protocol is

$$I_{AF} = \frac{1}{2} \log \left(1 + \gamma_{SD} + \frac{\gamma_{ST}\gamma_{TD}}{\gamma_{ST} + \gamma_{TD} + 1} \right) \quad (2.11)$$

In (2.11), the term $\frac{\gamma_{ST}\gamma_{TD}}{\gamma_{ST}+\gamma_{TD}+1}$ is due to the source-relay-destination channel. The expression I_{AF} is based on the assumption that the source uses independent and identically distributed (i.i.d) circularly symmetric Gaussian code books for the transmission. Factor $\frac{1}{2}$ is due to the half-duplex constraint. The AF protocol can achieve full diversity order, irrespective of the quality of the source-to-relay link.

2.2.3.2 Decode-and-Forward (DF) Protocol

In the DF protocol, the transmission from the source to the destination takes two time slots. In the first slot, the source transmits the signal and the relay operates in the receiving mode. During the second time slot, the relay decodes the signal from the source, re-encodes, and finally retransmits the message to the destination. The destination combines the signals from the source and relay using the maximal ratio combiner (MRC) [38]. Thus, the achievable instantaneous rate for the DF relay is given by

$$I_{DF} = \frac{1}{2} \min \{ \log(1 + \gamma_{ST}), \log(1 + \gamma_{SD} + \gamma_{TD}) \} \quad (2.12)$$

From (2.12), it is clear that if $\gamma_{ST} \leq \gamma_{SD} + \gamma_{TD}$, then diversity benefit due to the relay is lost. This is because the MRC detector at the destination ignores the impact of source-relay link. Hence, the DF protocol is useful only if the source-to-relay link is good. To address this deficiency, a variant of DF protocol is proposed to eliminate the error propagation from the relay [38].

2.2.3.3 Dynamic Decode-and-Forward (DDF) Protocol

The DF and the AF protocols are spectrally inefficient because the source and the relay takes two time slots to transmit one symbol. However, in the case of dynamic decode-and-forward(DDF) [46], the relay switches to the retransmission phase immediately after the successful decoding, thus finishing the transmission in a single time slot. Subsequently, the destination coherently combines the signals from the relay and the source thereby improves the spectral efficiency. Thus, the

instantaneous achievable-rate region for the DDF protocol is

$$I_{DDF} \leq f \log(1 + \gamma_{SD}) + (1 - f) \log(1 + \gamma_{SD} + \gamma_{TD}) \quad (2.13)$$

$$\text{where } f \triangleq \min \left\{ 1, \frac{R}{\log(1 + \gamma_{ST})} \right\} \quad (2.14)$$

In (2.14), f indicates the fraction of the time the relay listens to the source. The term $\log(1 + \gamma_{SD})$ indicates the achievable rate during the relay reception phase. The term $\log(1 + \gamma_{SD} + \gamma_{TD})$ indicates the achievable rate during the relay transmission phase. The destination detects the signal from the direct link alone during the relay-reception phase. However, it uses a joint decoder (JD) to detect the signals from both the source and the relay during the relay-retransmission phase.

2.3 Relaying Protocols for Wireless Energy

Harvesting

This section introduces the concept of wireless power transfer (WPT), details various WPT-receiver implementations to harvest the energy, and finally presents a review of the prior research on both traditional non-EH- and RF-EH-based relaying.

2.3.1 Wireless Power Transfer

The idea of wireless power transfer (WPT) has existed since the inception of electricity. Nikola Tesla conducted experiments using a radio frequency resonant transformer to transfer power over short distances without connecting wires in the early 20th century [64]. Since Tesla's work, several methods of WPT — such as near-field magnetic resonance, inductive coupling, laser-based transmission, and far-field RF energy transmission — have been introduced. However, serious efforts to realize practical systems based on WPT have not gained momentum until recently. There has been a recent surge in the use of electronic devices (laptops,

mobile phones, robots, and so forth), owing to the rapid advances in semiconductor and wireless communication technologies. Consequently, WPT has gained renewed prominence in the past two decades. Wireless charging can be achieved by near-field techniques such as inductive coupling [65] and magnetic resonance [66]. The research into these techniques has become a dominant topic over the past two decades. As a result of these efforts, a wireless power consortium (WPC) with over 650 members has adopted a “Qi” wireless charging standard for portable electronic devices [67]. However, such near-field techniques are not amenable to power remote devices. In contrast, RF-based EH is a far-field technology to transfer wireless energy over long distances. In RF-EH, radio signals, which typically carry information in the form of electromagnetic radiation, transport the energy as well.

2.3.2 Wireless Information and Power Transfer

Wireless information and power transfer based on RF-EH can be broadly divided into two categories. The first approach is based on the simultaneous wireless information and power transfer (SWIPT), where the receiver can decode the data as well as harvest the energy at the same time [68, 69]. However, implementing a pure SWIPT receiver poses practical constraints. Notably, the process of EH in the RF receiver chain destroys the information contained in the received waveform [70]. To overcome this limitation, Zhou et al. [70] proposed two receiver architectures based on time switching (TS) and power splitting (PS), respectively, to support both energy harvesting and signal detection using multiplexing techniques.

As shown in Figure 2.2(a), in a TS-based architecture, the receiver switches between energy harvesting (EH) and information decoding (ID) in time division multiplexing, whereas in PS-based design (as the name implies), the received signal power is split into two independent streams to facilitate both EH and ID (refer to Figure 2.2(b)). Thus, different tradeoffs can be assessed based on the fraction

Figure 2.2: Practical receiver designs for facilitating both energy and information transfer [4]

Figure 2.3: Energy-harvesting-based relay node: Time switching

of allocated time and the proportion of allotted power for TS and PS receivers, respectively. Note that this work primarily focuses on TS-based techniques.

With this brief background on WPT, we now introduce RF-EH-based relaying, which constitutes the basis of our work. Note that the terms RF-EH, WEH, and EH are used interchangeably in this work.

2.3.3 RF-EH-Based Relaying: Prior Work and Motivation

The fundamental difference between traditional relay-assisted systems and RF-EH-based counterparts lies in the method to power the intermediate relays. Therefore, the system model depicted in the earlier section applies to RF-EH-based systems as well (refer to Figure 2.1), albeit with a caveat, as mentioned earlier. In the RF-EH-based relay system, as illustrated in Figure 2.3, the relay operates in three modes using time switching [71, 72]: energy harvesting, information decoding (or listening), and retransmission. The timing

Figure 2.4: Timing: EH-based relaying protocols

aspects of various wireless-energy-harvesting (WEH)-based relaying protocols are further elaborated in Figure 2.4. In all these protocols, the WEH-based relay harvests the energy using the source's RF transmission during the first l_h symbol-intervals. However, the decoding (or listening) and the relaying phases differ across the protocols. Moreover, in orthogonal relaying protocols, the source node remains silent during the relaying (or retransmission) phase. In the case of EH-based orthogonal decode-and-forward (EH-ODF) protocol, as depicted in Figure 2.4(a), relay decodes the source's data for l_d symbol-intervals and after successful decoding, the decoded data is retransmitted to the destination for the remaining symbol-intervals (l_t). On the other hand, in EH-based orthogonal

amplify-and-forward (EH-OAF) protocol, relay listens to the transmission for l_d symbol-intervals, and the information is amplified and forwarded to the destination during the rest of the symbol intervals (l_t) (as in Figure 2.4(a)). In the case of non-orthogonal protocols, such as EH-based dynamic decode-and-forward (EH-DDF) and EH-based non-orthogonal amplify-and-forward (EH-NAF) protocols, the source node transmits the data for the entire codeword duration. The time-sharing details of EH-NAF and EH-DDF are shown in Figure 2.4(b) and 2.4(c), respectively. Note that in the case of EH-DDF, the relay switches to the retransmission phase immediately after the successful decoding, which is in contrast with the fixed protocols discussed earlier. In this protocol, the decoding and the forwarding intervals depend on the channel quality — or, in other words, the durations l_d and l_t respond dynamically to the channel conditions. In all these protocols, the harvest duration l_h is a fixed design parameter. Therefore, the harvested energy $E_{\mathcal{T}}$ at the relay $\mathcal{T}$ is given by

$$E_{\mathcal{T}} = \eta l_h |h|^2 P_S, \quad (2.15)$$

where $0 \leq \eta \leq 1$ is the RF-to-DC conversion efficiency [3], and P_S is the transmit power at $\mathcal{S}$.

In the following sections, past works on single-relay channels, multiple-relay-based channels, multiple-access relay channels, and interference-limited channels are presented.

2.3.3.1 Single-Relay System

As the name implies, a single-relay-based system consists of one relay (apart from source and destination nodes). Figure 1.3(a) illustrates such a system. The practical-receiver structures described in subsection 2.3.2 have been adopted for a single-relay-based system by Nasir *et al.* in their work [73]. Specifically, the authors considered WEH-based amplify-and-forward protocol in both delay-limited and non-delay-limited paradigms, and the system performance is characterized

by outage probability and ergodic capacity. Moreover, the optimal values of the energy-harvesting interval and the power-splitting ratio have been obtained for TS- and PS-based relaying schemes. Finally, using system throughput as a performance metric, the supremacy of TS-based relaying has been established for the low-SNR regimes. As a consequence, the authors proposed an adaptive TS relaying, in which the energy-harvest duration at the relay is optimized as per the source-to-relay channel quality [74]. For such a system, the analytical expressions for the achievable throughput have been obtained. Subsequently, the TS- and PS-based relaying schemes have been extended to DF protocol [71]. Notably, all these systems require full channel state information (CSI).

Li *et al.* [75] examined the benefit of adding an RF-EH-based AF relay to a point-to-point system concerning outage behavior in a quasi-static fading scenario. Unlike the traditional battery-powered system, the relay node may run out of energy at a certain exhaust probability. For this system, the closed-form expression for outage probability has been obtained as a function of energy-exhaust probability at the relay node. Based on the evaluation of results, it is concluded that for a smaller energy-exhaust probability, adding an RF-EH-based relay improves the system outage performance. Gu and Aissa studied [52] a single-relay-assisted system where the RF-EH-based relay harvests energy both from the received information signal and interference. The performances of TS- and PS-relaying protocols have been compared at various SNRs using outage capacity and ergodic capacity as performance measures. It is shown that at high SNRs, the PS scheme offers superior performance. In contrast, at low SNRs, the TS protocol outperforms PS protocol.

Krikidis *et al.* [76] proposed a low-complexity antenna-switching scheme to improve the outage performance in MIMO DF-relay channels. By using the principles of generalized selection combining (GSC), the proposed scheme employs a dynamic antenna switching between energy harvesting and information

decoding. The GSC-based antenna-switching policy allocates a set of the most robust paths for data decoding and the rest of the paths for energy harvesting. The optimal number of paths and the corresponding allocation strategy to minimize the outage probability has been investigated. Furthermore, the closed-form expression for outage probability has been derived for different configurations. An EH-based AF (EH-AF) protocol, in which the source also harvests energy from the relay apart from the energy-harvesting relay, was proposed by Chen et al. [77]. For the proposed EH-AF protocol, the authors derived a closed-form approximation for the average throughput in Rayleigh fading. Recently, the throughput performance of a two-hop network with battery-assisted TS-based EH relay using DF protocol was studied [78]. Furthermore, Di *et al.* [79] considered three different versions of wireless information and power transfer (WIPT) protocols for EH-based relay-assisted channel and proved that the incorporation of rateless codes [80] enhances the overall system performance. In their work, the authors also concluded that the protocols that consider the direct link from the source to the destination offers superior performance compared to the traditional dual-hop networks.

2.3.3.2 Multiple-Relays-Based System

As depicted in Figure 1.3(b), a natural extension of a single EH-relay-assisted network is a system with multiple relays. There are several studies related to multiple relay-based networks under the purview of traditional non-EH-based relay systems. It was first studied in work by Aref [81]. By using the cutset bound, the author developed binning policies that potentially achieve the capacity for deterministic broadcast-relay networks. Building up on [81], Gupta and Kumar [82] applied irregular encoding and successive decoding techniques. In [83], authors applied conventional encoding and sliding-window based decoding techniques. On the other hand, regular encoding and backward decoding are proposed in [84].

Even though the achievable rates of both the conventional encoding techniques are the same, the decoding delay of the sliding window technique is much lower than that of the backward decoding technique. A repetition-based DF protocol is proposed by Laneman [85] for multiple relays, and the performance is analyzed for fading relay channels. Though the repetition-based protocol provides full diversity, it has poor spectral efficiency. In repetition-based DF protocols, spectral efficiency becomes worse with the increase in the number of relays. To address this, a distributed space-time coding protocol to improve spectral efficiency while retaining the diversity order has been developed [37]. This protocol is later studied extensively in a number of works [38, 85–90]. Different from the above literature, Azarian *et al.* [46] proposed a DDF protocol for a multiple-relay-based network. In their work, the investigation of results manifested an improvement in diversity gain with the increase in the number of relay nodes at high SNRs.

From the EH-based-relay-network perspective, Atapattu *et al.* [91] derived closed-form expressions for outage probability and throughput, considering the Rayleigh fading and Gaussian for the first- and second-hop channels, respectively. Moreover, an approximation has been proposed for the optimal EH interval considering throughput as a performance metric. Subsequent studies have investigated relay-selection methodology for a two-relay network with separate information and energy receivers [92]. Notably, the results confirmed that there is a divergence between an optimal relay for information transmission and the strongest channel for energy harvesting. Consequently, a relay-selection tradeoff has been identified by leveraging the efficiency of information and energy transfer [92]. The authors in [93] considered a PS relaying in randomly distributed large-scale networks with strict QoS and RF-harvesting constraints. A noncooperative scheme and a relaying scheme regarding outage probability have been compared. Additionally, a random relay-selection policy has been proposed. For this system, a closed-form expression for outage probability has been derived

by using stochastic geometry. Note that all the aforementioned selection methods require global CSI.

2.3.3.3 Multiple Access Relay System (MARS)

As shown in Figure 1.3(c), a multiple access relay channel (MARC) can be viewed as a combination of multiple access channel (MAC) and a relay aiding multiple source users in communicating with the destination. A MARS-based system was first proposed by Kramer and Wijnngaarden [94]. Basing on the information theoretical principles related to single relay channel [36], the authors [94] derived capacity bounds for an AWGN MARC. Subsequent research has dealt with several capacity bounds employing various coding strategies [84, 95, 96]. However, the closed-form expression for the capacity of MARC has yet to be found. From the DMT perspective, Azarian *et al.* [97] studied the performance of DDF for MARS. It is shown that DDF achieves optimal diversity only in the low-multiplexing-gain regime for two-user MARS. Additionally, to improve the performance at high-multiplexing gains, DDF with automatic repeat-request (ARQ-DDF) has been proposed. It is proven that DDF with two ARQ rounds (ARQ-DDF) achieves optimality across all multiplexing gains. However, the constraint on ARQ rounds limits the usefulness of protocol in real-time latency-constrained applications. In the work of Abouelseoud and Nosratinia [98], it was shown that the compress-and-forward (CF) strategy achieves optimal diversity in the high-multiplexing-gain regime. On the contrary, CF suffers from significant performance degradation at lower multiplexing gains. Moreover, the CF scheme requires complex processing at the relay apart from the selection overhead involved in the opportunistic communication. In contrast to the works mentioned above which need complicated signal processing at the relay, Chen and Azarian [47] proposed a multiple-access amplify-forward (MAF) protocol, which substantially reduces the relay complexity while achieving the optimal DMT in

the high multiplexing regime. Thus, for the systems which operate at high SNRs, MAF offers an attractive architectural alternative to DDF and CF schemes.

The authors in [99] considered an EH-based MARS in which both the source nodes and the relay are powered by energy harvesting. Moreover, in this system, the nodes are allowed to transfer the energy to peers to improve the overall sum-rate. For this system, an algorithm to evaluate optimal joint-transmit power allocation to maximize the network sum-rate has been proposed. Subsequently, Rajaram *et al.* [100] considered an RF-EH-based MARS in which both source nodes and the relay are powered by WPT from a dedicated energy beam sent from the destination. In their work, the outage probability and the symbol-error rate have been derived for physical layer network coding (PLNC) and traditional network coding (NC) schemes by employing a variant of opportunistic energy harvesting (OEH). The performance of an OEH-based system is compared with a system that incorporates dynamic power splitting (DPS). It has been proven that the proposed OEH-based system outperforms the DPS-based system concerning symbol-error probability.

2.3.3.4 Relay-Assisted Interference-Limited System

The aggressive reuse of spectrum leads to inevitable interference at the intended receiver. In recent years, there has been a surge in interest in evaluating the merits of relaying in such scenarios. It is traditionally modeled as an interference channel with a relay (ICR), which is illustrated in Figure 1.3(d).

In [101], authors studied an interference channel in which a common relay aids two interfering source-destination pairs. For this system, the achievable rate region has been derived by using rate splitting at the sources [102] and also by employing DF as a relaying strategy. A simplified channel model in which the relay receives data from one source has been considered [103]. By using DF relaying at the relay and with joint decoding at the destination, an achievable-rate region has

been derived. It is shown that this region approaches that of the ICR-capacity region, even in the absence of rate splitting under certain channel conditions. A more sophisticated strategy that incorporates partial transmitter cooperation has been proposed for cognitive relay systems [104]. A capacity region has been determined under a strong-interference scenario. In [105], the authors have studied the sum-rate capacity using the full-duplex decode-and-forward relaying protocol. The finite-SNR performance was analyzed using the sum-rate capacity and the maximal generalized degrees-of-freedom [106, 107].

The EH-based relaying for ICR is still in the nascent state. In [108], authors investigated the performance of an EH-based ICR using AF-relaying protocol. By considering co-channel interference, analytical expressions for the outage probability, ergodic capacity, and diversity order have been derived. Moreover, the optimal power-splitting ratio, which minimizes the outage probability, has been characterized. The TS- and PS-based relaying strategies [73] have been adopted for Nakagami-m fading ICR [109]. The performance of EH-based AF protocol has been evaluated using the outage probability and the throughput as performance measures. Evaluation of numerical results showed that TS scheme is more sensitive to EH than the PS scheme.

Motivation

As detailed in this section, most of the existing literature related to EH-based relaying deals with either the maximum-achievable rate or the outage probability. Moreover, these studies invariably employ approximations in deriving the closed-form expressions for these metrics. In spite of the approximations used, the resultant analytical expressions involve complex functions such as Meijer-G and Bessel functions. Therefore, it is vital to investigate the interplay between these two fundamental metrics (maximum-achievable rate and outage probability). As described earlier, DMT is an excellent performance measure to

capture the divergence between the reliability and the data rate at high SNRs. In addition, by using the exponential order analysis [46], the DMT can be computed in closed-form even for more sophisticated wireless communication systems. These factors motivated us to investigate the performance of EH-based relay-assisted wireless communications systems using DMT.

2.4 Summary

In conclusion, we provide a summary along with the usefulness of the concepts presented in this chapter, for the progression of the thesis. This chapter begins with an introduction to the classical single-relay channel. By using this system model, the rate regions have been characterized for AF, DF, and DDF protocols. Subsequently, the definitions of performance metrics such as diversity gain, multiplexing gain, and diversity-multiplexing tradeoff (DMT), which are central to the analysis in this thesis, are presented. Next, a detailed survey of existing literature related to multiple relays, multiple-access relay, and relay-assisted interference systems has been presented. The relaying protocols presented in this chapter are investigated under the wireless energy harvesting (WEH) paradigm using DMT as a performance metric in chapters 3, 4, 5, and 6. Specifically, chapter 3 focuses on single relay-assisted and multiple relay-based systems. Chapter 4 investigates multiple-access relay system, chapter 5 presents a study on a relay-assisted interference-limited user, and finally, chapter 6 discusses the finite-SNR DMT.

Chapter 3

Single-User Relay Systems

3.1 Introduction

In this chapter, a single-user relay system — where N energy harvesting (EH)-based relays aid a source to transmit its message to the intended destination — has been considered. As described in chapter 2, non-orthogonal relaying protocols offer better diversity performance compared to their orthogonal counterparts. For this reason, this chapter focuses on two EH-based non-orthogonal relaying protocols: EH-based non-orthogonal amplify-and-forward (EH-NAF) protocol and EH-based dynamic decode-and-forward (EH-DDF) protocol.

In AF protocols, the relay simply amplifies and retransmits the signal without decoding. In contrast, in DF schemes, the relay decodes a source's data before transmitting it to the destination. Therefore, the complexity of DF relays is significantly higher compared to AF relays due to intrinsic signal-processing demands. Thus, in this chapter, the diversity-multiplexing tradeoff (DMT) analysis starts with a single-relay-based EH-NAF protocol. Subsequently, the study extends to EH-DDF protocol.

In the case of non-EH-based DDF relaying, the diversity gain improves with the increase in the number of relay nodes [46]. Inspired by this result, the DMT

study has been further extended to more generic N-relay-based EH-DDF protocol to investigate whether a similar improvement can be achieved even with EH-based relaying.

The main contributions of this chapter are summarized as follows:

- Derives closed-form expressions for DMTs of EH-based NAF and DDF protocols
- Shows that the performance of EH-NAF protocol approaches that of non-EH-based counterpart when the fraction of harvest duration is less than one-third of the total duration.
- Finds that the performance difference with reference to classical non-EH-based DDF cannot be eliminated by reducing the fraction of energy-harvesting duration.
- Shows that the diversity performance of EH-DDF improves with the increase in the number of relays.

The rest of the chapter is organized as follows. Section 3.2 presents the system model and the associated time-switching aspects of proposed EH-based protocols. Sections 3.3 and 3.4 investigate the achievable diversity gain for EH-NAF and EH-DDF protocols, respectively. Section 3.5 is devoted to the comparative study of proposed protocols. Finally, Section 3.6 concludes with the summary of the findings.

3.2 System Model

The proposed system model for a wireless network consisting of a source ($\mathcal{S}$), a destination ($\mathcal{D}$), and N EH-based relays is shown in Figure 3.1. The fading coefficients $\{g_i\}_{i=0}^N$ and $\{h_i\}_{i=1}^N$ are assumed to be independent and identically distributed complex Gaussian random variables with zero mean and unit variance. It is also assumed that the channel is quasi-static over the codeword interval, l .

 Figure 3.1: System model with N relay nodes

As detailed in Figure 2.3, all the relays are RF-EH-based with time-switching [71] among different modes of operation: energy harvesting (EH), information decoding/listening (ID/IL), and information retransmission (IR).

Time switching aspects of a single-relay ($N = 1$) based EH-NAF relaying is further illustrated in Figure 3.2. Relay harvests the energy during the first l_h

Figure 3.2: Operating modes: EH-NAF

symbol intervals, switches to information listening phase for l_d symbol intervals, and finally the information is forwarded to the destination for the rest of the symbol intervals (l_t). Note that the relay operates in half-duplex mode (i.e., it cannot receive and transmit simultaneously). Thus, the harvested energy E_i at the relay $\mathcal{T}_i$, $i \in \{1, \dots, N\}$, is given by

$$E_i = \eta l_h |h_i|^2 P_S, \quad (3.1)$$

where $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency [3] and P_S is the average transmission power at $\mathcal{S}$.

3.3 EH-NAF: Achievable DMT

In non-orthogonal protocols, the source node $\mathcal{S}$ transmits its message during the entire codeword duration at a rate of R BPCU. In the proposed EH-NAF protocol, the decoding and retransmitting intervals are considered to be equal. Therefore, as detailed in Figure 3.2, for $(l - l_h)/2$ symbol intervals, the relay listens to the source transmission, and for the rest of $(l - l_h)/2$ symbol intervals, it transmits the scaled version of the source-to-relay signal to the destination using all the harvested energy. Thus, using (3.1), the transmission power of the relay P_1 is given by

$$P_1 = \frac{E_1}{l_t} = \frac{2\eta l_h |h_1|^2 P_S}{l - l_h} \quad (3.2)$$

Remark 3.1. *In this work, as in several prior works [70, 73, 110], the power consumed by the transceiver circuitry at the relay is ignored.*

We denote the relay repetition gain by b and the information symbols during harvesting phase, listening phase, and the retransmission phase by x_h , x_1 , and x_2 respectively. By using this notation, the signals received at the destination can be written as:

$$y_h = g_0 x_h + n_{d,h} \quad (3.3)$$

$$y_1 = g_0 x_1 + n_{d,1} \quad (3.4)$$

$$y_2 = g_0 x_2 + b g_1 (h_1 x_1 + n_{t,1}) + n_{d,2} \quad (3.5)$$

where $n_{d,h}$, $n_{d,1}$, and $n_{d,2}$ are the noise observed by the destination during the harvest phase, the transmission phase, and the relaying phase, respectively. Additionally, $n_{t,1}$ is the noise observed by the relay. The repetition gain b is constrained by the quantum of energy harvested during l_h symbol intervals, thus

using (3.2)

$$b \leq \sqrt{\frac{2\eta l_h |h_1|^2 P_S}{(l - l_h)(|h_1|^2 \mathbb{E}[|x_1|^2] + \mathbb{E}[|n_{t,1}|^2])}} \quad (3.6)$$

$$\approx \sqrt{\frac{2\eta l_h}{l - l_h}}. \quad (3.7)$$

The high SNR equivalent of the constraint on b is given by (3.7). The exponential order of b is equal to zero, because (3.7) exclusively consists of scaling factors with no SNR-related terms [46]. Hence, the EH-NAF is equivalent to NAF [46] with the cooperation interval equal to $(l - l_h)/2$. Therefore, the pairwise error probability (PEP), P_{PE} , for the proposed EH-NAF system is upper-bounded by

$$P_{PE|g_0, g_1, h_1} \leq \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2}\right]^{-l_h} \cdot \det\left(I_2 + \frac{1}{2}\Sigma_s \Sigma_n^{-1}\right)^{-(l-l_h)/2}, \quad (3.8)$$

where Σ_s and Σ_n are the covariance matrices of message and noise components at the destination:

$$\Sigma_s = \begin{bmatrix} |g_0|^2 & g_0 g_1^* b^* h_1^* \\ g_0^* g_1 b h_1 & |g_0|^2 + |g_1|^2 |b h_1|^2 \end{bmatrix} E \quad (3.9)$$

$$\Sigma_n = \begin{bmatrix} \sigma_D^2 & 0 \\ 0 & \sigma_D^2 + |g_1|^2 |b|^2 \sigma_T^2 \end{bmatrix} \quad (3.10)$$

The noise term, $|g_1|^2 |b|^2 \sigma_T^2$, in (3.10) can be ignored in the asymptotic DMT analysis because it can be written as a nonpositive power of SNR (γ). By using (3.9) and (3.10), (3.8) can be rewritten as

$$P_{PE|g_0, g_1, h_1} \leq [1 + |g_0|^2 \gamma]^{-l_h} \cdot [1 + |g_0|^2 \gamma + (|g_0|^2 + |g_1|^2 |h_1|^2 |b|^2) \gamma + |g_0|^4 \gamma^2]^{-(l-l_h)/2} \quad (3.11)$$

Note that the scaling factors of SNR do not contribute towards the eventual DMT, thus omitted in (3.11).

Defining v_0, v_1 and u_1 as the exponential orders [46] of $1/|g_0|^2$, $1/|g_1|^2$ and

$1/|h_1|^2$, respectively, the outage region O^+ for EH-NAF can be defined as

$$O^+ = \left\{ (v_0, v_1, u_1) \in \mathbb{R}^{3+} \mid \epsilon(1 - v_0)^+ + \frac{1 - \epsilon}{2} \max \{ (1 - (v_1 + u_1))^+, 2(1 - v_0)^+ \} < r \right\}, \quad (3.12)$$

where $\epsilon = l_h/l$ and $(x)^+ \triangleq \max\{0, x\}$. By denoting $v_1' = v_1 + u_1$, considering the case where $0 \leq v_0, v_1' \leq 1$, and by applying Laplace's integration method [29], the diversity gain can be evaluated as

$$d(r) = \inf_{(v_0, v_1')} v_0 + v_1' \quad (3.13a)$$

$$\text{s.t. } \epsilon(1 - v_0)^+ + \frac{1 - \epsilon}{2} \max \{ (1 - v_1')^+, 2(1 - v_0)^+ \} < r$$

$$0 \leq v_0, v_1' \leq 1 \quad (3.13b)$$

The DMT of EH-NAF protocol can be characterized by solving the above optimization problem. The following theorem describes the respective closed-form expression.

Theorem 3.1. *The diversity gain achieved by the EH-NAF protocol is characterized by:*

1. for $\epsilon \leq \frac{1}{3}$

$$d(r) = (1 - r)^+ + (1 - 2r)^+ \quad (3.14)$$

2. and for $\epsilon > \frac{1}{3}$,

$$d(r) = \begin{cases} 1 + \left(1 - \frac{2r}{1-\epsilon}\right)^+, & 0 \leq r \leq \frac{1-\epsilon}{2} \\ \left(1 - \frac{r-\frac{1-\epsilon}{2}}{\epsilon}\right)^+, & \frac{1-\epsilon}{2} < r \leq \frac{1}{2} \\ (1 - r) & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (3.15)$$

Proof: Please refer to Appendix A.1. ■

As evident from (3.14) and (3.15), for a fraction of energy-harvest duration less than one-third of the total duration, the achievable DMT with the EH-NAF protocol is

Figure 3.3: EH-based dynamic decode-and-forward protocol

same as that of non-EH-based NAF scheme [46]. However, for $\epsilon \geq 1/3$, performance degrades due to the reduced cooperative phase.

Remark 3.2. To maximize the diversity performance of EH-NAF protocol, listening and retransmit symbol intervals are assumed to be equal ($l_d = l_t = \frac{l-l_h}{2}$).

3.4 EH-DDF: Achievable DMT

In this section, the DMT of more generic (N-relays-based) EH-DDF protocol has been analyzed. Unlike the fixed-relaying schemes, in dynamic schemes such as EH-DDF, the decoding and retransmitting phases vary with the channel quality. This dynamic relaying mechanism is illustrated in Figure 3.3. In the considered EH-DDF protocol, as in EH-NAF, $\mathcal{S}$ transmits data at a rate of R bits per channel use (BPCU) during every codeword. All the relays, $\{\mathcal{T}_p\}_{p=1}^N$, harvest the energy during the first l_h symbol intervals. The number of symbol intervals that the relay $\mathcal{T}_p$, $p \in \{1, \dots, N\}$ also must wait until it receives enough mutual information, lR , to decode the source message, given by

$$\sum_{j=0}^{p-1} l_j = \min \left\{ l - l_h, \left\lceil \frac{lR}{\log(1 + |h_p|^2 \frac{P_S}{\sigma_p^2})} \right\rceil \right\} \quad (3.16)$$

where $\lceil \cdot \rceil$ is the ceiling function, l_j is the number of symbol intervals in the codeword during which j relays are retransmitting the source message, and σ_p^2 denote the noise variance at the relay $\mathcal{T}_p$, $p \in \{1, \dots, N\}$. After the decoding phase, the relay $\mathcal{T}_p$ forwards the source's information during the remaining symbol intervals using all the harvested energy E_p for retransmission. Thus, using (3.1), the transmission power at the relay p is given by

$$P_p = \frac{E_p}{l_t}, \quad \text{where} \quad l_t = l - \left(l_h + \sum_{j=0}^{p-1} l_j \right). \quad (3.17)$$

By following the analysis of Azarian *et al.* [46], the pairwise error probability for the EH-DDF-based multi-relay system shown in Figure 3.1 is upper-bounded by

$$P_{PE|g_j, h_j} \leq \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2} \right]^{-(l_h + l_0)} \cdot \prod_{j=1}^N \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2} + \left(\sum_{i=1}^j |g_i|^2 \frac{P_i}{2\sigma_D^2} \right) \right]^{-l_j} \quad (3.18)$$

Using (3.17), (3.18) can be written as

$$P_{PE|g_j, h_j} \leq \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2} \right]^{-(l_h + l_0)} \cdot \prod_{j=1}^N \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2} + \left(\sum_{i=1}^j \frac{l_h \eta |h_i|^2}{l - (l_h + \sum_{k=0}^{j-1} l_k)} |g_i|^2 \right) \frac{P_S}{2\sigma_D^2} \right]^{-l_j} \quad (3.19)$$

In the case of traditional DDF protocol, the RHS of (3.19) contains only the channel gains related to relay-to-destination link, $\{g_i\}_0^N$. However, in the case of EH-DDF, the channel to be considered is a product of $|h_i|^2$ and $|g_i|^2$. The resultant composite-channel behavior determines the achievable DMT of EH-DDF protocol. Defining v_j and u_j as the exponential orders [46] of $1/|g_j|^2$ and $1/|h_j|^2$, respectively, we have

$$P_{PE|v_j, u_j} \leq \gamma^{-(l_h + l_0)(1-v_0)^+ + \sum_{j=1}^N -l_j(1 - \min\{v_0, v_1 + u_1, \dots, v_j + u_j\})^+},$$

As one notices, the term related to energy-harvesting interval l_h in (3.19) appears as a scaling factor and hence disappears in the exponential-based asymptotic analysis.

Suppose that the source uses a Gaussian codebook with a rate $R = r \log(\gamma)$,

or equivalently, the total number of codewords equal to γ^{r^l} , then the conditional error probability, P_E can be derived as

$$P_{E|v_j, u_j} \leq \gamma^{-l \left[\frac{l_h + l_0}{l} (1 - v_0)^+ + \sum_{j=1}^N \frac{l_j}{l} (1 - \min\{v_0, v_1 + u_1, \dots, v_j + u_j\})^+ - r \right]}.$$

The above error event occurs if $\{v_i\}_{i=0}^N$ and $\{u_i\}_{i=1}^N$ satisfy the following constraint

$$\frac{l_h + l_0}{l} \min\{1, v_0\} + \sum_{j=1}^N \frac{l_j}{l} \min\{1, v_0, v_1 + u_1, \dots, v_j + u_j\} \geq 1 - r.$$

By employing Laplace's integration technique [29], diversity gain related to the above error event can be evaluated as

$$\begin{aligned} d(r) &= \inf_{(v_i, u_i, \{f_i\}_0^N)} v_0 + \sum_{i=1}^N (v_i + u_i) \\ \text{s.t. } &\epsilon(1 - v_0)^+ + \sum_{i=0}^N f_i (1 - \min\{v_0, v_1 + u_1, \dots, v_i + u_i\})^+ \leq r \\ &v_i \geq 0, \quad u_i = \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k} \right), \end{aligned} \quad (3.20)$$

where u_i is the exponential order equivalent of (3.16) and $f_i \triangleq l_i/l$. The solution to the optimization problem above gives the DMT for the proposed protocol, as shown in Theorem 3.2.

Theorem 3.2. *The diversity gain achieved by the EH-DDF protocol is characterized by:*

1. *for the single relay ($N = 1$)*

$$d(r) = \begin{cases} 2 - \frac{9r}{4} \left(\frac{1-\epsilon}{1-(3\epsilon/2)} \right), & 0 \leq r \leq \left(\frac{2}{3} - \frac{5\epsilon}{6} \right) \\ \frac{1-r}{r+\epsilon}, & \left(\frac{2}{3} - \frac{5\epsilon}{6} \right) < r < (1 - \epsilon) \\ 1 - r, & (1 - \epsilon) \leq r \leq 1 \end{cases} \quad (3.21)$$

2. and for multiple relays ($N > 1$),

$$d(r) = \begin{cases} \frac{2(1-r)}{1+\epsilon} + \left((N+1) - \frac{2}{1+\epsilon}\right) \left(1 - \frac{2r}{1-\epsilon}\right), & 0 \leq r \leq \left(\frac{1-\epsilon}{2}\right) \\ \frac{1-r}{r+\epsilon}, & \left(\frac{1-\epsilon}{2}\right) < r < (1-\epsilon) \\ 1-r, & (1-\epsilon) \leq r \leq 1 \end{cases} \quad (3.22)$$

Proof: Please refer to Appendix A.2. ■

The DMT of the DDF protocol characterized by [46, Theorem 6] uniformly dominates the considered EH-DDF protocol. It is intuitive because the relays in EH-DDF assist the source for a shorter duration compared to the case in DDF. However, as detailed in the subsequent section, the surprising revelation is that this performance difference cannot be removed by reducing the fraction of energy harvest duration (ϵ).

3.5 Numerical Results and Protocol Comparisons

In this section, the diversity performance of proposed EH-based protocols has been compared against the state-of-the-art benchmarking schemes. Moreover, the impact of the harvesting intervals and the effect of the number of relays on the achievable diversity gain is also investigated.

For comparison purposes, the diversity gain achieved by the non-EH-based NAF protocol ($d_{NAF}(r)$) [46], non-EH-based DDF and protocol ($d_{EH-DDF}(r)$) [72], and the DMT upper-bound ($d_{UB}(r)$) are given below:

$$d_{NAF}(r) = (1-r) + N(1-2r)^+ \quad (3.23)$$

$$d_{DDF}(r) = \begin{cases} (N+1)(1-r), & 0 \leq r \leq \frac{1}{N+1} \\ 1 + \frac{N(1-2r)}{1-r}, & \frac{1}{N+1} \leq r \leq \frac{1}{2} \\ \frac{1-r}{r}, & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (3.24)$$

$$d_{UB}(r) = (N + 1)(1 - r) \quad (3.25)$$

Figure 3.4: DMT for the EH-NAF protocol

3.5.1 Single-Relay-Based Protocols

Figure 3.4 depicts the DMT performance of EH-NAF scheme for different energy-harvest intervals. In this figure, the genie-aided strategy corresponds to the case in which the relay has access to exact transmitted information message and is also the upper bound (UB) on the achievable DMT for the non-EH system. As can be observed from the figure, the performance of EH-NAF protocol is the same as that of non-EH-based NAF for the harvesting fraction (ϵ) less than one-third of the total duration. However, for $\epsilon > 1/3$, the performance deteriorates with the increase in harvest duration. This seemingly counterintuitive result is due to the infinite SNR assumption in deriving the DMT. Hence, this result applies

Figure 3.5: DMT for the EH-DDF protocol with one relay

only to high-SNR scenarios. Based on this observation, we conjecture that the non-EH-based NAF achieves the maximum-possible diversity gain, even if the fraction of listening duration is between $1/3$ and $1/2$.

The DMT for the single-relay-based system is shown in Figure 3.5. There is a performance difference between EH-DDF and non-EH-DDF [46] protocols even for the infinitesimal harvest duration ($\epsilon \approx 0$). This result is due to the composite channel behavior of a proposed system. The performance of EH-DDF also deteriorates with an increase in ϵ because the relay could forward the source message for a shorter fraction of the codeword. As evident from the Figure 3.5, the DMT curve for $\epsilon \approx 0$ coincides with that of non-EH-based DDF for $r > 2/3$.

Remark 3.3. *The maximum-achievable diversity gain of single-relay-based EH-DDF protocol can be deduced by solving (3.21) for $\epsilon \rightarrow 0$. The resultant diversity*

Figure 3.6: DMT for EH-based protocols

gain is given by

$$d(r) = \begin{cases} 2 - \frac{9r}{4}, & 0 \leq r \leq \frac{2}{3} \\ \frac{1-r}{r}, & \frac{2}{3} < r < 1. \end{cases} \quad (3.26)$$

Figure 3.6 shows the performance of both EH-DDF and EH-NAF schemes. As can be observed from the figure, EH-DDF outperforms the EH-NAF protocol across all the multiplexing gains for lower energy-harvesting intervals. However, EH-NAF dominates over EH-DDF at higher ϵ . This result is consistent with intuition because, in the case of DDF, the relay needs to decode the data before it participates in the retransmission. Thus, the probability of decoding failure at the relay increases with the increase in ϵ . However, in the case of NAF, the listening and the retransmission intervals are equal. Hence, the effect of an increase of ϵ is ameliorated.

Figure 3.7: DMT for the EH-DDF protocol with $N=5$

Figure 3.8: DMT for the EH-DDF protocol with $N = 5, 10$, and 20

3.5.2 Multiple-Relays-Based EH-DDF Protocol

Figure 3.7 shows the DMT performance for $N = 5$. Similar observations related to the performance penalty can be made for this system as well. However, in this case, the threshold at which the performance meets the DDF protocol is at $r \approx 1/2$. Finally, Figure 3.8 illustrates the DMT for different values of N . In the case of non-EH DDF, there is no performance difference with respect to a genie-aided protocol for multiplexing gain (r) lower than $1/(N + 1)$; on the other hand, the DMT of EH-DDF protocol diverges from genie-aided strategy right from $r = 0$. This behavior is again due to the product channel resulted out of EH-DDF.

Remark 3.4. *The maximum achievable DMT of multiple relays-based EH-DDF can be deduced by solving (3.22) for $\epsilon \rightarrow 0$. The resultant diversity gain is given by*

$$d(r) = \begin{cases} 2(1 - r) + (N - 1)(1 - 2r), & 0 \leq r \leq \frac{1}{2} \\ \frac{1-r}{r}, & \frac{1}{2} < r \leq 1 \end{cases} \quad (3.27)$$

3.6 Conclusions

Table 3.1: Comparison: Single user relay systems

EH-based Relaying	Advantages	Drawbacks
EH-NAF	Better performance at higher ϵ , simpler and low cost	Inferior diversity performance
EH-DDF	Best in class diversity	Complex signal processing at the relay, synchronization between the nodes
Multiple-relays-based EH-DDF	Up to $(N+1)$ -fold diversity with N -relays	Synchronization among multiple nodes, CSI acquisition, loss in diversity in high rate regime

In this chapter, the diversity-multiplexing tradeoff (DMT) is analyzed for energy-harvesting-based non-orthogonal amplify-and-forward (EH-NAF) and

dynamic decode-and-forward (EH-DDF) protocols. Through the analysis, it is shown that the performance of EH-NAF approaches that of the non-EH-based counterpart for a fraction of energy-harvesting duration (ϵ) less than one-third of the total duration. However, its performance deteriorates with the increase in energy-harvest duration for $\epsilon > 1/3$.

In the case of EH-DDF, it is observed that the proposed method of incorporating the energy-harvesting mechanism radically changes the channel behavior and thus results in inferior performance. It is shown that the performance of EH-DDF protocol improves with the reduction in the proportion of energy-harvesting interval. Subsequently, it is concluded that the performance difference between non-EH-based DDF and EH-DDF exists, even for infinitesimal harvest duration. It is also shown that the EH-DDF outperforms EH-NAF for lower ϵ ; however, it under-performs EH-NAF at higher ϵ . It is demonstrated that the diversity performance of EH-DDF protocol improves with the addition of more EH-based relays. However, it is observed that for the systems which operate at higher transmission rates, multiple relays based DDF protocol degenerates into a single relay based scheme. Finally, a comparison of considered relaying protocols is given in Table 3.1.

Chapter 4

Multiple Access Relay Systems

4.1 Introduction

In chapter 3, we investigated a single-user communication system, in which one or more energy-harvesting (EH)-based relays aid the transmission between the source and the destination. This chapter extends the discussion to multiuser systems. Specifically, the diversity-multiplexing tradeoff (DMT) of EH-based dynamic decode-and-forward (EH-DDF) protocol for multiple access relay system (MARS) is studied.

As detailed in chapter 2, for traditional non-EH-based systems, significant gains can be achieved by sharing a single relay among multiple source nodes in slow-fading environments. Inspired by these results, we investigate whether a similar performance can be achieved even with EH-based relaying. From the DMT perspective, Azarian et al. proposed a non-EH-based dynamic decode-and-forward (DDF) protocol [97] for a MARS. The authors showed that the DDF achieves optimal DMT at low multiplexing gains. Moreover, in chapter 3, the supremacy of EH-DDF over other relaying protocols has been established.

For this reason, in this chapter, EH-DDF has been chosen as a candidate to elucidate the benefits of adding a single EH-based relay to the traditional multiple

access channel (MAC). Moreover, as in chapter 3, the effect of varying the energy-harvest duration on the DMT has also been investigated. It is known that the knowledge of channel state information (CSI) at the transmitting nodes aids in achieving optimal performance. For this reason, this chapter also proposes an EH-DDF protocol based on limited feedback (EH-DDF-LF) to improve the diversity gain, especially at the higher multiplexing gains.

In this context, this chapter comprehensively deals with two variants of EH-based DDF protocols: EH-DDF and EH-DDF-LF. The main contributions of this work are given below:

- Presents a semi-analytic study of a MARS with EH-based relay and obtains performance curves for the DMT for two variants of DDF protocol: EH-DDF and EH-DDF-LF.
- Through extensive analytical studies, it is shown that the performance of EH-DDF protocol is inferior to that of non-EH-based DDF. However, it is proven that the performance of EH-DDF-LF is same as that of non-EH-based DDF in a high multiplexing-gain regime.
- Through a detailed analysis of DMT, it is proven that the EH-DDF-LF protocol achieves better diversity gain than that of EH-DDF across all possible energy-harvesting durations.

The rest of the chapter is organized as follows. Section 4.2 discusses the details of the proposed system model. Sections 4.3 and 4.4 detail the semi-analytic study of the DMT for the EH-DDF and EH-DDF-LF, respectively. Furthermore, these sections also discuss the impact of harvesting intervals on the achievable diversity gain for the proposed protocols. Section 4.5 presents the comparative study of proposed protocols. Section 4.6 provides a discussion on the analytical results. Finally, section 4.7 concludes the chapter.

4.2 System Model

Figure 4.1 shows the system model of the wireless relay network under consideration. It consists of two source nodes ($\mathcal{S}_1, \mathcal{S}_2$), an EH-based relay node ($\mathcal{T}$), and a single destination ($\mathcal{D}$) node. The fading coefficients $\{g_1, g_2, g_t\}$ and $\{h_1, h_2\}$ are assumed to be quasi-static over the codeword length l . As detailed in Figure 2.3, relay $\mathcal{T}$ relies on time-sharing-based EH mechanism to harvest the energy from the source's transmission. The timing aspects of EH-DDF-based relaying for MARS is further illustrated in Figure 4.2. The resultant harvested energy E_T at relay $\mathcal{T}$ is given by

$$E_T = \eta l_h (|h_1|^2 + |h_2|^2) P_S, \quad (4.1)$$

where $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency [3], l_h is the harvest duration, and P_S is the average transmission power at sources $\mathcal{S}_1$ and $\mathcal{S}_2$.

Figure 4.1: Multiple access relay system (MARS): System model with EH-based relay node

In the considered system, both the sources transmit data at a rate of $R_1 = R_2 = R/2$ bits per channel use (BPCU) during every codeword. In contrast to single user systems, the DDF relay in MARS needs to decode information from both the users. Consequently, the listening interval at the relay not only depends on individual source-to-relay channel realizations but also on the rate requirements.

Figure 4.2: Illustration of time-switching for EH-based dynamic decode-and-forward (DDF) protocol

In view of this, the decoding interval is given by

$$l_d = \min \left\{ l - l_h, \max \left\{ \left\lceil \frac{lR}{2\log(1 + \min\{|h_1|^2, |h_2|^2\}\gamma_T)} \right\rceil, \left\lceil \frac{lR}{\log(1 + (|h_1|^2 + |h_2|^2)\gamma_T)} \right\rceil \right\} \right\}, \quad (4.2)$$

where $\lceil \cdot \rceil$ is the ceiling function, and $\gamma_T (= P_S/\sigma_T^2)$ denotes the signal-to-noise ratio (SNR) at the relay $\mathcal{T}$, and σ_T^2 is the variance of the noise observed at the relay. As shown in Figure 4.2, once the relay successfully decodes the data, it retransmits the re-encoded data to the destination using $l - l_h - l_d$ symbol intervals using the entire harvested energy E_T . Following (4.1), the relay transmit power P_T is given by

$$P_T = E_T/l_t, \quad \text{where } l_t = l - (l_h + l_d). \quad (4.3)$$

4.3 DMT of EH-DDF Protocol

Since, in MARS, multiple users transmit their respective messages to the common destination, there is a need to define diversity and multiplexing gains for each of the users. In this section, we introduce the DMT definitions specifically for MARS, present some results used for performance comparison, and finally characterize the DMT performance of the proposed EH-DDF relaying protocol.

4.3.1 Preliminaries

The asymptotic definitions of multiplexing gain (r_i) and diversity gain (d_i) of user i , $i \in \{1, 2\}$ in a MARS are given as follows [97]:

$$d_i \triangleq -\lim_{\gamma \rightarrow \infty} \frac{\log(P_E^i(\gamma))}{\log(\gamma)} \text{ and } r_i \triangleq \lim_{\gamma \rightarrow \infty} \frac{R_i(\gamma)}{\log(\gamma)}, \quad (4.4)$$

where $\gamma (= P_S/\sigma_D^2)$ is the SNR at the destination $\mathcal{D}$, σ_D^2 is the variance of the noise observed at the destination $\mathcal{D}$, $P_E^i(\gamma)$ is the error probability, and R_i is the target data rate for user i . In this work, for the analytical tractability, we assume the symmetric scenario (i.e., the multiplexing gains r_1 and r_2 are equal to $r/2$). Thus, the overall multiplexing gain is r and the overall diversity gain is $d \triangleq d_1 = d_2$.

For the comparison purposes, an upper bound on the achievable diversity gain (d_{UB}) along with that of the traditional non-EH-based DDF protocol (d_{DDF}) for the symmetric two-user MARS are provided below [97]:

$$d_{UB}(r) \leq \begin{cases} 2 - r, & 0 \leq r \leq \frac{1}{2} \\ 3(1 - r) & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (4.5)$$

$$d_{DDF}(r) \geq \begin{cases} 2 - r, & 0 \leq r \leq \frac{1}{2} \\ 3(1 - r), & \frac{1}{2} \leq r \leq \frac{2}{3} \\ 2\frac{1-r}{r} & \frac{2}{3} \leq r \leq 1 \end{cases} \quad (4.6)$$

The DMT for an EH-DDF protocol is analyzed as follows: both the relay $\mathcal{T}$ and the destination $\mathcal{D}$ uses the joint decoder (JD) to simultaneously detect the desired signals from both the sources $\mathcal{S}_1$ and $\mathcal{S}_2$ [111]. Thus, the achievable rate region of the proposed system using EH-DDF protocol is given by

$$\frac{R}{2} \leq f \log(1 + P_S|g_1|^2) + (1 - f) \log(1 + P_S|g_1|^2 + P_T|g_t|^2) \quad (4.7a)$$

$$\frac{R}{2} \leq f \log(1 + P_S|g_2|^2) + (1 - f) \log(1 + P_S|g_2|^2 + P_T|g_t|^2) \quad (4.7b)$$

$$R \leq f \log(1 + P_S(|g_1|^2 + |g_2|^2)) +$$

$$(1 - f) \log(1 + P_S(|g_1|^2 + |g_2|^2) + P_T|g_t|^2), \quad (4.7c)$$

where $f = f_1 + \epsilon$, $\epsilon = l_h/l$, $f_1 = l_d/l$, and R is the total data rate (in BPCU) at the destination. The inequalities in (4.7a), (4.7b), and (4.7c) represent the rate constraints related to the detection of messages from source $\mathcal{S}_1$, source $\mathcal{S}_2$, and the joint detection of messages from both the sources $\mathcal{S}_1$ and $\mathcal{S}_2$. The constraints in (4.7a) and (4.7b) are equivalent owing to the symmetry of the network, thus, the evaluation of outage due to (4.7a) suffices for the analysis.

At asymptotically high SNR, the probability of error is upper bounded by the outage probability, P_O [47]. As in [46], we partition the joint outage error event $\mathcal{E}$ into two types of error events $\mathcal{E}_1$ and $\mathcal{E}_2$, i.e.,

$$\mathcal{E} = \mathcal{E}_1 \cup \mathcal{E}_2, \quad (4.8)$$

where $\mathcal{E}_1$ denotes the outage event related to individual target rate ($R/2$) of S_i , $i \in \{1, 2\}$ and $\mathcal{E}_2$ denotes the outage event related to the target sum-rate (R). By applying the union bound to (4.8), the overall probability of outage $P_{\mathcal{E}}$ can be bounded as

$$P_{\mathcal{E}} \geq \max\{P_{\mathcal{E}_1}, P_{\mathcal{E}_2}\}, \quad (4.9)$$

where $P_{\mathcal{E}_1}$ and $P_{\mathcal{E}_2}$ are the outage probabilities corresponding to outage error events $\mathcal{E}_1$ and $\mathcal{E}_2$, respectively. Hence, the achievable diversity gain $d_O(r)$ can be written as

$$d_O(r) = \min\{d_{\mathcal{E}_1}, d_{\mathcal{E}_2}\}, \quad (4.10)$$

where $d_{\mathcal{E}_{1(2)}}$ is the diversity gain considering $P_{\mathcal{E}_{1(2)}}$ alone.

4.3.2 Diversity Gain Based on Individual Target Rate Constraint

We denote α and $(1 - \alpha)$ as the fraction of harvested energy allocated towards sending the source $\mathcal{S}_1$'s and $\mathcal{S}_2$'s data, respectively. Using this notation, and also by using (4.7a), the error probability for the EH-DDF based MARS for error event $\mathcal{E}_1$ is upper bounded by [97]

$$P_{\mathcal{E}_1|g_1, g_2, g_t, h_1, h_2} \leq \left[1 + |g_1|^2 \frac{P_S}{2\sigma_D^2}\right]^{-(l_h + l_d)} \cdot \left[1 + |g_1|^2 \frac{P_S}{2\sigma_D^2} + |g_t|^2 \frac{P_T}{2\sigma_D^2}\right]^{-(l - l_h - l_d)} \quad (4.11)$$

By using (4.3), it can be rewritten as

$$P_{\mathcal{E}_1|g_1, g_2, g_t, h_1, h_2} \leq \left[1 + |g_1|^2 \frac{P_S}{2\sigma_D^2}\right]^{-(l_h + l_d)} \cdot \left[1 + |g_1|^2 \frac{P_S}{2\sigma_D^2} + \left(\frac{\alpha l_h \eta (|h_1|^2 + |h_2|^2)}{(l - l_h - l_d)} |g_t|^2\right) \frac{P_S}{2\sigma_D^2}\right]^{-(l - l_h - l_d)} \quad (4.12)$$

Note that, owing to RF-EH at the relay, the channel transforms into a product of $\sum_{i=1}^2 |h_i|^2$ and $|g_t|^2$. This radical change in the channel behavior differentiates the EH-DDF from the non-EH-based DDF protocol.

Defining v_j and u_j as the exponential orders of $1/|g_j|^2$ and $1/|h_j|^2$, respectively, and also by denoting $P_{\mathcal{E}_1|v_1, v_2, v_t, u_1, u_2}$ as $P_{\hat{\mathcal{E}}_1}$, the following Lemma helps us to evaluate the high SNR equivalent of (4.12).

Lemma 4.1. *The exponential order equivalent of (4.12) is given by:*

$$P_{\hat{\mathcal{E}}_1} \dot{\leq} \gamma^{-(l_h + l_d)(1 - v_1)^+ - (l - l_h - l_d)(1 - \min\{v_1, v_t + u_1, v_t + u_2\})^+} \quad (4.13)$$

Proof: Using Definition 2.5, the exponential order for R.H.S of (4.12) can be computed as

$$\lim_{\gamma \rightarrow \infty} \frac{-(l_h + l_d) \log \left[1 + |g_1|^2 \frac{\gamma}{2}\right]}{\log(\gamma)}$$

$$- \frac{(l - l_h - l_d) \log \left[1 + |g_1|^2 \frac{\gamma}{2} + \left(\frac{\alpha l_h \eta}{l - l_h - l_d} \right) ((|h_1^2| + |h_2^2|) |g_t|^2) \frac{\gamma}{2} \right]}{\log(\gamma)} \quad (4.14)$$

$$= -(l_h + l_d) [\max\{0, (1 - v_1)\}] \\ - (l - l_h - l_d) [\max\{0, (1 - v_1), (1 - (v_t + u_1)), (1 - (v_t + u_2))\}] \quad (4.15)$$

$$= -(l_h + l_d)(1 - v_1)^+ - (l - l_h - l_d)(1 - \min\{v_1, v_t + u_1, v_t + u_2\})^+ \quad (4.16)$$

where $(x)^+ \triangleq \max\{0, x\}$. Finally, by using the Definition 2.5, we get (4.13). $\blacksquare$

Remark 4.1. As per Lemma 4.1, all the scaling factors including the terms related to energy-harvesting interval (l_h) and the fraction of power allocated to forward the data from source $\mathcal{S}_1$ (i.e., α), are subsumed in the high-SNR transition from (4.14) to (4.15).

Assuming that the source $\mathcal{S}_1$ uses a Gaussian codebook to encode its message with a rate $\frac{r}{2} \log(\gamma)$ into a codeword vector of length l , then the conditional error probability $P_{\mathcal{E}_1}$ can be derived as [29]

$$P_{\mathcal{E}_1} \leq \gamma^{-l \left[\frac{(l_h + l_d)}{l} (1 - v_1)^+ + \frac{l - l_h - l_d}{l} (1 - \min\{v_1, v_t + u_1, v_t + u_2\})^+ - \frac{r}{2} \right]}$$

Using the Laplace integration technique, the diversity gain ($d_{\mathcal{E}_1}$) related to the error event $\mathcal{E}_1$ can be evaluated as

$$d_{\mathcal{E}_1}(r) = \inf_{(v_1, v_2, v_t, u_1, u_2) \in O_{\{1\}}^+} \{v_1 + v_2 + v_t + u_1 + u_2\}, \quad (4.17)$$

where $\inf$ is the infimum and $O_{\{1\}}^+$ is the outage region related to the error event $\mathcal{E}_1$ and is given by

$$O_{\{1\}}^+ \triangleq \left\{ (v_1, v_2, v_t, u_1, u_2) \in \mathbb{R}^{5+} \mid \right. \\ \left. f(1 - v_1)^+ + (1 - f)(1 - \min\{v_1, v_t + u_1, v_t + u_2\})^+ \leq \frac{r}{2} \right\}, \quad (4.18)$$

and the value of $f_1 (= f - \epsilon)$ is derived from the high SNR equivalent of (4.2) and is given by

$$f_1 = \min \left\{ 1, \max \left\{ \frac{r}{2(1 - \max\{u_1, u_2\})^+}, \frac{r}{(1 - \min\{u_1, u_2\})^+} \right\} \right\} \quad (4.19)$$

The corresponding optimization problem to determine $d_{\mathcal{E}_1}(r)$ can be formally defined as:

$$\begin{aligned}
 (P_1) : & \inf (v_1 + v_2 + v_t + u_1 + u_2) \\
 \text{s.t.} & f(1 - v_1)^+ + (1 - f)(1 - \min\{v_1, v_t + u_1, v_t + u_2\})^+ \leq \frac{r}{2} \\
 & 0 \leq v_1, v_2, v_t, u_1, u_2 \leq 1 \\
 & f_1 = \max \left\{ \frac{r}{2(1 - \max\{u_1, u_2\})^+}, \frac{r}{(1 - \min\{u_1, u_2\})^+} \right\}
 \end{aligned} \tag{4.20}$$

By denoting $u_{\max} = \max\{u_1, u_2\}$ and $u_{\min} = \min\{u_1, u_2\}$, the optimization problem (P_1) can be rewritten as

$$\begin{aligned}
 & \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\
 \text{s.t.} & f(1 - v_1)^+ + (1 - f)(1 - \min\{v_1, v_t + u_{\min}\})^+ \leq \frac{r}{2} \\
 & 0 \leq v_1, v_2, v_t, u_{\max}, u_{\min} \leq 1 \\
 & f_1 = \max \left\{ \frac{r}{2(1 - u_{\max})^+}, \frac{r}{(1 - u_{\min})^+} \right\}
 \end{aligned} \tag{4.21}$$

The solution to the above optimization problem gives the DMT related to $\mathcal{E}_1$ and it can be solved by segmenting the constraint region into two parts based on the value of f_1 as detailed below:

Case 1 : $\frac{r}{2(1 - u_{\max})^+} \geq \frac{r}{(1 - u_{\min})^+}$

In this case,

$$\frac{1 + u_{\min}}{2} \leq u_{\max} \leq \left(1 - \frac{r}{2(1 - \epsilon)}\right) \tag{4.22}$$

Optimization problem to determine the diversity gain related to $\mathcal{E}_1$ ($d_{\mathcal{E}_1}(r)$) for this region can be written by substituting the value of f_1 in (4.21) as shown below:

$$\begin{aligned}
 d_{\mathcal{E}_1}(r) = & \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\
 \text{s.t.} & \left(\frac{r}{2(1 - u_{\max})^+} + \epsilon \right) (1 - v_1) \\
 & + \left(1 - \epsilon - \frac{r}{2(1 - u_{\max})} \right) (1 - (v_t + u_{\min})) \leq \frac{r}{2}
 \end{aligned} \tag{4.23}$$

$$\begin{aligned} \frac{1 + u_{\min}}{2} &\leq u_{\max} \leq \left(1 - \frac{r}{2(1 - \epsilon)}\right) \\ 0 &\leq v_1, (v_t + u_{\min}) \leq 1, \quad 0 \leq u_{\min} \leq \left(1 - \frac{r}{(1 - \epsilon)}\right) \end{aligned}$$

As can be observed from (4.23), the constraint is nonlinear. Thus, it cannot be solved by using conventional linear programming techniques. However, the optimum value can be found by exhaustively regressing through all the possible values of $u_{\max}$ and $u_{\min}$ for a given value of r .

Case 2 : $\frac{r}{2(1-u_{\max})^+} < \frac{r}{(1-u_{\min})^+}$

In this case,

$$(2u_{\max} - 1) \leq u_{\min} \leq \left(1 - \frac{r}{1 - \epsilon}\right) \quad (4.24)$$

Similar to the earlier case, the diversity gain related to $\mathcal{E}_1 (d_{\mathcal{E}_{12}}(r))$ for the second region can be written by substituting the value of f in (4.21) as shown below:

$$\begin{aligned} d_{\mathcal{E}_{12}}(r) &= \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\ \text{s.t. } &\left(\frac{r}{(1 - u_{\min})^+} + \epsilon\right) (1 - v_1) \\ &+ \left(1 - \epsilon - \frac{r}{1 - u_{\min}}\right) (1 - (v_t + u_{\min})) \leq \frac{r}{2} \\ &(2u_{\max} - 1) \leq u_{\min} \leq \left(1 - \frac{r}{(1 - \epsilon)}\right) \\ &0 \leq (v_t + u_{\min}) \leq 1, \quad 0 \leq u_{\max} \leq \left(1 - \frac{r}{2(1 - \epsilon)}\right) \end{aligned} \quad (4.25)$$

The infimum is found through exhaustive search owing to the non-linear constraint as in the earlier case.

Remark 4.2. *In practice, the exhaustive regression is computationally inefficient. However, the complexity in getting the optimum value has been substantially reduced by segmenting the optimization problem into two constraint regions (or search spaces) as shown in (4.23) and (4.25). Moreover, for a given $u_{\max}$ and $u_{\min}$, all the optimization problems defined in this research are reduced to simplified linear programming problems. Therefore, all these problems can be effectively solved by interior point methods in polynomial time. In particular, there is an*

Figure 4.3: EH-DDF: The impact of the fraction of energy harvest duration (ϵ) on DMT related to outage error event $\mathcal{E}_1$

interior point algorithm which solves (4.25) to any fixed precision n in $O(n^{3.5})$ time [112]. Most importantly, these computations are typically performed during the system design to evaluate the DMT. Thus, such calculations can be carried out offline.

The resultant diversity gain ($d_{\mathcal{E}_1}(r)$) considering the $\mathcal{E}_1$ error is given as:

$$d_{\mathcal{E}_1}(r) = \min\{d_{\mathcal{E}_{11}}(r), d_{\mathcal{E}_{12}}(r)\}, \quad \forall r \in [0, 1] \quad (4.26)$$

and the same is depicted in Figure 4.3. As shown in Figure 4.3, the diversity gain related to $\mathcal{E}_1$ deteriorates with the increase in the energy harvest duration. This result is primarily due to the dynamic forwarding feature of DDF protocol. In EH-DDF, the increase in harvest duration results in the decrease in the forwarding interval for DDF thus affects the diversity performance. Moreover, the effect of an increase in harvesting energy does not increase diversity performance in the case of

Figure 4.4: EH-DDF: The impact of the fraction of energy harvest duration (ϵ) on DMT related to outage error event $\mathcal{E}_2$

high-SNR-based asymptotic analysis. This effect can be observed in Lemma 4.1.

4.3.3 Diversity Gain Based on Sum-rate Constraint

The error probability related to the sum-rate ($\mathcal{E}_2$) can be characterized by

$$P_{\mathcal{E}_2|g_1, g_2, g_t, h_1, h_2} \leq \left[1 + \frac{1}{2}(|g_1|^2 + |g_2|^2) \frac{P_S}{2\sigma_D^2} \right]^{-(l_h + l_d)} \cdot \left[1 + \frac{1}{2}(|g_1|^2 + |g_2|^2) \frac{P_S}{2\sigma_D^2} + \frac{1}{2}|g_t|^2 \frac{P_T}{2\sigma_D^2} \right]^{-(l - l_h - l_d)} \quad (4.27)$$

By using (4.3) and exponential orders of $|g_1|^2$, $|g_2|^2$, and $|g_t|^2$, (4.27) can be written as,

$$P_{\mathcal{E}_2} \leq \gamma^{-(l_h - l_d)(1 - \min\{v_1, v_2\})^+ - (l - l_h - l_d)(1 - \min\{v_1, v_2, v_t + u_1, v_t + u_2\})^+} \quad (4.28)$$

Defining O_2^+ as

$$O_2^+ \triangleq \left\{ (v_1, v_2, v_t, u_1, u_2) \in \mathbb{R}^{5+} \mid f(1 - \min\{v_1, v_2\})^+ \right\}$$

Figure 4.5: DMT for the EH-DDF protocol

$$+ (1 - f)(1 - \min\{v_1, v_2, v_t + u_1, v_t + u_2\})^+ \leq r \} \quad (4.29)$$

Without losing the generality, we assume $v_1 \leq v_2$. Thus, the solution to the optimization problem defined below gives the DMT related to $\mathcal{E}_2$.

$$\begin{aligned} d_{\mathcal{E}_2}(r) &= \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\ \text{s.t. } & f(1 - v_1)^+ + (1 - f)(1 - \min\{v_1, v_t + u_{\min}\})^+ \leq r \\ & 0 \leq v_1, v_2, v_t, u_{\max}, u_{\min} \leq 1, \quad v_1 \leq v_2 \\ & f_1 = \max \left\{ \frac{r}{2(1 - u_{\max})^+}, \frac{r}{(1 - u_{\min})^+} \right\} \end{aligned} \quad (4.30)$$

As in the case of $\mathcal{E}_1$ related error event, owing to the inherent nonlinearity, (4.30) can be solved by the exhaustive search through all the possible values of $u_{\max}$ and $u_{\min}$ for a given value of r . The resultant diversity gain ($d_{\mathcal{E}_2}(r)$) is shown in Figure 4.4. The effect of ϵ on the diversity gain related to $\mathcal{E}_2$ is similar to that of diversity gain related to $\mathcal{E}_1$. Because the arguments related to energy harvest

duration are valid for $\mathcal{E}_2$ as well.

Finally, the DMT achieved by the EH-DDF protocol can be found by taking the minimum between $d_{\mathcal{E}_1}(r)$ and $d_{\mathcal{E}_2}(r)$ as shown below:

$$d_{EH-DDF}(r) = \min\{d_{\mathcal{E}_1}(r), d_{\mathcal{E}_2}(r)\}, \quad \forall r \in [0, 1] \quad (4.31)$$

Thus, by using (4.31) and the results in Figure 4.3 and Figure 4.4, the DMT achieved by the EH-DDF protocol can be derived. As shown in Figure 4.5, the DMT of non-EH-based DDF protocol [97, **Lemma 1**] uniformly dominates the considered EH-DDF protocol. It is intuitive because the relay in EH-DDF assists the sources for less duration compared to the case in traditional DDF. Moreover, for $r \geq 2/3$, the diversity performance deviates from the “Upper Bound” for non-EH-based DDF due to the reduction of retransmission phase. It can be noted that a similar trend can also be observed for EH-DDF.

In the subsequent section, limited-feedback-based EH-DDF protocol (EH-DDF-LF) is considered to reduce the performance gap on achievable DMT.

4.4 Limited-Feedback-Based EH-DDF Protocol (EH-DDF-LF)

In the preceding section, we considered EH-DDF protocol and investigated its DMT using semi-analytic study. In this realm of EH-based protocols, a new dimension that can be added to improve the over-all diversity gain is channel state information (CSI) feedback. In this section, we propose limited-feedback-based EH-DDF protocol (EH-DDF-LF) and derive its DMT. In this system model, it is assumed that the destination transmits feedback information using ACK/NACK flags to the relay. Moreover, our analysis does not include the energy overhead related to ACK/NACK feedback mechanism. Note that the omission of this penalty does not affect the resultant DMT because

the constant factors are subsumed in the high SNR based asymptotic analysis.

4.4.1 Protocol Description

The ACK/NACK based limited feedback is generated using the following steps:

1. First, source nodes $\mathcal{S}_1$ and $\mathcal{S}_2$ broadcast their respective pilot symbols to facilitate channel estimation
2. Using the received pilot packet, destination $\mathcal{D}$ estimates the channel gains g_1 and g_2 . If the estimated channel gain of the respective link is strong enough to meet the individual target rate $(R/2)$, the destination $\mathcal{D}$ sends *ACK*; otherwise, it returns a *NACK*.

As per the above mechanism, the proposed LF-based system operates in four distinct modes as shown in Table 4.1 and in Figure 4.6. In this figure, C_1 and C_2 represent the instantaneous channel capacities of $\mathcal{S}_1 - D$ and $\mathcal{S}_2 - D$ links, respectively, and are given as

$$C_i = \log(1 + |g_i|^2 \gamma), \quad i \in \{1, 2\}, \quad (4.32)$$

where γ is the operating SNR ($\triangleq P_S/\sigma_D^2$). In Table 4.1, the flags θ_1 and θ_2 represent the feedback information related to $\mathcal{S}_1$ and $\mathcal{S}_2$, respectively.

Table 4.1: Limited-feedback-based EH-DDF protocol: Operating modes

Mode	θ_1	θ_2	Remarks
M_1	ACK	ACK	Both the direct links are good
M_2	NACK	ACK	$\mathcal{S}_2 - D$ link is good
M_3	ACK	NACK	$\mathcal{S}_1 - D$ link is good
M_4	NACK	NACK	Both the direct links are in error

The channel estimates and the associated rate constraints are further described below:

Figure 4.6: Limited feedback: Operating modes based on the instantaneous channel capacities C_1 and C_2

- Mode M_1 : In this mode, the individual rate $(R/2)$ requirement is satisfied for both the users using the direct links alone, i.e.,

$$\log(1 + |g_1|^2 \gamma) \geq \frac{R}{2}, \quad \log(1 + |g_2|^2 \gamma) \geq \frac{R}{2} \quad (4.33)$$

In this mode, the relay $\mathcal{T}$ stays idle.

- Mode M_2 : In this mode, $\mathcal{D}$ can decode only $\mathcal{S}_2$'s data but not the $\mathcal{S}_1$'s data using the direct links, i.e.,

$$\log(1 + |g_1|^2 \gamma) < \frac{R}{2}, \quad \log(1 + |g_2|^2 \gamma) \geq \frac{R}{2}, \quad (4.34)$$

thus the relay $\mathcal{T}$ forwards the data of $\mathcal{S}_1$ alone.

- Mode M_3 : This mode is equivalent to mode M_2 with the roles of $\mathcal{S}_1$ and $\mathcal{S}_2$ reversed, and it also exhibits the same DMT due to symmetry. Hence, for brevity, the analysis of this mode has been omitted in this work.
- Mode M_4 : In this mode, destination $\mathcal{D}$ cannot decode data from both $\mathcal{S}_1$ and $\mathcal{S}_2$ using the direct links alone, i.e.,

$$\log(1 + |g_1|^2\gamma) < \frac{R}{2}, \quad \log(1 + |g_2|^2\gamma) < \frac{R}{2}, \quad (4.35)$$

and the relay $\mathcal{T}$ forwards the data of both $\mathcal{S}_1$ and $\mathcal{S}_2$.

The total outage probability for the considered system, P_O , can be expressed as the sum of four joint probabilities related to the each of the operating modes as given below

$$\begin{aligned} P_O &= P(O|M_1)P(M_1) + P(O|M_2)P(M_2) \\ &\quad + P(O|M_3)P(M_3) + P(O|M_4)P(M_4) \\ &= 2 P(O, M_2) + P(O, M_4) \quad (\because P(O|M_1) = 0), \end{aligned} \quad (4.36)$$

where the factor 2 appears due to the symmetry between mode M_2 and mode M_3 (i.e., $P(O, M_2) = P(O, M_3)$). Also, note that in mode M_1 , there is no outage. Hence, this mode is not considered for further analysis.

In the following subsection, we define the possible outage error events for operating modes $M_2(M_3)$ and M_4 . Note that the DMT based on mode M_3 (d_{O,M_3}) is equal to that of mode M_2 owing to the mode symmetry. Hence, the analysis related to mode M_3 has been omitted in the subsequent discussion.

4.4.2 Outage Error Events

As in the case of EH-DDF, the overall outage error event in each operating mode is partitioned into two events $\mathcal{E}_1$ and $\mathcal{E}_2$ related to individual target rate and the overall sum-rate, respectively. Thus, by applying the union bound, the

achievable diversity gain $d_{O,M_j}(r)$, $j \in \{2, 3, 4\}$ for operating mode M_j can be written as

$$d_{O,M_j}(r) = \min\{d_{O,M_{j1}}(r), d_{O,M_{j2}}(r)\} \quad (4.37)$$

Thus, the overall DMT for the EH-DDF-LF can be written as

$$d_{EH-DDF-LF}(r) = \min_{j \in \{2, 3, 4\}} \{d_{O,M_j}(r)\} \quad (4.38)$$

Achievable DMT based on the outage event definitions for these operating modes are discussed below:

4.4.2.1 Achievable DMT in Mode M_2

As shown in Figure 4.6(b), in operating mode M_2 , the direct link between the source $\mathcal{S}_2$ and the destination $\mathcal{D}$ is good. In other words, the direct link can satisfy the rate requirement regarding single-user outage for source $\mathcal{S}_2$. Therefore, the EH-based relay forwards the data from only source $\mathcal{S}_1$. The constraint set based on the definition of mode M_2 is given by (4.34). By using the Definition 2.5, the corresponding high-SNR (or exponential order) equivalents can be derived as follows:

$$\begin{aligned} \frac{\log(1 + |g_1|^2 \gamma)}{\log \gamma} < \frac{r}{2} &\Leftrightarrow (1 - v_1)^+ < \frac{r}{2} \\ v_1 &> \left(1 - \frac{r}{2}\right) \end{aligned} \quad (4.39a)$$

$$\begin{aligned} \frac{\log(1 + |g_2|^2 \gamma)}{\log \gamma} \geq \frac{r}{2} &\Leftrightarrow (1 - v_2)^+ \geq \frac{r}{2} \\ v_2 &\leq \left(1 - \frac{r}{2}\right) \end{aligned} \quad (4.39b)$$

These additional constraints are now part of the DMT optimization problems in operating mode M_2 . Therefore, the optimization problems (4.21) and (4.30) which are defined for a system without feedback needs to be reformulated for a system with limited feedback using the constraint set given in (4.39).

The rate region for this operating mode can be characterized by equations (4.7a) and (4.7c). Hence, the analysis for the evaluation of diversity gain $d_{O,M_{21}}$ related to error event $\mathcal{E}_1$ follows the approach described in the previous section. Moreover, in this mode, the relay $\mathcal{T}$ forwards only the $\mathcal{S}_1$'s data to the destination. By considering the joint detection [113] of the desired signal (corresponding to the source $\mathcal{S}_1$) and the interfering signal (corresponding to the source $\mathcal{S}_2$), the relay decoding interval l_d in mode M_2 is given by

$$l_d = \min \left\{ l - l_h, \max \left\{ \left\lceil \frac{lR}{2\log(1 + \min\{|h_1|^2, |h_2|^2\}\gamma_T)} \right\rceil, \left\lceil \frac{lR}{\log(1 + |h_1|^2)\gamma_T} \right\rceil \right\} \right\} \quad (4.40)$$

Note that the second and third terms in (4.40) are related to individual target rate of $R/2$ from the source $\mathcal{S}_1$ and the target sum-rate R , respectively. The corresponding high SNR equivalent is given by

$$f_1 = \min \left\{ 1, \max \left\{ \frac{r}{2(1 - u_1)^+}, \frac{r}{(1 - u_{\min})^+} \right\} \right\} \quad (4.41)$$

By using the earlier definitions of $u_{\max}$ and $u_{\min}$, the diversity gain ($d_{O,M_{21}}(r)$) related to $\mathcal{E}_1$ for operating mode M_2 can be determined by solving the following optimization problem:

$$\begin{aligned} d_{O,M_{21}}(r) &= \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\ \text{s.t } f(1 - v_1)^+ + (1 - f)(1 - (v_t + u_{\min}))^+ &\leq \frac{r}{2} \\ 0 \leq (v_t + u_{\min}) \leq 1, \quad \left(1 - \frac{r}{2}\right) \leq v_1 \leq 1 \\ v_1 \geq (v_t + u_{\min}), \quad 0 \leq v_2 \leq \left(1 - \frac{r}{2}\right) \\ f_1 &= \max \left\{ \frac{r}{2(1 - u_{\max})^+}, \frac{r}{(1 - u_{\min})^+} \right\} \end{aligned} \quad (4.42)$$

The analysis follows as in the previous section (ref. (4.21)), except that the optimization problem additionally embeds the constraints related to mode M_2 (ref. (4.39)). The solution to the above optimization problem gives the DMT based on $\mathcal{E}_1$ error event in mode M_2 . Figure 4.7 shows the achievable DMT and

Figure 4.7: Mode M_2 : The impact of the fraction of energy harvest duration (ϵ) on DMT related to error event $\mathcal{E}_1$

its effect on the fraction of harvest duration (ϵ) for this case. As described in the previous section, the diversity gain decreases with the increase in the fraction of energy harvest duration (ϵ) due to the reduced cooperation interval. Moreover, for $r > 1 - \epsilon$, the EH-based relay $\mathcal{T}$ fails to decode the source $\mathcal{S}_1$'s data and the system performance degrades to that of a point-to-point channel. Similarly, the diversity gain ($d_{O,M22}$) related to error event $\mathcal{E}_2$ can be found by solving the following optimization problem:

$$\begin{aligned}
 d_{O,M22}(r) &= \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\
 \text{s.t. } & f(1 - v_2)^+ + (1 - f)(1 - \min\{v_2, v_t + u_{\min}\})^+ \leq r \\
 & 0 \leq v_t, u_{\max}, u_{\min} \leq 1, \quad 0 \leq v_2 \leq \left(1 - \frac{r}{2}\right) \\
 & 0 \leq (v_t + u_{\min}) \leq 1, \quad \left(1 - \frac{r}{2}\right) \leq v_1 \leq 1 \\
 & f_1 = \max \left\{ \frac{r}{2(1 - u_{\max})^+}, \frac{r}{(1 - u_{\min})^+} \right\}
 \end{aligned} \tag{4.43}$$

Figure 4.8: Mode M_2 : The impact of the fraction of energy harvest duration (ϵ) on DMT related to error event $\mathcal{E}_2$

The constraint in (4.43) results from the rate region definition. By following the analysis as in section 4.3.3, the solution to the above optimization problem gives the DMT based on $\mathcal{E}_2$ error event in mode M_2 . Figure 4.8 plots the DMT performance for different fractions of harvest duration (ϵ). As depicted in Figure 4.8, the diversity performance severely degraded for $r > 1 - \epsilon$. This effect is mainly due to the failure in decoding source $\mathcal{S}_1$'s message at the relay.

Remark 4.3. *The optimization problems defined in (4.42) and (4.43) are essentially the mode M_2 counterparts of (4.21) and (4.30), respectively.*

4.4.2.2 Achievable DMT in Mode M_4

In this operating mode, none of the direct links can support the required rate. Hence, the relay $\mathcal{T}$ forwards the data from both the sources. The decoding interval l_d for this mode is given by (4.2) and the corresponding high SNR equivalent is

given by (4.19).

The proposed system operates in mode M_4 if the constraints in (4.35) are satisfied. The corresponding high SNR equivalents are given as:

$$\begin{aligned} \log(1 + |g_1|^2 \gamma) &< \frac{R}{2} \Leftrightarrow v_1 > \left(1 - \frac{r}{2}\right) \\ \log(1 + |g_2|^2 \gamma) &< \frac{R}{2} \Leftrightarrow v_2 > \left(1 - \frac{r}{2}\right) \end{aligned} \quad (4.44)$$

Hence, the rate region for this operating mode can be characterized by equations (4.7a), (4.7b) and (4.7c). Thus, the evaluation of diversity gain $d_{O,M_{41}}$ related to error event $\mathcal{E}_1$ for this operating mode follows the approach described in the previous section. Therefore, the linear optimization problem related to the error event $\mathcal{E}_1$ in mode M_4 can be formally defined as

$$\begin{aligned} d_{O,M_{41}}(r) &= \inf (v_1 + v_2 + v_t + u_{\max} + u_{\min}) \\ \text{s.t } f(1 - v_1)^+ + (1 - f)(1 - \min\{v_1, v_t + u_{\min}\})^+ &\leq \frac{r}{2} \\ 0 \leq v_t, u_{\max}, u_{\min} &\leq 1, \quad v_1 \geq (v_t + u_2) \\ 0 \leq (v_t + u_{\min}) &\leq 1, \quad \left(1 - \frac{r}{2}\right) \leq v_1, v_2 \leq 1 \\ f_1 &= \max \left\{ \frac{r}{2(1 - u_{\max})^+}, \frac{r}{(1 - u_{\min})^+} \right\} \end{aligned} \quad (4.45)$$

As one can notice, the above optimization problem is similar to problem (P_1) in section 4.3.2 except for the constraints related to operating mode. As given in (4.44), the search region for both v_1 and v_2 is above $(1 - r/2)$. Hence, $d_{O,M_{41}}$ is always greater than $(2 - r)$ which in turn greater than the diversity gain upper bound (d_{UB}) given in (4.5). Now, by following the same argument, the diversity gain $d_{O,M_{42}}(r)$ related to the error event $\mathcal{E}_2$ in mode M_4 is also greater than $(2 - r)$. In other words, the maximum achievable diversity gain of EH-DDF-LF system hinges on the DMT in mode M_2 . The DMTs for the EH-DDF-LF protocol for various fractions of energy harvest duration (ϵ) are plotted in Figure 4.9. We can see from Figure 4.9, though the diversity performance of EH-DDF-LF protocol is inferior to that of non-EH-based DDF protocol, its performance approaches the

Figure 4.9: DMT for the EH-DDF-LF protocol

upper bound in the high-multiplexing-gain regime. However, due to the reasons described earlier, the performance of this protocol degrades to that of a typical MAC channel for $r > 1 - \epsilon$.

4.5 Numerical Results and Protocol Comparisons

The DMT comparison of the proposed EH-based DDF protocols for MARS is shown in Figure 4.10. In this figure, the upper bound corresponds to the case in which the relay has access to exact information messages from both the sources a priori. As can be observed from Figure 4.10, the diversity performance of both EH-DDF and EH-DDF-LF improves with the decrease in the fraction of harvest duration (ϵ). Because the reduction in harvest interval aids the relay to forward the sources' message for a longer fraction of the codeword. However, note that

the performance difference persists between EH-DDF and non-EH-based DDF protocols [46] even for $\epsilon \approx 0$. This result is due to the composite product channel behavior of the proposed system. As can be observed in Figure 4.10, EH-DDF-

Figure 4.10: Comparison of the DMTs achieved by EH-based and non-EH-based DDF protocols

LF scheme uniformly dominates EH-DDF across all the multiplexing gains. This result can be intuitively interpreted as follows. The channel conditions in which relay receives an ACK for one source and a NACK for another source determines the overall DMT of the system. In this case, the relay in traditional DDF protocol continues to forward the data of both the users. Whereas in EH-DDF-LF, the relay aids the source whose direct link is weak. The relaxation of relay forwarding constraint helps in improving the diversity gain. We can see that the proposed EH-DDF-LF incurs only a minute overhead compared to EH-DDF protocol while achieving better diversity across all multiplexing gains. Since the advantage of limited feedback (LF) is more pronounced in the higher multiplexing gain regime,

it is recommended to employ such a feedback channel when the system is proposed to be operated at higher transmission rates.

4.6 Discussion

In this work, apart from the characterization of asymptotic DMT for EH-based DDF protocols, we have assessed the loss in diversity gain for different energy-harvesting fractions (ϵ). The rationale behind this objective rests on the following assertions. In the case of EH-DDF protocol, there are two divergent effects of ϵ . First, the increase in ϵ results in the decrease in the forwarding interval, thus deteriorating the diversity performance. Second, the increase in harvest duration leads to an increase in harvested energy, that improves diversity. However, in the case of asymptotic DMT presented in this chapter, only the first effect is retained in the high-SNR transition (ref. Lemma 4.1). Thus, the diversity gain decreases with the increase in ϵ value as SNR $\gamma \rightarrow \infty$. Hence, at high SNRs, the optimum ϵ always tends to 0. However, we conjecture that the optimum value of ϵ varies in the low-SNR regime.

4.7 Summary

This chapter proposes two variants of energy-harvesting-based dynamic decode-and-forward (DDF) protocols for multiple access relay based system (MARS). In the first variant, we have derived the diversity-multiplexing tradeoff (DMT) of RF energy-harvesting-based DDF protocol (EH-DDF). It is observed that the proposed method of incorporating the energy-harvesting mechanism radically changes the channel behavior and thus results in inferior performance. It is shown that the performance of the proposed EH-DDF protocol improves with the reduction in the proportion of energy-harvesting interval. It is concluded that the performance difference between non-EH-based DDF and EH-DDF exists even for infinitesimal harvest duration. Subsequently, the DDF protocol is

adapted, considering limited feedback. It is shown that the system with limited feedback achieves substantially better diversity compared to the one without feedback information.

The high-SNR-based DMT analysis provides significant insights into the effects of energy harvesting on diversity performance. However, it conceals some of the impact related to the quantum of energy harvested apart from the other limitations of the asymptotic-based study. These issues are addressed in chapter 6, where the finite SNR-based analysis for RF EH-based systems is discussed.

Chapter 5

Interference-Limited Relay System

5.1 Introduction

In systems considered in chapters 2 and 3, destination node is assumed to receive only the desired signal. However, in practice, nodes experience interference from the nearby transmitters due to the broadcast nature of wireless communication signals. In this chapter, we consider an interference-limited relay-assisted system. As we show, the energy-harvesting (EH)-based relay improves the diversity gain of the interference-limited user. Similar to the analysis in earlier chapters, the influence of time-sharing parameter on diversity performance has also been quantified.

As mentioned in chapter 2, the DMT of the traditional interference channel (IC) with relay (ICR) has been extensively studied in the literature. However, to the extent of our knowledge, the DMT for half-duplex-based DDF has not yet been investigated for an interference-limited relay-aided scenario. In this context, this chapter focuses on the DMT of an interference-limited user employing a traditional non-EH-based relay using DDF protocol in the moderate-interference

regime. Subsequently, we extend our analysis for the system with an RF-EH-based relay. Finally, the performance of these systems has been compared against classical reference schemes.

Note that the reason for choosing moderate interference regime is that it is essentially the worst among the three interference possibilities: weak, strong, and moderate. In such scenarios, the joint decoder (JD) offers the best performance by simultaneously decoding the desired signal and the interfering signal [114].

To that end, the following are the contributions of this chapter:

- Derives closed-form expressions for the DMTs of an interference-limited user using battery-assisted non-EH-based DDF and RF-EH-based DDF protocols. It is observed that adding a relay to the interference-limited system improves the diversity gain across all the multiplexing gains for both non-EH and RF-EH variants.
- Demonstrates that the DMT meets the performance upper-bound in a low-multiplexing-gain regime for the non-EH-based DDF protocol
- For the RF-EH-based system, it is shown that the diversity performance degrades with the proportional increase in harvest duration. However, the numerical analysis revealed that the degree of degradation is minimal in the high-multiplexing-gain regime. This intriguing result is due to the dominance of interference over the harvest duration at high multiplexing gains.

The rest of the chapter is organized as follows. The next section describes the system model and discusses the case in which the intermediate relay nodes are powered by wireless energy harvesting. Section 5.3 details the analytic study of the DMT for both non-EH-based and RF-EH-based DDF protocols. Section 5.4 presents the comparative study of proposed protocols. Furthermore, this section also discusses the impact of harvesting intervals on the achievable diversity gain for the RF-EH-based DDF protocol. Finally, Section 5.5 concludes the chapter.

Figure 5.1: System model with an energy harvesting based relay

5.2 System Model

As shown in Figure 5.1(a), a system with two source nodes ($\mathcal{S}_1, \mathcal{S}_2$), two destination nodes ($\mathcal{D}_1, \mathcal{D}_2$), and two half-duplex relays ($\mathcal{T}_1, \mathcal{T}_2$) is considered. In this, $\mathcal{D}_1$ and $\mathcal{D}_2$ are interference-limited users. The fading coefficients h_{ij} , $ij \in \{11, 13, 31, 21, 12, 22, 24, 42\}$ are assumed to be quasi-static, i.e., the path gains are constant over a codeword of length, l . The additive noises Z_1, Z_2, Z_3 , and Z_4 are considered to be zero-mean, mutually independent, and white complex Gaussian. Further, it is assumed that the system is symmetric. Hence, as shown in Figure 2.3, only the interference-limited user $\mathcal{D}_1$ is considered for the DMT analysis.

In the case of RF-EH-based DDF protocol, the relay $\mathcal{T}_1$ operates in three modes, as shown in Figure 2.3: energy harvesting, information decoding, and retransmission using time-switching [73]. It harvests the energy and store it in a battery for the first l_h symbols, decodes the data from the source $\mathcal{S}_1$ during l_d symbol transmissions, and after successful decoding, the information is forwarded to the destination $\mathcal{D}_1$ by expending all the stored energy for the rest of the codeword duration ($l_t = l - l_h - l_d$). The fraction of energy harvest duration has been denoted by $\epsilon (= l_h/l)$. However, in the case of non-EH-based DDF, the energy harvesting phase is absent because the relay $\mathcal{T}_1$ is powered by a fixed power source. Therefore,

in this case, the harvest duration l_h is equal to zero.

The received signals at $\mathcal{D}_1$ and $\mathcal{T}_1$ at symbol interval i are denoted by $Y_{1,i}$, and $Y_{3,i}$ respectively. The channel inputs from source nodes $\mathcal{S}_1, \mathcal{S}_2$, and relay $\mathcal{T}_1$ at symbol interval i are denoted by $X_{1,i}, X_{2,i}$ and $X_{3,i}$, respectively. The relationship between the channel inputs and its outputs at symbol interval i is given by:

$$Y_{1,i} = \begin{cases} h_{11,i}X_{1,i} + h_{21,i}X_{2,i} + Z_{1,i} & 1 \leq i \leq l_h + l_d \\ h_{11,i}X_{1,i} + h_{21,i}X_{2,i} + h_{31,i}X_{3,i} + Z_{1,i} & l_h + l_d + 1 \leq i \leq l \end{cases} \quad (5.1a)$$

$$Y_{3,i} = \begin{cases} h_{13,i}X_{1,i} + Z_{3,i} & l_h + 1 \leq i \leq l_h + l_d, \\ 0 & \text{otherwise,} \end{cases} \quad (5.1b)$$

where $Z_{1,i}$ and $Z_{3,i}$ are noise samples observed at symbol interval i by $\mathcal{D}_1$ and $\mathcal{T}_1$, respectively. These channel relations are used in deriving the DMT for the interference-limited user in the subsequent section.

5.3 Diversity Multiplexing Tradeoff Analysis

In the proposed system, sources $\{\mathcal{S}_i\}_{i=1}^2$ transmit data at a rate of R_1 and R_2 bits per channel use (BPCU), respectively, during every symbol-interval in the codeword, and the associated multiplexing gains are denoted by r_1 and r_2 , respectively. For the performance comparison purposes, the DMTs of various reference schemes are presented in the subsequent subsection.

5.3.1 DMT of Reference Schemes:

The diversity gain achieved by three interference-free single-relay based reference schemes are presented. The first scheme is the genie-aided strategy in which the relay is assumed to know the source information message a priori and thus provides an absolute upper bound (UB) for the achievable DMT (i.e., $d(r) = 2(1 - r)$) [98]. The second baseline scheme is the DDF protocol [46,

equation 14], and finally the third reference scheme is the EH-based counterpart of second reference scheme (EH-DDF) [72, equation 7]. Further, to elucidate the importance of incorporating a relay, the DMTs of a point-to-point (P2P) link (d_{P2P}) and an interference-limited user (d_{IL}) are given, respectively, as [115]:

$$d_{P2P}(r) = (1 - r)^+, \quad d_{IL}(r) = \min\{(1 - r)^+, 2(1 - 2r)^+\} \quad (5.2)$$

Note that the $d_{IL}(r)$ is also a lower-bound ($d_{LB}(r)$).

5.3.2 Non-EH-Based Relay

The analysis starts with a traditional non-EH-based relay system whose DMT, in turn, provides an upper-bound for the RF-EH-based system. In this system model, the relay is powered by a fixed power source. Thus, there is no energy harvesting phase. Therefore, it starts with the decoding phase and the number of symbols the relay listens to decode the source $\mathcal{S}_1$'s data is equal to

$$l_d = \min \left\{ l, \frac{lR_1}{\log(1 + |h_{13}|^2\gamma)} \right\}, \quad (5.3)$$

and the high-SNR equivalent [46] of (5.3) is given by:

$$u_{13} = \left(1 - \frac{r_1}{f_1} \right)^+ \quad (5.4)$$

where $f_1 \triangleq l_d/l$ and u_{13} is the exponential order of $1/|h_{13}|^2$.

Since we are dealing with only one interference-limited user, i.e., $\mathcal{D}_1$, for notational convenience, we drop the subscripts i from $\mathcal{D}_i$ and $\mathcal{T}_i$ henceforth.

5.3.2.1 Achievable Rate Region of Interference-Limited User

As discussed earlier, the interference-limited user $\mathcal{D}$ uses the JD to detect the desired signal from source $\mathcal{S}_1$ [111]. Thus, the achievable rate region (R_1, R_2) at destination $\mathcal{D}$ of the proposed system using DDF protocol is given by

$$\begin{aligned} R_1 &\leq f_1 \log(1 + P_S |h_{11}|^2) \\ &\quad + (1 - f_1) \log(1 + P_S |h_{11}|^2 + P_T |h_{31}|^2) \end{aligned} \quad (5.5a)$$

$$R_1 + R_2 \leq f_1 \log(1 + P_S|h_{11}|^2 + P_S|h_{21}|^2) + (1 - f_1) \log(1 + P_S(|h_{11}|^2 + |h_{21}|^2) + P_T|h_{31}|^2), \quad (5.5b)$$

where the relay transmit power, P_T , is considered to be equal to P_S . Inequalities in (5.5a) and (5.5b) represent the rate constraints related to the detection of message from source $\mathcal{S}_1$ and the joint detection of messages from source $\mathcal{S}_1$ and source $\mathcal{S}_2$, respectively. Note that, owing to the use of JD, the individual rate constraint related to the detection of interfering signal from source $\mathcal{S}_2$ is absent. Thus, there are two kinds of outage regions denoted by $O_{\{1\}}$ and $O_{\{1,2\}}$, based on (5.5a) and (5.5b), respectively. In this chapter, we assume $R_1 = R_2 = R$ and $r_1 = r_2 = r$.

We partition the overall outage error event $\mathcal{E}$ into two error events $\mathcal{E}_1$ and $\mathcal{E}_2$ based on the outage regions $O_{\{1\}}$ and $O_{\{1,2\}}$, respectively, i.e., $\mathcal{E} = \mathcal{E}_1 \cup \mathcal{E}_2$. Hence, the achievable diversity gain for non-EH-based DDF protocol is given by

$$d_{non-EH-DDF}(r) = \min\{d_{\mathcal{E}_1}(r), d_{\mathcal{E}_2}(r)\}, \quad (5.6)$$

and $d_{\mathcal{E}_1}(r)$ can be written as $P_{\mathcal{E}_1(2)} \doteq \gamma^{-d_{\mathcal{E}_1(2)}}$, where $P_{\mathcal{E}_1(2)}$ is the error probability corresponding to outage event $\mathcal{E}_1(2)$ and $d_{\mathcal{E}_1(2)}$ is the diversity gain considering $P_{\mathcal{E}_1(2)}$ alone. Next, we focus on the computation of diversity gains based on these error events.

5.3.2.2 Error Event Related to Individual Rate

This problem is equivalent to the traditional single-relay DDF protocol; thus the diversity gain for this category is given by [46, equation 14]

$$d_{\mathcal{E}_1}(r) = \begin{cases} 2(1 - r), & 0 \leq r < \frac{1}{2} \\ \frac{1-r}{r} & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (5.7)$$

5.3.2.3 Error Event Related to Sum-rate

The error probability corresponding to sum-rate $P_{\mathcal{E}_2}$ is upper-bounded by [46]

$$P_{\mathcal{E}_2|h_{ij}, ij \in \{11, 21, 13, 31\}} \leq \left[1 + (|h_{11}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} \right]^{-l_d} \cdot \left[1 + (|h_{11}|^2 + |h_{31}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} \right]^{-(l-l_d)}, \quad (5.8)$$

and the corresponding diversity gain $d_{\mathcal{E}_2}$ is given by

$$d_{\mathcal{E}_2} \triangleq \inf_{O_{E_2}^+} \{v_{11} + v_{21} + v_{31} + u_{13}\}, \quad (5.9)$$

where $\inf$ is the infimum, v_{ij} is the exponential order of $1/|h_{ij}|^2$ and $O_{\mathcal{E}_2}^+$ is the non-negative subset of $\mathbb{R}^5$ that satisfy the following constraints¹

$$f_1(1 - \min\{v_{11}, v_{21}\})^+ + (1 - f_1)(1 - \min\{v_{11}, v_{31}, v_{21}\})^+ \leq 2r \quad (5.10)$$

The diversity gain $d_{\mathcal{E}_2}$ in (5.9) can be expressed as

$$d_{\mathcal{E}_2}(r) = \inf_{f_1} (u_{13}(r, f_1) + \lambda_2(r, f_1)) \quad (5.11)$$

where $u_{13}(r, f_1)$ is given by (5.4) and $\lambda_2(r, f_1)$ is given as

$$\lambda_2(r, f_1) = \inf (v_{11} + v_{21} + v_{31}) \quad (5.12)$$

The function $\lambda_2(r, f_1)$ for this error event can be evaluated by solving the following optimization problem:

$$\begin{aligned} \lambda_2(r, f_1) &= \inf (v_{11} + v_{21} + v_{31}) \\ \text{s.t } f_1 \min\{v_{11}, v_{21}\} + (1 - f_1) \min\{v_{11}, v_{21}, v_{31}\} &\geq (1 - 2r) \\ 0 &\leq v_{11}, v_{21}, v_{31} \leq 1 \end{aligned} \quad (5.13)$$

By using standard linear programming techniques, the solution to the above optimization problem can be written as

$$\lambda_2(r, f_1) = \begin{cases} 3(1 - 2r), & 0 \leq f_1 < \frac{2}{3} \\ 3 - \frac{2r}{1-f_1}, & \frac{2}{3} \leq f_1 \leq 1 - 2r \\ \frac{2(1-2r)}{f_1}, & 1 - 2r \leq f_1 \leq 1 \end{cases} \quad (5.14)$$

¹ $\mathbb{R}^N$ denotes the set of real N-tuples

and

$$\lambda_2(r, f_1) = \begin{cases} 3(1 - 2r), & 0 \leq f_1 < \frac{2}{3} \\ \frac{2(1-2r)}{f_1} & \frac{2}{3} \leq f_1 \leq 1 \end{cases} \quad (5.15)$$

Thus, using (5.4), (5.14), and (5.15),

$$d_{\mathcal{E}_2}(r) = 3(1 - 2r) \quad 0 \leq r < \frac{1}{2} \quad (5.16)$$

Finally, by using (5.7), and (5.16), the DMT for the non-EH-relay based interference-limited user is given by

$$d_{non-EH-DDF}(r) = \begin{cases} 2(1 - r), & 0 \leq r < \frac{1}{4} \\ 3(1 - 2r), & \frac{1}{4} \leq r \leq \frac{1}{2} \\ 0 & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (5.17)$$

The non-EH-based DDF achieves the optimal tradeoff (the genie-aided upper bound) for lower multiplexing gains. In fact, in this multiplexing gain regime, the non-EH-DDF resembles a system with two transmit and one receive antennas with no degenerative effects of interference. Moreover, in this region, the dominant error event is related to individual rate constraint. However, as shown in (5.17), the diversity performance degrades in the high-multiplexing-gain regime. This result is attributed to two factors. First, the detrimental effects of interference from an unintended user. Second, the limited cooperation from the relay due to the elongated decoding phase. These two effects manifest themselves in the sum-rate related error event.

5.3.3 RF-EH-Based Relay

We now extend the analysis to the RF-EH-based relay system. In this model, the relay $\mathcal{T}$ is entirely powered by source $\mathcal{S}_1$'s RF radiation. As detailed in Figure 2.3, during the first l_h symbols duration, relay $\mathcal{T}$ harvests the energy and is given

by

$$E_T = \eta l_h |h_{13}|^2 P_S, \quad (5.18)$$

where $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency. This entire harvested energy is used to retransmit the source $\mathcal{S}_1$'s data to the destination $\mathcal{D}_1$, thus the relay transmit power P_T is given by:

$$P_T = E_T / l_t \quad (5.19)$$

Therefore, the achievable rate region for RF-EH-based relay system can be obtained by replacing $f_1 = f_1 + \epsilon$ in (5.5). As in the case of the non-EH-based relay, the joint error event $\hat{\mathcal{E}}$ is written as a union of two error events $\hat{\mathcal{E}}_1$ and $\hat{\mathcal{E}}_2$ corresponding to an individual target rate of source $\mathcal{S}_1$ and the overall sum-rate, respectively. Therefore, the achievable diversity gain for RF-EH-based DDF protocol is given by

$$d_{EH-DDF}(r) = \min\{d_{\hat{\mathcal{E}}_1}(r), d_{\hat{\mathcal{E}}_2}(r)\} \quad (5.20)$$

A detailed analysis to find explicit expressions for diversity gains based on these error events is given below.

5.3.3.1 Error Event Related to Individual Rate

This problem is equivalent to the RF-EH-based single-relay DDF protocol, thus the diversity gain for this category is given by [72, equation 7]

$$d_{\hat{\mathcal{E}}_1}(r) = \begin{cases} 2 - \frac{9r}{4} \left(\frac{1-\epsilon}{1-(3\epsilon/2)} \right), & 0 \leq r \leq \left(\frac{4-5\epsilon}{6} \right) \\ \frac{1-r}{r+\epsilon}, & \left(\frac{4-5\epsilon}{6} \right) < r < (1-\epsilon) \\ (1-r) & (1-\epsilon) \leq r \leq 1 \end{cases} \quad (5.21)$$

5.3.3.2 Error Event Related to Sum-rate

As in the case of non-EH-based system, the sum-rate related error probability $P_{\hat{\mathcal{E}}_2}$ is upper-bounded by

$$P_{\hat{\mathcal{E}}_2|h_{ij}, ij \in \{11, 21, 13, 31\}} \leq \left[1 + (|h_{11}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} \right]^{-(l_h + l_d)} \cdot \left[1 + (|h_{11}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} + |h_{31}|^2 \frac{\eta l_h |h_{13}|^2 P_S}{2l_t \sigma_D^2} \right]^{-(l - l_h - l_d)} \quad (5.22)$$

The diversity gain, $d_{\hat{\mathcal{E}}_2}$, for this category can be derived by solving the following optimization problem:

$$\begin{aligned} d_{\hat{\mathcal{E}}_2}(r, f) &= \inf (v_{11} + v_{21} + v_{31} + u_{13}) \\ \text{s.t. } &f \min\{v_{11}, v_{21}\} + (1 - f) \min\{v_{11}, v_{21}, v_{31} + u_{13}\} \geq (1 - 2r) \\ &0 \leq v_{11}, v_{21}, v_{31}, u_{13} \leq 1, \end{aligned} \quad (5.23)$$

where $f = f_1 + \epsilon$. The solution is given in the following lemma

Lemma 5.1. *The solution of the optimization problem defined in (5.23) is given by:*

1. for $0 \leq \epsilon \leq \frac{1}{9}$

$$d_{\hat{\mathcal{E}}_2}(r) = \begin{cases} \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)} \right)^+, & 0 \leq r \leq \frac{4}{7} + \frac{9\epsilon}{14} \\ \frac{2(1-2r)}{r+\epsilon} & \frac{4}{7} + \frac{9\epsilon}{14} \leq r \leq \frac{1}{2} \end{cases} \quad (5.24)$$

2. and for $\frac{1}{9} \leq \epsilon \leq 1$

$$d_{\hat{\mathcal{E}}_2}(r) = \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)} \right)^+ \quad (5.25)$$

Proof: Please refer to the Appendix B.1. ■

Finally, by using (5.21), (5.24), and (5.25), we get the DMT for the RF-EH-based DDF protocol as

1. for $0 \leq \epsilon \leq \frac{1}{9}$

$$d_{EH-DDF}(r) = \begin{cases} 2 - 9r \left(\frac{(2-\epsilon)}{(4+\epsilon)(4-5\epsilon)} \right), & 0 \leq r \leq \frac{8}{31} + \frac{170\epsilon}{961} \\ \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)} \right)^+, & \frac{8}{31} + \frac{170\epsilon}{961} \leq r \leq \frac{8+9\epsilon}{14} \\ \frac{2(1-2r)}{r+\epsilon} & \frac{8+9\epsilon}{14} \leq r \leq \frac{1}{2} \end{cases} \quad (5.26)$$

2. and for $\frac{1}{9} \leq \epsilon \leq 1$

$$d_{EH-DDF}(r) = \begin{cases} 2 - 9r \left(\frac{(2-\epsilon)}{(4+\epsilon)(4-5\epsilon)} \right), & 0 \leq r \leq \frac{8}{31} + \frac{170\epsilon}{961} \\ \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)} \right)^+ & \frac{8}{31} + \frac{170\epsilon}{961} \leq r \leq \frac{1}{2} \end{cases} \quad (5.27)$$

The excellent diversity performance of the DDF protocol can also be observed for the RF-EH-based variant. As in the case of non-EH-based DDF, for lower multiplexing gains, the DMT performance depends on single user error event. On the other hand, the sum-rate error event is dominant in the high-multiplexing-gain regime. Due to the complicated nature of expressions, much of the insights are drawn using the performance plots in the subsequent section.

5.4 Numerical Results and Protocol Comparisons

In this section, the DMT of an interference-limited relay-aided user is compared with various reference schemes. Additionally, the impact of energy-harvesting duration on the achievable DMT for RF-EH-based system is also discussed.

5.4.1 Non-EH-Based Relay-Aided Interference-Limited User

The DMT for the non-EH-based relay-aided interference-limited user is shown in Figure 5.2. As evident from the figure, the inclusion of relay improves the performance of interference-limited user across all the multiplexing gains

Figure 5.2: DMT of interference-limited user using non-EH-based relay

Figure 5.3: DMT of interference-limited user using RF-EH-based relay

Figure 5.4: DMT of interference-limited user using RF-EH-based relay at higher multiplexing gains

compared to the interference-limited user without relay scenario (diversity lower bound (LB) in Figure 5.2). Also, for multiplexing gains less than 0.25, the performance approaches that of genie-aided upper-bound [98]. As shown in equation (5.17), the individual rate constraint is the limiting factor in the low-multiplexing-gain regime. However, for higher multiplexing gains, the resultant diversity gain hinges on the sum-rate constraint, which in turn depends on the interference from source $\mathcal{S}_2$. Thus, the DMT diverges in this multiplexing gain regime and eventually offers no diversity advantage at multiplexing gain greater than half.

5.4.2 RF-EH-Based Relay-Aided Interference-Limited User

Figure 5.3 shows the DMT of an RF-EH-based relay-assisted interference-limited user for various fractions of energy-harvesting durations (ϵ). It is observed that there is a performance degradation even for infinitesimal harvest duration $\epsilon (\approx 0)$ at lower multiplexing gains. This result arises from the resultant composite channel behavior owing to energy harvesting. Also, the EH-based system exhibits degradation in performance with the increase in energy-harvesting duration. This result is intuitive because the proportional increase in harvest duration results in the proportional decrease in cooperation phase. In the high-multiplexing-gain regime, as Figure 5.4 indicates, RF-EH-based interference-limited user's performance approaches that of the non-EH-based counterpart for low to moderate ϵ values ($\epsilon < 0.3$). This result indicates that the interference is the limiting factor rather than the energy-harvesting duration at higher multiplexing gains.

5.5 Summary

In this chapter, closed-form solutions for diversity-multiplexing tradeoffs of traditional DDF and RF-EH-based DDF protocols for the interference-limited user have been derived. These results showed that the inclusion of a relay improves the DMT of the interference-limited user. Similarly, it is observed that an RF-EH-based relay system performs almost as well as its non-EH-based counterpart. The numerical analysis further revealed that the diversity gain drops to zero for multiplexing gains greater than half due to the dominant effect of interference. Thus, exploring solutions to improve the performance in this regime would be a promising future direction.

Chapter 6

Finite-SNR

Diversity-Multiplexing Tradeoff for Energy-Harvesting-Based Relay Channels

6.1 Introduction

As detailed in the earlier chapters, the asymptotic diversity-multiplexing tradeoff (DMT) provides a DMT upper-bound for a given system. Unfortunately, it does not reveal the tradeoff between diversity and multiplexing gains at low to moderate signal-to-noise ratio (SNR). Thus, there is a need to characterize the DMT for finite-SNR regimes to assess the complete picture of the parameters involved. The framework to evaluate finite-SNR DMT (f-DMT) was first proposed for point-to-point MIMO links [54] and now widely used as a performance metric in the literature [116–118]. However, to the best of our knowledge, only one previous study has considered f-DMT for EH-based systems [119]. In their work, Chen *et al.* derived closed-form expressions for the outage

probability, ergodic capacity, and f-DMT for a two-way half-duplex energy-harvesting (EH)-based amplify-and-forward (AF) relaying channel using a power-splitting (PS)-based receiver architecture.

In this chapter, we analyze the f-DMT of EH-based AF and decode-and-forward (DF) protocols for a single half-duplex relay-based system using time switching (TS)-based relaying [73]. Even though the primary focus of this work is f-DMT, closed-form expressions for the outage probability, diversity order, and asymptotic DMT are also provided. The impact of relay position on the outage probability is also investigated. Furthermore, the influence of the time-sharing parameter (ϵ) on the chosen performance metrics is analyzed. Finally, it is shown that the addition of an EH-based relay node can improve the diversity gain, even in the finite-SNR regime. Unsurprisingly, this study confirms the findings of our earlier studies related to asymptotic DMT [120, 121].

The main contributions of this chapter are summarized below:

- Derives closed-form expressions for the outage probability, diversity order, f-DMT, and asymptotic DMT for EH-based AF and DF protocols.
- Investigates the impact of relay position on the outage probability and concludes that the optimal performance is achieved when the relay is placed either near the source or the destination.
- Through extensive analytical and simulation studies, it is shown that both AF and DF offer similar diversity performance except for some marginal differences. At lower multiplexing gains, EH-DF and EH-AF protocols achieve better diversity gain in low-SNR regimes and high-SNR regimes, respectively. However, at higher multiplexing gains, DF outperforms AF across all SNRs. Moreover, as SNR approaches to infinity, it is demonstrated that both the EH-AF and EH-DF achieve the same diversity gain that, predictably, coincide with the asymptotic DMT counterparts.
- Analyzes the impact of the time-sharing parameter (ϵ) on the achievable

diversity gain. This study confirms that the optimal value of ϵ depends on the operating SNR in low- and moderate-SNR regimes. However, at very high SNRs, the infinitesimal ϵ value achieves maximum diversity gain. Once again, these results reaffirm the earlier observations related to asymptotic DMT [120, 121].

The rest of the chapter is organized as follows. Section 6.2 introduces the system model and the definitions of diversity and multiplexing gains as functions of SNR. The performance analysis of AF and DF protocols are provided in sections 6.3 and 6.4, respectively. Section 6.5 presents numerical results at finite SNRs for various time-sharing factors. A discussion on the finite-SNR results and interpretations of the asymptotic diversity gain as SNR approaches infinity is also given in this section. Chapter summary is given in section 6.6.

6.2 System Model

As depicted in Figure 6.1, a half-duplex relay channel in which the source $\mathcal{S}$ transmits its data to the destination $\mathcal{D}$ aided by a EH-based relay node $\mathcal{R}$ has been considered. The channel fading coefficients $h_{s,r}$, $h_{r,d}$, and $h_{s,d}$ are assumed to be zero-mean complex Gaussian random variables with unit variance. Moreover, the channel gains are assumed to be quasi-static over a coding block. The distances between $\mathcal{S} \rightarrow \mathcal{R}$, $\mathcal{R} \rightarrow \mathcal{D}$, and $\mathcal{S} \rightarrow \mathcal{D}$ are denoted by d_1 , d_2 , and d_3 , respectively. The source node transmits the energy as well as the information using TS-based relaying (TSR) [71].

Now onwards, to keep the notation simple, we drop the prefix EH while referring to proposed protocols EH-AF and EH-DF when it is clear from the context. For both AF and the DF protocols, it is assumed that the total energy per packet is $E(= P_s T)$, where T is the total number of channel uses and P_s is the average transmit power. As shown in Figure 6.1, the TSR mechanism involves

Figure 6.1: System Model: Half-duplex single EH-based relay channel

three disjoint phases. In the first phase, $\mathcal{S}$ transmits the power wirelessly to the relay $\mathcal{R}$ using $T_h = \epsilon T$ channel uses, where ϵ denotes the time sharing factor, that is a fraction of the channel uses allocated for EH. In this phase, $\mathcal{R}$ harvests the energy using $\mathcal{S}$'s radio transmission. Subsequently, in the second phase, $\mathcal{S}$ transmits its data using $T_s = (1 - \epsilon)T/2$ channel uses. In this phase, both $\mathcal{R}$ and $\mathcal{D}$ listen to the transmitted signal due to the broadcast nature of the channel. Note that the source $\mathcal{S}$ consumes all the available energy during these first two phases. Therefore, the resultant transmit power $\hat{P}_s$ is given by:

$$\hat{P}_s = \frac{E}{\epsilon T + \frac{(1-\epsilon)T}{2}} = \psi P_s, \quad (6.1)$$

where $\psi = \frac{2}{1+\epsilon}$ is the power scaling factor. The received signals in the second phase at $\mathcal{R}$ and $\mathcal{D}$, respectively, are given as follows:

$$y_r = \sqrt{\psi \delta_1 P_s} h_{s,r} x_s + n_r \quad (6.2a)$$

$$y_{d,2} = \sqrt{\psi \delta_3 P_s} h_{s,d} x_s + n_{d,2}, \quad (6.2b)$$

where $n_r \sim \mathcal{N}(0, 1)$ and $n_{d,2} \sim \mathcal{N}(0, 1)$ are the received noise samples at the relay and the destination, respectively, and $\delta_i = \frac{1}{d_i^\alpha}$, $i \in \{1, 2, 3\}$ is the path loss,

and n is the path loss exponent. Finally, during the third phase, the relay shifts to transmit mode and forwards the processed received data to the destination $\mathcal{D}$. In this model, it is assumed that the relay $\mathcal{R}$ is entirely powered by source $\mathcal{S}$'s RF radiation. Therefore, the EH-based relay $\mathcal{R}$ expends all the harvested energy and also consumes the rest of the channel uses $T_r = (1 - \epsilon)T/2$ during retransmission. The quantum of harvested energy during the first phase is given by

$$E_r = \eta \delta_1 \epsilon T |h_{s,r}|^2 \hat{P}_s, \quad (6.3)$$

where $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency [3]. The relay transmit power P_r is given by

$$P_r = \frac{2E_r}{(1 - \epsilon)T} \quad (6.4)$$

that, together with (6.1) and (6.3), results in

$$P_r = \frac{2\eta\epsilon\psi\delta_1}{(1 - \epsilon)} |h_{s,r}|^2 P_s \quad (6.5)$$

and by denoting $\bar{\eta} = \frac{2\eta\epsilon}{1-\epsilon}$, (6.5) can be further rewritten as

$$P_r = \bar{\eta} \psi \delta_1 |h_{s,r}|^2 P_s \quad (6.6)$$

The third phase differs regarding processing at the relay between AF and DF protocols. The details of each protocol are described in the following subsections.

6.2.1 EH-AF Protocol

In this protocol, the relay amplifies the signal received during the second phase and retransmits the scaled version of the received data in the third phase. Thus, the transmitted signal from the relay x_r is given by

$$x_r = \frac{\sqrt{P_r} y_r}{\sqrt{\psi \delta_1 |h_{s,r}|^2 P_s + \sigma_{n_r}^2}}, \quad (6.7)$$

where $\sigma_{n_r}^2 (= 1)$ is the variance of the noise observed at the relay. Substitution of (6.6) in (6.7) yields the following:

$$x_r = \sqrt{\frac{\bar{\eta} \psi \delta_1 |h_{s,r}|^2 P_s}{\psi \delta_1 |h_{s,r}|^2 P_s + \sigma_{n_r}^2}} y_r \quad (6.8)$$

By denoting the amplification factor $a = \sqrt{\frac{\bar{\eta} \psi \delta_1 |h_{s,r}|^2 P_s}{\psi \delta_1 |h_{s,r}|^2 P_s + \sigma_{n_r}^2}}$ and by using (6.2a), the received signals at $\mathcal{D}$ during the third phase are given as follows:

$$\begin{aligned} y_{d,3}^{AF} &= a \sqrt{\delta_2} h_{r,d} \left(\sqrt{\psi \delta_1 P_s} h_{s,r} x_s + n_r \right) + n_{d,3} \\ &= a \sqrt{\psi \delta_1 \delta_2 P_s} h_{r,d} h_{s,r} x_s + a \sqrt{\delta_2} h_{r,d} n_r + n_{d,3}, \end{aligned} \quad (6.9)$$

where $n_{d,3} \sim \mathcal{N}(0, 1)$ denotes the noise samples at the destination during phase III.

6.2.2 EH-DF Protocol

In the DF relaying protocol, the EH-based relay decodes, re-encodes, and finally retransmits the message. There are several variants of DF protocol in the literature: DF, DF with diversity combining, and selective DF [38]. In the case of DF protocol, the destination performs detection based only on the signal received from the relay in phase III. Whereas in the case of diversity combining, by exploiting the broadcast nature of the channel, the destination detects the source message by combining both the source-destination signal in phase II and the relay-to-destination signal in phase III using maximal ratio combiner (MRC). While the performance of diversity combining technique is better than the basic approach, the achievable rate is still limited by the quality of source-to-relay link. To overcome this deficiency, in this work, we consider selective DF in which the relay stays silent during the third phase if it fails to decode the source's message during the second phase. Therefore, the received signals at the destination $\mathcal{D}$ during the third phase

are given as follows:

$$y_{d,3}^{DF} = \begin{cases} \sqrt{\eta} \psi \delta_1 \delta_2 P_s h_{s,r} h_{r,d} x_s + n_{d,3}, & \text{successful decoding} \\ 0, & \text{otherwise} \end{cases} \quad (6.10)$$

6.2.3 Preliminaries

In this subsection, we recall the definitions of diversity and multiplexing gains in the realm of finite SNR, γ [122]. Traditionally, the DMT is defined for infinite SNR using asymptotic versions of multiplexing gain (r) and the diversity gain (d) and are given by (2.9). It can be noticed that these definitions subsume the behavior at realistic SNRs. The focus of this chapter is to characterize the DMT at finite SNRs and data rates to estimate the validity of asymptotic DMTs for EH-based relay systems.

The f-DMT is expressed as [122]:

$$r = \frac{R}{\log(1 + \gamma)} \quad (6.11)$$

$$d(r, \gamma) = -\frac{d(\ln P_{out}(r, \gamma))}{d(\ln \gamma)} = \frac{-\gamma}{P_{out}(r, \gamma)} \frac{dP_{out}(r, \gamma)}{d\gamma} \quad (6.12)$$

where R is the given target data rate in bits per channel use (BPCU) and $P_{out}(r, \gamma)$ is the outage probability, which is a function of multiplexing gain r and SNR γ . In other words, in the finite SNR paradigm, for fixed multiplexing gain r and SNR γ , the diversity gain $d(r, \gamma)$ is defined as the negative slope of log-log plot of outage probability versus SNR.

In addition to f-DMT, this work also characterizes the diversity order for a given SNR γ and a fixed target transmission rate of R . It can be defined as follows:

$$d(\gamma) = \frac{-\gamma}{P_{out}(\gamma)} \frac{dP_{out}(\gamma)}{d\gamma} \quad (6.13)$$

In the following two sections, using the above-described preliminaries, the

detailed theoretical analysis for the outage probability, diversity order, f-DMT, and asymptotic DMTs for the proposed EH-based AF and DF protocols have been presented.

6.3 EH-Based Amplify-And-Forward (EH-AF)

Protocol

In AF protocol, the relay is not required to decode the source $\mathcal{S}$'s data, implying reduced relay complexity. Consequently, we shall first develop the analysis for EH-AF and then extend the discussion to EH-DF protocol in the next section. As discussed earlier, to derive the f-DMT, first the outage probability and its derivative are to be computed.

6.3.1 Outage Probability of EH-AF Protocol

The channel input-output relations described in (6.2b) and (6.9) can be compactly represented using matrices as:

$$\mathbf{y}_d = \mathbf{A}x_s + \mathbf{B}\mathbf{z}, \quad (6.14)$$

where

$$\mathbf{y}_d = \begin{bmatrix} y_{d,2} \\ y_{d,3} \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} \sqrt{\psi\delta_3\gamma} h_{s,d} \\ a\sqrt{\psi\delta_1\delta_2\gamma} h_{r,d} h_{s,r} \end{bmatrix}, \quad (6.15)$$

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & a\sqrt{\delta_2} h_{r,d} & 1 \end{bmatrix}, \quad \mathbf{z} = \begin{bmatrix} n_{d,2} & n_r & n_{d,3} \end{bmatrix}^T \quad (6.16)$$

Then, the mutual information of the relay channel using AF protocol (I_{AF}) is given by [38]:

$$I_{AF} = \left(\frac{1 - \epsilon}{2} \right) \log \det \left(I_2 + \mathbf{A}\mathbf{A}^\dagger (\mathbf{B}\mathbf{B}^\dagger)^{-1} \right) \quad (6.17)$$

Next, by substituting (6.16) in (6.17) yields the following:

$$I_{AF} = \left(\frac{1-\epsilon}{2} \right) \log \left(1 + \psi \delta_3 \gamma |h_{s,d}|^2 + \frac{a^2 \psi \delta_1 \delta_2 \gamma |h_{r,d}|^2 |h_{s,r}|^2}{1 + a^2 \delta_2 |h_{r,d}|^2} \right) \quad (6.18)$$

Thus, the probability of outage for the given target rate of R can be expressed as

$$\begin{aligned} P_{out}^{AF} &= \Pr [I_{AF} < R] \\ &= \Pr \left[1 + \psi \delta_3 \gamma |h_{s,d}|^2 + \frac{a^2 \psi \delta_1 \delta_2 \gamma |h_{r,d}|^2 |h_{s,r}|^2}{1 + a^2 \delta_2 |h_{r,d}|^2} < 2^{\frac{2R}{1-\epsilon}} \right] \\ &= \Pr \left[|h_{s,d}|^2 + \frac{|h_{r,d}|^2 |h_{s,r}|^2}{\frac{\delta_3}{a^2 \delta_1 \delta_2} + \frac{\delta_3}{\delta_1} |h_{r,d}|^2} < \frac{2^{2\hat{R}} - 1}{\psi \delta_3 \gamma} \right] \end{aligned} \quad (6.19)$$

where $\hat{R} = \frac{R}{1-\epsilon}$. By denoting $X = |h_{s,d}|^2$, $Y = |h_{r,d}|^2$, $Z = |h_{s,r}|^2$, $c_1 = \frac{\delta_3}{a^2 \delta_1 \delta_2}$, $c_2 = \frac{\delta_3}{\delta_1}$, and $\zeta_3 = \frac{1}{\psi \delta_3 \gamma} [2^{2\hat{R}} - 1]$, (6.19) can be rewritten as

$$P_{out}^{AF} = \Pr \left[X + \frac{Y Z}{c_1 + c_2 Y} < \zeta_3 \right] \quad (6.20)$$

The following Lemma evaluates the CDF of a combination of exponential random variables that in turn helps us to evaluate the outage probability of AF protocol.

Lemma 6.1. *The cumulative distribution function (CDF) $F_\Lambda(\lambda)$ with $\Lambda = X + \frac{YZ}{c_1 + c_2 Y}$ is given by*

$$F_\Lambda(\lambda) = \begin{cases} 1 - e^{-\lambda} \left(1 + \frac{1}{c_1} - 2\lambda K_2(2\sqrt{c_1}\lambda) \right), & c_2 = 1 \\ 1 - e^{-\lambda} \left(1 + \frac{1}{c_1} \sum_{m=0}^{\infty} \frac{2^{2m}}{m!} \left(\frac{1-c_2}{4c_1} \right)^m \right. \\ \left. \left[G_{1,3}^{2,1} \left(\sqrt{c_1}\lambda, \frac{1}{2} \middle| \begin{matrix} 1 \\ m+1, m+2, 0 \end{matrix} \right) \right] \right), & \text{otherwise} \end{cases} \quad (6.21)$$

where $K_2(\cdot)$ and $G(\cdot)$ are the second order modified Bessel function of the second kind and the Meijer-G function [123], respectively.

Proof: The proof is given in Appendix C.1. ■

A closed-form expression for the outage probability of EH-based AF protocol is given in the following theorem.

Theorem 6.1. *The outage probability of EH-AF protocol is given by*

$$P_{out}^{AF} = \begin{cases} 1 - e^{-\zeta_3} \left(1 + \frac{1}{c_1} - 2\zeta_3 K_2(2\sqrt{c_1\zeta_3}) \right), & c_2 = 1 \\ 1 - e^{-\zeta_3} \left(1 + \frac{1}{c_1} \sum_{m=0}^{\infty} \frac{2^{2m}}{m!} \left(\frac{1-c_2}{4c_1} \right)^m \right. \\ \left. \left[G_{1,3}^{2,1} \left(\sqrt{c_1\zeta_3}, \frac{1}{2} \middle| \begin{matrix} 1 \\ m+1, m+2, 0 \end{matrix} \right) \right] \right), & otherwise \end{cases} \quad (6.22)$$

Proof: By substituting $\lambda = \zeta_3$, the outage probability given in (6.22) follows from Lemma 6.1. ■

As shown in the preceding theorem, the outage probability expression is composed of two relay positioning scenarios. In the first case, the distance between the source to the relay and the distance between the source and the destination are considered to be equal. On the other hand, the second case captures the rest of the relay positioning scenarios. In the next subsection, we compute the diversity order for EH-AF protocol for both these cases.

6.3.2 Finite SNR Diversity Order of EH-AF Protocol

Diversity order signifies how fast the outage probability reduces with SNR. Traditionally, the diversity order is characterized at an asymptotically high SNR. However, in this work, the focus is on finite SNR version. It can be computed using the outage probability expressions derived in Theorem 6.1 and the definition of finite SNR diversity (6.13). The following corollary summarizes this result.

Corollary 6.1. *The diversity order of EH-based AF protocol is given by*

$$\tilde{d}_f^{AF}(\gamma) = \begin{cases} \frac{\zeta_3 e^{-\zeta_3}}{P_{out}(\gamma)} \left[1 + \frac{1}{c_1} - 2\zeta_3 K_2(2\sqrt{c_1\zeta_3}) - 2\sqrt{c_1\zeta_3} K_1(2\sqrt{c_1\zeta_3}) \right], & \delta_3 = \delta_1 \\ \frac{\zeta_3 e^{-\zeta_3}}{P_{out}(\gamma)} \left(1 + \sum_{m=0}^{\infty} \frac{1}{m!} \left(\frac{1-c_2}{c_1} \right)^m \right. \\ \left. \left[\frac{1}{c_1} G_{1,3}^{2,1}(\sqrt{c_1\zeta_3}) - (c_1\zeta_3)^m B_1(2\sqrt{c_1\zeta_3}) \right] \right), & \text{otherwise} \end{cases} \quad (6.23)$$

where $K_1(\cdot)$ is the first order modified Bessel function of the second kind, and $B_1(x) = xK_1(x)$.

Proof: The proof is given in Appendix C.2. ■

In the next subsection, the diversity order results have been extrapolated to derive the f-DMT, that eventually captures the diversity gain across all the multiplexing gains and the SNRs.

6.3.3 f-DMT of EH-AF Protocol

While the diversity order provides the performance at a fixed rate of R , the f-DMT captures the diversity performance across the spectrum of transmission rates (through multiplexing gain r). In this subsection, we characterize the f-DMT for AF protocol by extending the results derived in Theorem 6.1 and Corollary 6.1.

Proposition 6.1. *The probability of outage for the given target rate of $R = r \log(1 + \gamma)$ is equivalent to the results given in Lemma 6.1 with $\lambda = \frac{1}{\psi\delta_3\gamma} \left[(1 + \gamma)^{\frac{2r}{1-\epsilon}} - 1 \right]$.*

Proof: The probability of outage for the given target rate of $R = r \log(1 + \gamma)$ can be expressed as

$$\begin{aligned} P_{out}^{AF} &= \Pr [I_{AF} < r \log(1 + \gamma)] \\ &= \Pr \left[|h_{s,d}|^2 + \frac{|h_{r,d}|^2 |h_{s,r}|^2}{\frac{\delta_3}{a^2 \delta_1 \delta_2} + \frac{\delta_3}{\delta_1} |h_{r,d}|^2} < \frac{1}{\psi\delta_3\gamma} \left[(1 + \gamma)^{\frac{2r}{1-\epsilon}} - 1 \right] \right] \end{aligned} \quad (6.24)$$

The above problem formulation is equivalent to (6.20) with $\zeta_3 = \frac{1}{\psi\delta_3\gamma} \left[(1 + \gamma)^{\frac{2r}{1-\epsilon}} - 1 \right]$. Therefore, the outage probability expression in (6.24) follows Lemma 6.1. ■

Based on the above proposition, the DMT for AF protocol is characterized in the following corollary.

Corollary 6.2. *The f-DMT of EH-based AF protocol is given by*

$$d_f^{AF}(r, \gamma) = \begin{cases} \frac{\Theta_3 e^{-\zeta_3}}{P_{out}(\gamma)} \left[1 + \frac{1}{c_1} - 2\zeta_3 K_2(2\sqrt{c_1\zeta_3}) - 2\sqrt{c_1\zeta_3} K_1(2\sqrt{c_1\zeta_3}) \right], & \delta_3 = \delta_1 \\ \frac{\Theta_3 e^{-\zeta_3}}{P_{out}(\gamma)} \left(1 + \sum_{m=0}^{\infty} \frac{1}{m!} \left(\frac{1-c_2}{c_1} \right)^m \right. \\ \quad \left. \left[\frac{1}{c_1} G(\sqrt{c_1\zeta_3}) - (c_1\zeta_3)^m B_1(2\sqrt{c_1\zeta_3}) \right] \right), & \text{otherwise} \end{cases} \quad (6.25)$$

where $\Theta_3 = -\gamma \frac{d\zeta_3}{d\gamma} = \zeta_3 - \frac{2\hat{r}}{\psi\delta_3} (1 + \gamma)^{2\hat{r}-1}$, and $\hat{r} = \frac{r}{1-\epsilon}$.

Proof: The f-DMT is analogous to the finite SNR diversity order except for the formulation of outage probability given in Proposition 6.1. Therefore, the proof for this corollary follows the steps detailed in Appendix C.2. Thus, for brevity, omitted the detailed proof. ■

In the next subsection, we derive the asymptotic (or infinite SNR) DMT.

6.3.4 Asymptotic DMT of EH-AF Protocol

The asymptotic DMT can be derived from the high SNR version of outage probability (6.20). The result is summarized in the following corollary.

Corollary 6.3. *The asymptotic diversity gain achieved by the EH-based AF protocol is characterized by:*

$$d^{AF}(r) = 2 \left(1 - \frac{2r}{1-\epsilon} \right)^+ \quad (6.26)$$

Proof: By using (6.11), (6.19) can be rewritten as

$$P_{out}^{AF} = \Pr \left[1 + \psi\delta_3\gamma|h_{s,d}|^2 + \frac{a^2\psi\delta_1\delta_2\gamma|h_{r,d}|^2|h_{s,r}|^2}{1 + a^2\delta_2|h_{r,d}|^2} < (1 + \gamma)^{2\hat{r}} \right] \quad (6.27)$$

Note that at asymptotically high SNR, the scaling factors and also the noise factors do not contribute towards the DMT [46]. Thus, defining v_s, v_r and u as the exponential orders [46] of $1/|h_{s,d}|^2$, $1/|h_{r,d}|^2$ and $1/|h_{s,r}|^2$, respectively, the outage region for AF can be defined as

$$O^+ = \{(v_s, v_r, u) \in \mathbb{R}^{3+} \mid \max \{(1 - (v_r + u))^+, (1 - v_s)^+\} < 2\hat{r}\} \quad (6.28)$$

By denoting $v'_r = v_r + u$, considering the case where $0 \leq v_s, v'_r \leq 1$, and using the Laplace integration technique, the diversity gain can be evaluated by solving the following optimization problem [121]:

$$\begin{aligned} d^{AF}(r) &= \inf_{(v_s, v'_r)} v_s + v'_r \\ \text{s.t. } &\max \left\{ (1 - v'_r)^+, (1 - v_s)^+ \right\} < 2\hat{r} \end{aligned} \quad (6.29a)$$

$$0 \leq v_s, v'_r \leq 1 \quad (6.29b)$$

In the above optimization problem, $\inf$ gives the infimum (largest lower bound) of a set. It is easy to show that for the given constraints, $d^{AF}(r)$ is given by (6.26) and thus complete the proof. ■

Remark 6.1. *Corollary 6.3 implies that for a multiplexing gain of zero ($r = 0$), the EH-based AF protocol achieves full diversity (i.e., $d^{AF}(0) = 2$).*

6.4 EH-Based Decode-And-Forward (EH-DF)

Protocol

As in the case of AF protocol, the performance metrics: outage probability, diversity order, f-DMT, and the asymptotic DMT have been considered for DF protocol as well. The following subsections discuss each of these performance metrics in detail.

The following lemma is needed to evaluate the outage probability of EH-based DF protocol. Note that as defined earlier, X, Y , and Z are exponential random

variables.

Lemma 6.2. *The cumulative distribution function (CDF) $F_\Lambda(\lambda)$ with $\Lambda = X + cYZ$ is given by*

$$F_\Lambda(\lambda) = 1 - c - e^{-\lambda} + 2\lambda K_2 \left(2\sqrt{\frac{\lambda}{c}} \right), \quad (6.30)$$

where c is a constant, and $K_2(\cdot)$ is the second order modified Bessel function of the second kind.

Proof: The proof is given in Appendix C.3. ■

6.4.1 Outage Probability of EH-DF Protocol

The following theorem describes the closed-form expression for the outage probability.

Theorem 6.2. *The outage probability of EH-DF protocol is given by*

$$P_{out}^{DF} = 1 - e^{-\zeta_3} - e^{-\zeta_1} \left(\kappa - 2\zeta_3 K_2 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \right), \quad (6.31)$$

where $\zeta_1 = \frac{1}{\psi\delta_1\gamma} \left[2^{2\hat{R}} - 1 \right]$, and $\kappa = \frac{\bar{\eta}\delta_1\delta_2}{\delta_3}$.

Proof: For DF protocol, the probability of outage for a given target rate R is given as [116]:

$$P_{out}^{DF} = P(E_1)P(E_3) + P(E_2) - P(E_1)P(E_2), \quad (6.32)$$

where E_1 , E_2 , and E_3 are the error events detected at the relay, at the destination with the relay helping, and at the destination after the relay fails to decode the message, respectively. $P(E_i)$, $i \in \{1, 2, 3\}$ are the respective probabilities for the outage error events E_i , $i \in \{1, 2, 3\}$. The outage events and the corresponding

inequalities are listed below [116]:

$$\begin{aligned}
 E_1 : \frac{1-\epsilon}{2} \log(1 + \psi\delta_1 P_s |h_{s,r}|^2) &< R \\
 E_2 : \frac{1-\epsilon}{2} \log(1 + \psi\delta_3 P_s |h_{s,d}|^2 + \bar{\eta} \psi\delta_1 \delta_2 P_s |h_{s,r}|^2 |h_{r,d}|^2) &< R \\
 E_3 : \frac{1-\epsilon}{2} \log(1 + \psi\delta_3 P_s |h_{s,d}|^2) &< R
 \end{aligned} \tag{6.33}$$

The computation of closed-form expressions for $P(E_1)$ and $P(E_3)$ is straightforward since they are corresponding to point-to-point links and are given by:

$$\begin{aligned}
 P(E_1) &= \Pr \left[|h_{s,r}|^2 < \frac{1}{\psi\delta_1\gamma} \left[2^{2\hat{R}} - 1 \right] \right] \\
 &= \Pr \left[|h_{s,r}|^2 < \zeta_1 \right] = 1 - e^{-\zeta_1},
 \end{aligned} \tag{6.34}$$

and

$$\begin{aligned}
 P(E_3) &= \Pr \left[|h_{s,d}|^2 < \frac{1}{\psi\delta_3\gamma} \left[2^{2\hat{R}} - 1 \right] \right] \\
 &= \Pr \left[|h_{s,d}|^2 < \zeta_3 \right] = 1 - e^{-\zeta_3},
 \end{aligned} \tag{6.35}$$

where $\zeta_i = \frac{1}{\psi\delta_i\gamma} \left[2^{2\hat{R}} - 1 \right]$, $i \in \{1, 3\}$.

Next, we compute the closed-form expression for $P(E_2)$.

$$\begin{aligned}
 P(E_2) &= \Pr \left[(1 + \psi\delta_3\gamma |h_{s,d}|^2 + \bar{\eta} \psi\delta_1 \delta_2 \gamma |h_{s,r}|^2 |h_{r,d}|^2) < 2^{2\hat{R}} \right] \\
 &= \Pr \left[X + \kappa Y Z < \frac{1}{\psi\delta_3\gamma} \left[2^{2\hat{R}} - 1 \right] \right] \\
 &= \Pr [X + \kappa Y Z < \zeta_3]
 \end{aligned} \tag{6.36}$$

By noting that the probability of error for event E_2 (i.e., $P(E_2)$) defined in (6.36) is equivalent to the CDF derived in Lemma 6.2. Thus, $P(E_2)$ is obtained by substituting λ and c with ζ_3 and κ , respectively, in Lemma 6.2. The resultant closed-form expression for $P(E_2)$ is shown as follows:

$$P(E_2) = 1 - \kappa - e^{-\zeta_3} + 2\zeta_3 K_2 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \tag{6.37}$$

Finally, by using (6.32), (6.34), (6.35), and (6.37), we get (6.31) and thus

completes the proof. ■

6.4.2 Finite SNR Diversity Order of EH-DF Protocol

The finite SNR diversity order of the DF protocol is computed using the closed-form expression for outage probability given in (6.31) and the definition of diversity order given in (6.13). The following corollary summarizes the result.

Corollary 6.4. *The diversity order of EH-based DF protocol is given by*

$$\tilde{d}_f^{DF}(\gamma) = \frac{e^{-\zeta_1}}{P_{out}(\gamma)} \left[\zeta_3 e^{-(\zeta_3 - \zeta_1)} + \zeta_1 \left(\kappa - 2\zeta_3 K_2 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \right) - \zeta_3 \left(2\sqrt{\frac{\zeta_3}{\kappa}} K_1 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \right) \right] \quad (6.38)$$

Proof: The proof is given in Appendix C.4. ■

6.4.3 f-DMT of EH-DF Protocol

Here, we derive the f-DMT for DF protocol using the results obtained in the previous subsections. The following corollary is the DF counterpart of Corollary 6.2.

Corollary 6.5. *The f-DMT of EH-based DF protocol is characterized by:*

$$d_f^{DF}(r, \gamma) = \frac{e^{-\zeta_1}}{P_{out}(r, \gamma)} \left[\Theta_3 e^{-(\zeta_3 - \zeta_1)} + \Theta_1 \left(\kappa - 2\zeta_3 K_2 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \right) - \Theta_3 \left(2\sqrt{\frac{\zeta_3}{\kappa}} K_1 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \right) \right], \quad (6.39)$$

where $\Theta_i = -\gamma \frac{d\zeta_i}{d\gamma} = \left[\zeta_i - \frac{2\hat{r}}{\psi\delta_i} (1 + \gamma)^{2\hat{r}-1} \right]$, $\forall i \in \{1, 2, 3\}$.

Proof: We have omitted the detailed proof here, since similar to the arguments presented in Corollary 6.2, by replacing ζ_3 with $\frac{1}{\psi\delta_3\gamma} [(1 + \gamma)^{2\hat{r}} - 1]$ in the outage expression for DF protocol given in (6.22), the f-DMT can be computed by following the steps detailed in Appendix C.4. ■

6.4.4 Asymptotic DMT of EH-DF Protocol

The asymptotic DMT can be derived from the high SNR version of outage probability given in (6.31). The result is summarized in the following corollary.

Corollary 6.6. *The asymptotic diversity gain achieved by the EH-based DF protocol is characterized by:*

$$d^{DF}(r) = 2 \left(1 - \frac{2r}{1 - \epsilon} \right)^+ \quad (6.40)$$

Proof: We outline the proof for the sake of brevity since it is analogous to the earlier published work [120]. As detailed in Section 6.3.4, the scaling factors disappear in the asymptotic DMT analysis. Thus, by using the notation introduced in Section 6.3.4, the exponential order equivalents of the rate region definitions given in (6.34), (6.35), and (6.36) are represented by:

$$O^+ = \left\{ (v_s, v_r, u) \in \mathbb{R}^{3+} \mid (1 - u)^+ < 2\hat{r}, (1 - v_s)^+ < 2\hat{r}, \right. \\ \left. \max \{ (1 - (v_r + u))^+, (1 - v_s)^+ \} < 2\hat{r} \right\} \quad (6.41)$$

By considering the case where $0 \leq v_s, v_r, u \leq 1$, and using the Laplace integration technique, the diversity gain can be evaluated by solving the following optimization problem [121]:

$$d^{DF}(r) = \inf_{(v_s, v_r, u)} v_s + v_r + u \\ \text{s.t. } \max \{ (1 - (v_r + u))^+, (1 - v_s)^+ \} < 2\hat{r} \quad (6.42a)$$

$$(1 - v_s)^+ < 2\hat{r}, \quad (1 - u)^+ < 2\hat{r} \quad (6.42b)$$

$$0 \leq v_s, v_r, u \leq 1 \quad (6.42c)$$

It is easy to show that for the given constraints, $d^{DF}(r)$ is given by (6.40) and thus complete the proof. ■

Remark 6.2. *The asymptotic diversity performance of EH-based DF protocol is the same as that of EH-based AF protocol. Therefore, as in the case of AF protocol,*

EH-based DF protocol achieves the asymptotic diversity order of 2.

6.5 Simulation Results and Protocol Comparisons

Figure 6.2: EH-AF protocol: Outage probability versus SNR for different multiplexing gains (r) and time sharing factors (ϵ)

In this section, simulation results are obtained to evaluate the performance of proposed EH-based relaying protocols in terms of outage probability, diversity order, and f-DMT. Without loss of generality, the following parameters have been considered: average transmit power $P_s = 1$ W, path loss exponent $n = 3.7$, energy conversion efficiency $\eta = 1$, and the target data rate $R = 0.2$ bit per channel use (BPCU). It is also assumed that the distance between the source $\mathcal{S}$ and the destination $\mathcal{D}$ is normalized to 1 and the relay is placed between the source ($x = 0, y = 0$) and the destination ($x = 1, y = 1$).

Figure 6.3: EH-DF protocol: Outage probability versus SNR for different multiplexing gains (r) and time sharing factors ($\epsilon \in \{0.01, 0.1, 0.2\}$)

It has been made evident in the earlier Sections that the outage probability expressions derived through Theorem 6.1 and Theorem 6.2 form the basis for the derivation of the rest of the results. Therefore, first, numerical results are provided to analyze and also verify the accuracy of the derived analytical expressions for outage probabilities for both AF and DF protocols using Monte Carlo simulations. Figure 6.2 and Figure 6.3 plot the simulated (and analytical) outage probabilities for AF and DF protocols, respectively, for various time-sharing factors (ϵ) and multiplexing gains (r). Lines represent the results based on simulation, and the symbol markers are based on analytical closed-form expressions. Throughout this section, ϵ value is chosen from $\{0.01, 0.10, 0.20\}$ to elucidate the impact of TS. It is evident from Figure 6.2 and Figure 6.3 that the results based on analytical expressions presented in Theorem 6.1 and Theorem 6.2, respectively, matches with the simulation results for both the protocols. Furthermore, it can be seen that both

of them offer a similar outage performance. As illustrated in Figure 6.2 and Figure 6.3, in the higher-multiplexing-gain regime, the infinitesimal ϵ (e.g. $\epsilon = 0.01$) offers better outage performance. Whereas in low to medium-multiplexing-gain regimes, the infinitesimal ϵ is optimal only at lower SNRs. Another interesting revelation is that there is no virtue in allotting higher than 20% of channel uses for energy harvesting. In other words, across the whole spectrum of operating SNRs, the optimum ϵ is always between 0 and 0.2.

Remark 6.3. *In EH-based protocols, the effect of the fraction of energy harvest duration (ϵ) manifests in two divergent effects. First, the increase in ϵ results in the increase in harvested energy, which in turn reduces the outage probability. Second, the increase in ϵ reduces the forwarding interval, thus aggravates the outage probability. Thus, there is a trade-off in arriving at an optimum ϵ in finite-SNR regime. However, at asymptotically high SNR, the reduction in co-operation phase plays a dominant role in comparison to the marginal increase in harvested energy [124].*

(a) SNR: 0 dB

(b) SNR: 90 dB

Figure 6.4: EH-AF protocol: Outage probability versus relay position

Next, the results are presented to capture the impact of relay position on outage performance at both low and very high SNRs. In Figure 6.4(a) and Figure 6.4(b), the outage probability for AF protocol is plotted against the normalized relay position for low and very high SNRs, respectively. It can be observed from the figures that the system offers the best outage performance when the EH-based relay

Figure 6.5: EH-DF protocol: Outage probability versus relay position

is either near the source or the destination. These results are contrary to the earlier observations related to non-EH relay-based systems, in which the optimal position of the relay is near the midpoint of the source and destination [125]. This intriguing result can be attributed to the wireless energy harvesting mechanism. For this reason, the subsequent simulations consider the relay position as $(x = 0.95, y = 0.01)$. As shown in Figure 6.5(a) and Figure 6.5(b), note that a similar trend can be observed for DF protocol as well. In Figure 6.6, the finite SNR diversity gain for both AF and DF protocols for different time-sharing parameters (ϵ) is presented. It is difficult to obtain insights from finite SNR diversity order expressions given in (6.23) and (6.38). However, as depicted in Figure 6.6, employing the closed-form expressions assists in obtaining numerical results for different time-sharing parameters (ϵ). First, it can be observed in Figure 6.6 that the DF offers marginally better performance in the low-SNR regime, whereas AF performs better in the high SNR scenarios. Secondly, for both AF and DF, the optimum ϵ depends on the SNR. As an example, it can be observed from Figure 6.6 that for SNRs between 10 and 20, $\epsilon = 0.1$ (among $\epsilon \in \{0.01, 0.1, 0.2\}$) offers best performance. Finally, as shown in the inset of the figure, the influence of ϵ is nominal in the high-SNR regime.

In Figure 6.7, we compare the f-DMT performance of proposed EH-based AF and DF protocols at different operating SNRs. Without loss of generality, $\epsilon =$

Figure 6.6: EH-based protocols: finite-SNR diversity order for time sharing factors ($\epsilon \in \{0.01, 0.1, 0.2\}$)

0.1 has been chosen. In Figure 6.7, EH-UB and nonEH-UB refer to asymptotic SNR bounds for EH-based and traditional non-EH-based systems, respectively [121]. It can be seen that the f-DMT performance improves with the increase in SNR and eventually converges to EH asymptotic bound for both AF and DF protocols at asymptotically high SNRs. Moreover, the difference in finite SNR and asymptotic diversity gains is significant in the high-multiplexing-gain regime. Finally, note that the f-DMT performance of both AF and DF protocols exhibit similar behavior across all the multiplexing gains. Even though DF offers better performance compared to AF, the difference is negligible. Thus, for brevity, the subsequent discussion focuses only on the DF protocol.

The f-DMT performance of DF protocol is compared at low, moderate, high, and asymptotically high SNRs for various time-sharing parameters in Figure 6.8. Note that in Figure 6.8, 0 dB, 20 dB, 50 dB, and 100 dB reflect low, medium, high,

 Figure 6.7: EH-based protocols: f-DMT for $\epsilon = 0.1$

and asymptotically high-SNR regimes, respectively. As shown in Figure 6.8, similar to the earlier observations, the optimum ϵ is a function of multiplexing gain and the SNR. However, at asymptotically high SNR, the infinitesimal ϵ value (i.e., $\epsilon = 0.01$) offers the highest diversity gain across all the multiplexing gains. This result agrees with our earlier work related to asymptotic DMT [120, 121]. Moreover, it is also observed that the infinitesimal ϵ offers the best diversity performance at higher multiplexing gains across all SNRs. As highlighted in the figure, the transition point at which $\epsilon = 0.01$ becomes optimal moves up with the increase in SNR. Therefore, comparing with the asymptotic DMT analysis, it is found that the f-DMT reveals the complete interplay between the time-sharing parameter and the SNR.

Figure 6.8: EH-DF protocol: f-DMT for SNRs of 0 dB, 20dB, 50 dB, and 100 dB and for time sharing factors $\epsilon \in \{0.01, 0.1, 0.2\}$. The dotted curves represent f-DMT for asymptotically high SNR (100 dB)

6.6 Summary

In this chapter, the diversity-multiplexing tradeoffs (DMT) of wireless-energy-harvesting (EH)-based AF and DF relaying protocols in the finite-SNR regime have been characterized. Unlike the traditional non-EH-based protocols, it was shown that both EH-based protocols (EH-AF and EH-DF) offer a similar diversity performance across all SNRs. As conjectured in the literature, the diversity gain achieved by both the proposed protocols at low to moderate SNRs is significantly lower than the asymptotic estimate. Moreover, the investigation of results revealed the detailed information concerning the effect of energy-harvesting factor (ϵ) on finite SNR DMT (f-DMT). While confirming the optimality of infinitesimal ϵ at very high SNRs, this work emphasizes the importance of finding optimal ϵ at arbitrary operating SNR. Additionally, this study concluded that the best outage

performance is achieved when the EH-based relay is either close to the source or the destination. Finally, this work unveiled the complete interplay between the time-sharing parameter (ϵ) and the SNR in addition to providing results related to f-DMT.

Chapter 7

Optimal Scheduling Algorithms for EH-Based Systems

7.1 Introduction

Throughout this thesis, it has been considered that there is no power consumption due to the signal processing circuitry in an energy-harvesting (EH)-based relay. However, in low power applications such as sensor networks, these overheads may not be ignored. To appreciate the impact of such costs, in this chapter, a simplistic model in which the data and energy arrive at predetermined times has been considered. The primary objective is to compare and contrast the state-of-the-art optimal scheduling algorithms, which ignores these costs vis-à-vis the systems that consider these overheads. For this purpose, transmission-completion time (or equivalently the maximum achievable throughput) has been considered as the performance metric.

The early works related to battery-powered (BP) wireless networks [126, 127], as well as energy EH-based networks [6, 128], completely ignored the power dissipation associated with the circuitry, such as microcontrollers, sensing circuitry, filters, power-supply subsystem, and so on. For such system models, it

has been established that the amount of energy needed to transmit a fixed amount of information decreases with the increase in transmit-duration [6, 126]. In other words, lazy scheduling algorithms, in which the transmission power is reduced by increasing the transmission duration, are considered optimal. On the other hand, a significant information-theoretic result related to capacity per unit cost for stationary memoryless channels has been proposed [129]. It is shown that signaling, which is not bursty either in frequency or in time, cannot achieve the minimum cost per bit [130]. This implication goes against lazy scheduling algorithms. Thus, it is conjectured that if one includes significant processing cost, it is possible that the optimal scheduling algorithms proposed in the literature might become suboptimal.

Apart from maximizing the energy efficiency (EE) (bits-per-joule), improving the spectral efficiency (SE) (bits-per-second-per-Hz) is tantamount in today's data-hungry applications. Therefore, it is vital to examine the interplay between these two critical metrics instead of studying unilaterally in one particular direction. The trade-off between EE and SE, where EE is a monotonically decreasing function of SE is derived in [126]. However, once the circuit overheads are included, the relation is no longer monotonic but follows the curve shown in Figure 7.1 [5].

Typically, a wireless node operates in three modes: active, idle, and sleep. It is highly desirable to reduce power consumption during all the modes of operation. In general, the power consumption in idle mode is substantial while adding nothing to overall data throughput [131]. Thus, it is always recommended to put the node to sleep while it is not being used for transmission [131]. In the case of sensor networks, the time and the energy to wake up is significant [132]. Therefore, it is essential to consider sleep-to-wake-up power consumption while deriving optimal algorithms. In this chapter, all these overheads are collectively referred to as “processing cost.”

This work adapts state-of-the-art algorithms for more practical

Figure 7.1: EE-SE trade-off for circuit power overhead scenario [5]

power-consumption scenarios that include circuit-power consumption and nonzero sleep-to-wake-up costs. To that end, the following are the contributions of this chapter:

- First, the performance of state-of-the-art transmission algorithms under the purview of nonzero circuit overheads has been investigated. It is shown that the existing algorithms become sub-optimal under these conditions.
- Second, the existing algorithms have been adapted to regain the optimality.
- Finally, simulation results are provided to illustrate the benefits of our approach.

The rest of the chapter is organized as follows. System model is presented in 7.2. Single user capacity with overheads for BP communication system is considered in Section 7.3. Section 7.4 solves the transmission completion time minimization problem for an EH-based network with various overheads. Section 7.5 provides the numerical simulation study and finally Section 7.6 summarizes the chapter.

7.2 System Model with Overheads

The average energy consumption in the wireless node for transmitting a packet of data is given by [132]

$$E = \frac{(p + p_\alpha)l}{R} + p_\alpha \tau_\alpha + p_\beta \tau_\beta, \quad (7.1)$$

where p is the transmit power which drives the RF antenna, p_α is the power consumption of the circuitry, l is the size of the data packet (in bits), R is the data rate (in bits per second, bps), τ_α is the time it takes to wake up from the sleep state, p_β is the power consumption in sleep mode, and τ_β is the time during which the system is in sleep mode. Note that the only component which contributes to the data transmission is p , and the rest is the overhead.

In practice, p_β is significantly smaller compared to p_α and thus can be ignored [133]. Moreover, this work assumes fixed circuit processing power, p_α , which is independent of p . We denote processing cost related to sleep-to-wake-up with E_α which is equal to $p_\alpha \tau_\alpha$. This simplification enables us to solve a tractable problem that reveals valuable insights w.r.to the influence of overheads over scheduling algorithms. We use the following rate function for the analytical study,

$$R(p(t)) = W \log_2 \left(1 + \frac{hp(t)}{WN_0} \right), \quad (7.2)$$

where $R(p(t))$ is the instantaneous achievable data rate for transmit power p at time t , W is the channel bandwidth, N_0 is the Noise power spectral density, and h is the attenuation power loss. In this model, we can get an immediate insight by replacing the cost of transmitting a symbol with $(p + p_\alpha) * l_{on}$, where l_{on} is equal to l/R . It is visible that the increase in l_{on} drives the overhead cost ($p_\alpha * l_{on}$) higher. Based on this, one can deduce that the transmitting at extremely low power for longer duration in the presence of nonzero circuit power is inefficient w.r.to energy efficiency. To start with, we consider a wireless node that needs to transmit B_0 bits of data using E_0 units of energy to its counterpart by a deadline T as shown

Figure 7.2: Single link battery-powered system model with all the data available at $t=0$.

Figure 7.3: Power vs rate for single link battery-powered System model with all the data available at $t=0$ and with processing cost, p_α .

in Figure 7.2. The resultant problem definition as follows:

$$\begin{aligned}
 & \underset{p, t}{\text{minimize}} && T \\
 & \text{subject to} && E(t) \leq E_0, \quad 0 \leq t \leq T \\
 & && B(T) = B_0
 \end{aligned} \tag{7.3}$$

Where $\mathbf{p}$ and $\mathbf{t}$ are the transmission power vector and the corresponding duration vector respectively. $E(t)$ and $B(t)$ are the energy consumed and the transmitted data respectively up to time t . Optimal solution to the above optimization problem can be found by solving for p in the equation below

$$B_0 = \frac{E_0 - E_\alpha}{p + p_\alpha} W \log_2 \left(1 + \frac{hp}{WN_0} \right) \tag{7.4}$$

For example, given $B_0 = 55.8 \text{ Mbits}$, $E_0 = 4.5 \text{ J}$, $E_\alpha = 0.25 \text{ J}$, $p_\alpha = 0.1159w$, $W = 1 \text{ MHz}$, $h = -80 \text{ dB}$, and, $N_0 = 10^{-16} \text{ W/Hz}$, the rate function (7.4) is shown

Figure 7.4: Battery-powered system model with intermittent data availability

in Figure 7.3. We must select the solution with the higher power to minimize T , i.e., $p = 0.236w$ and $l = 4.25/(0.236 + 0.1159) = 12.07s$. The most important inference from the Figure 7.3 is that the maximum energy efficiency can be achieved at unique optimum power, $p_o = 0.079w$, unlike in the system with no overheads. p_o can be derived by maximizing the rate function given in (7.4). p_o and p_α are related by the following equation [130],

$$p_o = \frac{p_\alpha - 1}{W(e^{-1}(p_\alpha - 1))} - 1, \quad (7.5)$$

where the W is the Lambert W-function [134].

7.3 BP: Single User Channel with Processing Costs

In this section, we consider the optimal scheduling algorithm that minimizes the energy consumption [126]. Data arrives during transmission in M discrete time instants as shown in Figure 7.4, and the objective is to transmit all the data by deadline T while consuming minimum energy:

$$\begin{aligned} & \underset{r, l}{\text{minimize}} && E(T) \\ & \text{subject to} && B(t) \leq \sum_{i: t_i < t} B_i, \quad 0 \leq t \leq T \\ & && B(T) = \sum_{i=0}^M B_i \end{aligned} \quad (7.6)$$

In the absense of processing costs, the solution to the above problem follows the

throughput maximization algorithm proposed in [126] as shown below:

$$r_0 = \min_{k \in \{0, \dots, M\}} \left\{ \frac{\sum_{i=0}^k B_i}{t_{k+1}} \right\}, \quad (7.7)$$

$$k_0 = \min \left\{ k : \frac{\sum_{i=0}^k B_i}{t_{k+1}} = r_0 \right\} + 1, \quad l_0 = t_{k_0} \quad (7.8)$$

For $j \geq 0$,

$$r_{j+1} = \min_{k \in \{0, \dots, M-k_j\}} \left\{ \frac{\sum_{i=0}^k B_{k_j+i}}{t_{k_j+1} - t_{k_j}} \right\}, \quad (7.9)$$

$$k_{j+1} = k_j + \min \left\{ k : \frac{\sum_{i=0}^k B_{k_j+i}}{t_{k_j+1} - t_{k_j}} = r_{j+1} \right\} + 1, \quad (7.10)$$

$$l_{j+1} = t_{k_{j+1}} - t_{k_j} \quad (7.11)$$

where $k \in \{1, \dots, M - k_j\}$ and $t_{M+1} = T$. The pair r_j and l_j , $j \in \{1, \dots, J\}$, defines the optimal schedule of transmission rates and transmission times respectively. Where $J = \min \{j : k_j = M\}$. However, if we consider nonzero p_α , this algorithm becomes suboptimal because the optimum transmission power is no longer towards zero but is unique based on the processing cost (7.5). In developing the optimal algorithm for this problem, one need to consider the optimum transmission rate, r_{opt} corresponding to p_o apart from the causality constraints. The adaptation needed to bring back the optimality in the presence of circuit processing costs are as follows:

$$\text{if } r_j \leq r_{opt}, j \in \{1, \dots, J\} \quad (7.12)$$

$$\text{then } r'_j = r_{opt}, l'_j = l_j - l_{jsleep}.$$

Where the pairs (r'_j, l'_j) , $j \in \{1, \dots, J\}$ are the optimum transmission rate and transmission time respectively, and l_{jsleep} represents the length of time during which the system is in sleep mode in j th transmission interval. As we can observe from (7.13), it is no longer suboptimal to put the transmitter in sleep mode.

The above two phase on-off solution becomes sub-optimal for nonzero τ_α because of recurrent sleep-to-wake-up transitions. This issue can be resolved by

consolidating all the sleep intervals in (7.13) as follows:

$$r_0'' = 0, l_0'' = \sum_{j=1}^J l_{j\text{sleep}}, \quad (7.13)$$

$$r_j'' = r_j', \quad l_j'' = l_j - l_{j\text{sleep}}.$$

Where the pairs $(r_j'', l_j''), j \in \{0, \dots, J\}$ are the optimum transmission rate and transmission time respectively.

7.4 EH: Single User Channel with Processing Costs

Optimal algorithms for short-term throughput maximization and transmission completion time minimization for EHWSNs was thoroughly investigated in [6]. However, authors assumed the overhead, p_α as zero. In this work, we study the short-term throughput maximization problem for single user communication system considering nonzero overhead costs.

7.4.1 System Model and Problem Formulation

The system model with energy-arrival information is shown in Figure 7.5. For

Figure 7.5: Simplified system model with initial data availability

nonzero p_α , the optimization problem can be reformulated as:

$$\min_{p, l} \quad T \quad (7.14)$$

$$\text{s.t.} \quad \sum_{i=1}^i (p_i + p_\alpha) l_i \leq \sum_{i: t_i < t} E_i, \quad 0 \leq t \leq T \quad (7.15)$$

$$B(T) = B_0 \quad (7.16)$$

Where T is the transmission completion time, E_i is the quantum of energy harvested at time instant t_i , $i \in \{0, \dots, N-1\}$. Every proposed transmission policy should satisfy the energy-causality constraints given in (7.15). The goal of the optimal algorithm is to minimize T using the available harvested energy.

The procedure proposed in [6, Algorithm 1] cannot be used directly for the system with overheads as it unilaterally follows the lazy scheduling procedure. However, the basic tenets [6, Lemma 1,2,3] can still be used to find the optimal algorithm. To solve the above EH problem, we can use the results obtained in the BP model developed in the earlier section.

If we consider a single epoch case, then the above problem becomes a battery-powered case in which all the energy and data are available at $t = 0$. The optimal transmission power, p_o for a given p_α is given by (7.5) and the corresponding transmit duration is $l_{on}^* = E_0/(p_o + p_\alpha)$. In the case of multiple epochs, the algorithm given in [6] need to be adapted to cater to the scenario with processing costs as shown in the theorem below:

Theorem 7.1. *For a given B_0 and p_α , the policy is optimal if and only if it has the following structure:*

$$\sum_{n=1}^N R(p_n)l_n = B_0 \quad (7.17)$$

and for $n \in \{1, 2, \dots, N\}$,

$$i_n = \arg \min_{i: s_i \leq T} \left\{ \frac{\sum_{j=i_{n-1}}^{i-1} E_j}{s_i - s_{i_{n-1}}} \right\} \quad (7.18)$$

$$p_n = \max \left\{ \frac{\sum_{j=i_{n-1}}^{i-1} E_j}{s_i - s_{i_{n-1}}}, p_o \right\} \quad (7.19)$$

$$l_n = s_{i_n} - s_{i_{n-1}} - l_{n_{sleep}} \quad (7.20)$$

Where $l_{n_{sleep}}$ is the sleep interval during n^{th} transmit slot. The adapted algorithm in (7.1) performs exactly like that of the algorithm given in [5, Table I]. However, similar to the BP case in section 7.3, once we include the sleep-to-wake-

up costs, the on-off algorithm becomes suboptimal. This issue can be resolved by aggregating all the sleep intervals in (7.20) as follows:

$$p'_0 = 0, l_0 = \sum_{n=1}^N l_{n_{sleep}} \quad (7.21)$$

$$p'_n = p_n, l'_n = s_{i_n} - s_{i_{n-1}} - l_{n_{sleep}}, n \in \{1, \dots, N\}$$

Where the pairs $(p'_n, l'_n), n \in \{0, \dots, N\}$ are the optimum transmission power and transmission time respectively. Likewise, the discussion can be extended to the scenario, in which packets arrive during the transmission.

7.5 Simulation Results

In this section, we consider two distinct possibilities. In one case, sleep-to-wake-up is infinitesimally small ($E_\alpha = 0$) while in the other case it is considered to be substantial. For both the scenarios, we compute the total power vector, $\mathbf{p}_{tot}$ and the associated duration vector, $\mathbf{l}_t$ that minimizes the transmission completion time. In this example, B_0 is set as $55.8 Mbits$ and the p_α as $115.9 mw$. The energy arrival times, $\mathbf{t}=[0, 4, 6, 11, 14, 16, 18]s$ and the corresponding energy quantum, $\mathbf{E}=[0.5, 0.5, 0.5, 1, 0.5, 0.75, 0.5]J$ are considered respectively.

- $E_\alpha = 0$

As shown in Figure 7.6(a), the scheduling algorithm proposed for the ideal system (with no overheads) [6] becomes suboptimal. It takes $T = 20s$ to complete the transmission and the associated vectors are: $\mathbf{p}_{tot} = [0.125, 0.14285, 0.3, 0.31264]w$, and $\mathbf{l}_t = [4, 7, 5, 4]s$. This suboptimality has been resolved for $E_\alpha = 0$ by a two-phase solution in [5]. As shown in Figure 7.6(b), two-phase algorithm finishes the transmission in $18.07s$ and its respective power and duration vectors are: $\mathbf{p}_{tot} = [0.195, 0, 0.195, 0, 0.3, 0.375, 7.143]w$, and $\mathbf{l}_t = [2.56, 1.44, 5.12, 1.88, 5.2, 0.07]s$. The optimal total-power and duration vectors for the algorithm proposed in this chapter

Figure 7.6: Scheduling policies for zero sleep-to-wake-up cost(E_α) (a) Allocation policy in [6] (b) Allocation policy in [5] (c) Optimal allocation policy

are $\mathbf{p}_{tot} = [0, 0.079, 0.184, 0.259, 7.03]w$, and $\mathbf{l}_t = [3.32, 7.68, 5, 2, 0.07]s$ respectively. As shown in Figure 7.6(c), this scheduling also achieves optimality.

- $E_\alpha = 58mJ$

In this example, sleep-to-wake-up time, τ_α is chosen as $0.5s$. The resultant overhead, E_α , is $58mJ$. As can be observed from Figure 7.7(b), two-phase algorithm [5] outperforms the scheduling policy proposed in [6]. The

Figure 7.7: Scheduling policies for nonzero sleep-to-wake-up cost ($E_\alpha = 58mJ$): (a) Allocation policy in [6] (b) Allocation policy in [5] (c) Optimal allocation policy

respective power and duration vectors are: $\mathbf{p}_{tot} = [0.195, 0, 0.1159, 0.195, 0, 0.1159, 0.32, 0.375, 0.8305]w$, and $\mathbf{l}_t = [2.56, 1.44, 0.5, 4.83, 1.67, 0.5, 4.5, 2, 0.6]s$. However, due to the recurrent sleep-to-wake-up events, this algorithm becomes suboptimal. It is resolved by our proposed algorithm by aggregating the sleep intervals as shown in Figure 7.7(c). This procedure completes the transmission in 18.18s and the associated vectors are: $\mathbf{p}_{tot} = [0, 0.1159, 0.195, 0.3, 0.375, 2.8]w$, and $\mathbf{l}_t = [3.07, 0.5, 7.43, 5, 2, 0.178]s$.

7.6 Summary

In this chapter, the impact of circuit processing overheads on the optimality of transmission algorithms has been quantified. The analysis started with a traditional battery-powered case, that was modified to include nonzero circuit overhead. For such a model, with the help of the LambertW function [134], the minimum critical power has been deduced. Moreover, it is found that the critical power depends only on the given overhead, not on the transmit power. We used this result to optimize the algorithms for EH-based systems. For ease of exposition, the analysis in this chapter considered the same performance metrics (transmission completion time or maximum throughput) as in the state-of-the-art [5, 6, 128], to compare the classical algorithms with the adapted counterparts. Since the critical power exclusively depends on the overheads, it is essential to conduct the study on circuit processing overheads apart from focusing on the actual transmit power.

Chapter 8

Conclusions and Future Work

This thesis focused on the performance analysis of wireless-energy-harvesting (WEH)-based relay-assisted communication systems using diversity-multiplexing tradeoff (DMT) as a performance metric.

In the first part of this thesis, traditional relaying strategies such as amplify-and-forward (AF), decode-and-forward (DF), and dynamic decode-and-forward (DDF) protocols have been adapted to assess the benefits of incorporating EH-based relays in single-user systems. Our study not only underscored the merits of EH-based relays but also proved that the performance of such systems approached that of their traditional non-EH counterparts when the fraction of time spent on energy harvesting is minimal. These surprising results are particularly useful in exploring EH-relay-based network rollouts in areas where the cost of replacing relay nodes (or the batteries) is substantial. Even though in our study, EH-based DDF (EH-DDF) protocol offered superior performance compared to EH-based non-orthogonal AF (EH-NAF) protocol, the latter is considerably simpler to implement. Thus, the comparison of DMT performance provides valuable inputs to the system developers in choosing the optimum solution.

Contrary to traditional non-EH-based relay-assisted systems, it was observed

that the straightforward extension of EH-based relaying protocols to multiple user systems has limitations. In particular, the diversity performance of EH-DDF for multiple access relay system (MARS) became inferior when compared to traditional battery-powered MARS. In our work, a limited-feedback-based EH-DDF protocol has been proposed to redress the loss in performance. It has been concluded that a little feedback overhead makes the EH relevant even for multiple user networks. These results decisively impacted the rest of our work, especially in exercising caution while extending the EH-based relay methodology to different wireless systems.

Wireless communication systems pursue two divergent objectives: higher data rates and better quality of service. In cellular communications, the first objective is typically achieved through aggressive frequency reuse, which, in turn, leads to interference. In particular, users on cell-edge experience the worst kind of interference. Even for this system, our study revealed the efficacy of incorporating a single EH-based relay.

In EH-based systems, there are two factors that affect diversity performance: the fraction of resources spent on energy harvesting and the quantum of energy harvested. In the asymptotic DMT study, the secondary effect (i.e., the quantum of energy harvested) has been subsumed in the analysis. Thus, for in all the systems mentioned above, the optimum diversity performance has been consistently observed when the fraction of energy harvest duration (ϵ) is infinitesimal. This limitation is addressed by extending the DMT study to arbitrary (finite) SNRs. In this work, we have also investigated the finite SNR DMT of both AF and DF protocols for a single EH-based relay system. Contrary to asymptotic DMT analysis, the finite SNR study captured the complete picture across all the SNRs. Moreover, finite-SNR-based DMT results confirmed the optimality of infinitesimal ϵ at very high SNRs while emphasizing the necessity in finding the optimal ϵ at arbitrary operating SNR. Additionally, this study concluded that the best outage

performance is achieved when the EH-based relay is either close to the source or the destination.

In summary, using DMT as a performance metric, we have demonstrated that the principle objectives (higher data-rates and more reliability) of wireless communication systems can be achieved with WEH-based relay-assisted systems.

8.1 Future Work

This section outlines several possible future directions for the work presented in this thesis. Throughout this thesis, a time-switching-based EH in which the relay operates in three modes— energy harvesting, listening/decoding, and retransmission— has been considered. However, there is an alternative method to implement these protocols using power splitting (PS) approach in which the transmit power is shared between the energy harvesting and the data transmission. Therefore, all the proposed protocols can be adapted to PS-based relaying. Moreover, instead of in-band relaying, in which the receiver harvests the energy from the signal source's radiation, a dedicated transmitter to power all the nodes in the system can be explored.

Several works have been devoted to devising efficient relaying strategies for traditional battery-powered systems. In particular, opportunistic compress-and-forward (CF) schemes that achieve DMT upper bound for non-EH-based relaying can be investigated for EH-based-relay systems. Moreover, hybrid relaying techniques that exploit the benefits of several strategies can also be investigated. In addition, it was recently shown that for EH-based systems that consider full CSI, the harvested energy could be augmented by nonlinear-EH that relies on waveform precoding [135, 136]. Thus, the DMT study for EH-based relay-assisted systems that involves the full CSI is of high importance.

In this work, a finite-SNR DMT analysis is presented for orthogonal AF and DF

protocols to elucidate the effect of energy-harvest duration on diversity performance at an arbitrary SNR assuming perfect CSI at the receiver. This study can be extended to non-orthogonal variants such as EH-DDF to obtain more practical insights. Furthermore, in real systems, neither the transmitter nor the receiver has access to ideal CSI owing to the errors which originate from estimation variance, the time lag between channel estimation and its actual use, quantization errors, and so on. Since, for traditional non-EH based systems, the diversity performance degrades with the degradation in the channel estimates, we conjecture that the imperfect receive CSI leads to inferior diversity performance even in EH-based systems. Therefore, it would be interesting to pursue finite SNR DMT analysis using limited or imperfect CSI as future work.

Another topic that has not been exhaustively considered in this research is the study on the effects of non-idealities such as circuit-processing overheads, decoding power, inefficiencies in EH, and the overheads in energy storage and retrieval. Therefore, a further detailed study in this direction is required to facilitate the practical implementation of WEH-based relay-assisted communication systems.

Appendix A

Proofs of Theorems in Chapter 3

A.1 Proof of Theorem 3.1

The optimization problem defined in (3.13) can be solved by identifying two disjoint constraint regions

1. $2(1 - v_0)^+ \geq (1 - v_1')^+$

It is easy to see from (3.13) that for this category,

$$d(r) = (1 - r)^+ + (1 - 2r)^+. \quad (\text{A.1})$$

2. $2(1 - v_0)^+ < (1 - v_1')^+$

For this case, the (3.13) can be rewritten as

$$\begin{aligned} d(r) &= \inf_{(v_0, v_1')} v_0 + v_1' \\ \text{s.t. } &\epsilon(1 - v_0)^+ + \frac{1 - \epsilon}{2}(1 - v_1')^+ < r \end{aligned} \quad (\text{A.2a})$$

$$(1 - v_1')^+ \geq 2(1 - v_0)^+ \quad (\text{A.2b})$$

$$0 \leq v_0, v_1' \leq 1 \quad (\text{A.2c})$$

Based on ϵ , the constraint region for the above problem can be further subdivided into two regions as shown below

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(a) $\epsilon \leq \frac{1}{3}$

Figure A.1: Outage region: $\epsilon \leq \frac{1}{3}$, $0 \leq r \leq \frac{1}{2}$

Figure A.1 and Figure A.2 depict the constraint regions for $\epsilon \leq \frac{1}{3}$. As can be seen from these figures, the achievable diversity gain for $\epsilon \leq \frac{1}{3}$ is given as

$$d(r) = \begin{cases} (1-r)^+ + (1-2r)^+ & 0 \leq r \leq \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (\text{A.3})$$

(b) $\epsilon > \frac{1}{3}$

Similar to the earlier case, Figure A.3 and Figure A.4 illustrate the constraint regions for $\epsilon > \frac{1}{3}$. Referring to these figures, the achievable diversity gain for $\epsilon > \frac{1}{3}$ can be written as

$$d(r) = \begin{cases} 1 + \left(1 - \frac{2r}{1-\epsilon}\right)^+ & 0 \leq r \leq \frac{1-\epsilon}{2} \\ \left(1 - \frac{r - \frac{1-\epsilon}{2}}{\epsilon}\right)^+ & \frac{1-\epsilon}{2} < r \leq \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (\text{A.4})$$

Now, (A.1), (A.3) and (A.4), result in (3.15) and the proof is complete.

 Figure A.2: Outage region: $\epsilon \leq \frac{1}{3}$, $\frac{1}{2} \leq r \leq 1$

A.2 Proof of Theorem 3.2

We only need to consider the case where $1 \geq v_0 \geq (v_1 + u_1) \geq \dots \geq (v_j + u_j)$, $\forall j \leq N$ [46]. Hence, we can restrict the solution space for the problem defined in (3.20) as follows,

$$\begin{aligned}
 d(r) &= \inf_{(v_i, u_i, \{f_i\}_0^N)} v_0 + \sum_{i=1}^N (v_i + u_i) \\
 \text{s.t. } &\epsilon v_0 + \sum_{i=0}^N f_i v_i \geq 1 - r - \sum_{i=1}^N f_i u_i \\
 &1 \geq v_0 \geq (v_1 + u_1) \geq \dots \geq (v_N + u_N) \geq 0 \\
 &v_i \geq 0, u_i = \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k}\right)^+, i \in \{1, \dots, N\}
 \end{aligned} \tag{A.5}$$

For $v_0 \leq 1$, using the constraint set of (A.5), f_0 is lower bounded as follows

$$f_0 \geq \frac{1 - r - \sum_{i=1}^N f_i (v_i + u_i)}{v_0} - \epsilon \geq 1 - r - \sum_{i=1}^N f_i u_i - \epsilon \geq \frac{1 - \epsilon}{2},$$

Figure A.3: Outage region: $\epsilon > \frac{1}{3}$, $0 \leq r \leq \frac{1}{2}$

also, there is one more constraint for f_0 based on $u_i \geq 0$, i.e., $f_0 \geq r$. By defining $x_i \triangleq (i + 1)(v_i - v_{i+1})$, $\{i = 0, \dots, N - 1\}$, $x_N \triangleq (N + 1)v_N$, it can be easily seen that

$$\sum_{i=0}^N v_i = \sum_{i=0}^N x_i, \quad \epsilon v_0 + \sum_{i=0}^N f_i v_i = \sum_{i=0}^N \frac{\epsilon + \sum_{k=0}^i f_k}{i + 1} x_i \quad (\text{A.6})$$

Using (A.6), (A.5) can be rewritten in terms of x_i as

$$\begin{aligned} d(r) &= \inf_{(x_i, u_i, \{f_i\}_0^N)} x_0 + \sum_{i=1}^N (x_i + u_i) \\ \text{s.t.} \quad &\sum_{i=0}^N \frac{\epsilon + \sum_{k=0}^i f_k}{i + 1} x_i \geq \left(1 - r - \sum_{i=1}^N f_i u_i\right) \\ &x_i \geq 0, \quad u_i = 1 - \frac{r}{\sum_{k=0}^{i-1} f_k}, \quad i \in \{1, \dots, N\} \\ &f_0 \geq \max \left\{ \frac{1 - \epsilon}{2}, r \right\} \end{aligned} \quad (\text{A.7})$$

By using the standard linear programming technique, (A.7) can be rewritten as

$$\inf_{(x_i, u_i, \{f_i\}_0^N)} x_0 + \sum_{i=1}^N (x_i + u_i) = \frac{(p + 1) \left(1 - r - \sum_{i=1}^N f_i u_i\right)}{\epsilon + \sum_{k=0}^p f_k} + \sum_{i=1}^N u_i \quad (\text{A.8})$$

 Figure A.4: Outage region: $\epsilon > \frac{1}{3}$, $\frac{1}{2} \leq r \leq 1$

$$\text{where } p = \arg \max_{0 \leq j \leq N} \left\{ \frac{\epsilon + \sum_{k=0}^j f_k}{j+1} \right\}, \quad f_0 \geq \max \left\{ \frac{1-\epsilon}{2}, r \right\},$$

$$\text{and } \left(\epsilon + \sum_{k=0}^p f_k \right) \geq (p+1) \left(1 - r - \sum_{i=1}^N f_i u_i \right)$$

Using (A.8), we can characterize the DMT as:

$$d(r) = \inf_{(p, u_i, \{f_i\}_{i=0}^N)} \frac{(p+1)(1-r)}{\epsilon + \sum_{k=0}^p f_k} + \sum_{i=1}^N \left(1 - \frac{(p+1)f_i}{\epsilon + \sum_{k=0}^p f_k} \right) u_i \quad (\text{A.9})$$

$$\text{s.t. } u_i = \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k} \right), \quad i \in \{1, \dots, N\}$$

$$f_0 \geq \max \left\{ \frac{1-\epsilon}{2}, r \right\}$$

We can prove that the objective function of the optimization problem in (A.9) is an increasing function of p by showing that its partial derivative with respect to p is positive for all the values of $\{f_i\}_{i=0}^N$, i.e.,

$$\frac{\partial d}{\partial p} = \frac{(1-r)}{\epsilon + \sum_{k=0}^p f_k} - \frac{1}{\epsilon + \sum_{k=0}^p f_k} \sum_{i=1}^N f_i u_i > 0 \quad (\text{A.10})$$

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$$\because (1-r) > (1-f)u_N \geq \sum_{i=1}^N f_i u_i$$

Hence, the infimum of (A.9) with reference to p occurs at $p = 0$ and now (A.9) can be rewritten as

$$\begin{aligned} d(r) = \inf_{\{f_i\}_{i=0}^N} & \frac{(1-r)}{\epsilon + f_0} + \sum_{i=1}^N \left(1 - \frac{f_i}{\epsilon + f_0}\right) \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k}\right) \\ \text{s.t. } f_0 & \geq \max \left\{ \frac{1-\epsilon}{2}, r \right\} \end{aligned} \quad (\text{A.11})$$

Lemma A.1. *The objective function of (A.11) is an increasing function of f_i , $1 \leq i \leq (N-1)$ for given f_0 and ϵ .*

Proof: For $N = 2$, The objective function of (A.11) can be written as

$$\begin{aligned} d(r, f_0, f_1, f_2) = & \frac{1-r}{\epsilon + f_0} + \left(1 - \frac{f_1}{\epsilon + f_0}\right) \left(1 - \frac{r}{f_0}\right) \\ & + \left(1 - \frac{f_2}{\epsilon + f_0}\right) \left(1 - \frac{r}{f_0 + f_1}\right). \end{aligned} \quad (\text{A.12})$$

If f_1 increases to $f_1 + \delta$, then f_2 decreases to $f_2 - \delta$ for fixed f_0 and ϵ ($\because \epsilon + f_0 + f_1 + f_2 = 1$), hence

$$\begin{aligned} d(r, f_0, f_1 + \delta, f_2 - \delta) = & \frac{1-r}{\epsilon + f_0} + \left(1 - \frac{f_1 + \delta}{\epsilon + f_0}\right) \left(1 - \frac{r}{f_0}\right) \\ & + \left(1 - \frac{f_2 - \delta}{\epsilon + f_0}\right) \left(1 - \frac{r}{f_0 + f_1 + \delta}\right). \end{aligned} \quad (\text{A.13})$$

By subtracting (A.12) from (A.13), we get

$$\begin{aligned} \Delta d = & \left(\frac{\delta}{\epsilon + f_0}\right) \left(\frac{r}{f_0} - \frac{r}{f_0 + f_1 + \delta}\right) \\ & + \left(1 - \frac{f_2}{\epsilon + f_0}\right) \left(\frac{r}{f_0 + f_1} - \frac{r}{f_0 + f_1 + \delta}\right) > 0 \quad \text{for } \delta > 0. \end{aligned} \quad (\text{A.14})$$

Hence, $d(r, f_0, f_1, f_2)$ is an increasing function of f_1 for a given f_0 and ϵ . By the principle of induction, we can conclude that (A.11) is an increasing function of $(f_1, \dots, f_{N-1})$ for a given f_0 and ϵ . This completes the proof. ■

By substituting the optimum values of $\{f_i\}_{i=1}^{N-1}$ based on Lemma A.1, and by

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also replacing f_N with $(1 - f_0 - \epsilon)$ in (A.11), we get

$$d(r) = \inf_{(f_0)} \frac{1-r}{f_0 + \epsilon} + \left(\frac{(N+1)(f_0 + \epsilon) - 1}{f_0 + \epsilon} \right) \left(1 - \frac{r}{f_0} \right) \quad (\text{A.15})$$

$$\text{s.t. } f_0 \geq \max \left\{ \frac{1-\epsilon}{2}, r \right\}$$

By taking the first derivative of (A.15) with respect to f_0 and using the fact that $\sqrt{1-x} \approx 1 - \frac{x}{2}$ for $x \ll 1$, the candidate values of f_0 which minimizes (A.15) can be found as

$$f_0 = \max \left\{ \frac{2}{N+2} - \frac{(2N+3)\epsilon}{2N+4}, \frac{1-\epsilon}{2}, r \right\} \quad (\text{A.16})$$

For $N = 1$, the first term on the right hand side (RHS) of (A.16) is the optimal value for f_0 . While for $N > 1$, the second term on the RHS of (A.16) is the optimal value for f_0 . Using these optimal values, the first two diversity order terms in (3.21) and (3.22) can be obtained. Finally, when $f_0 \geq 1 - \epsilon$, none of the relays participate in the retransmission phase, hence, the diversity gain is equal to that of a point-to-point link $(1 - r)$. Hence, proved.

Appendix B

Proof of Lemma in Chapter 5

B.1 Proof of Lemma 5.1

By setting $v_{11} = v_{21}$, and after further simplification,

$$\begin{aligned} d_{\hat{\mathcal{E}}_2}(r, f) &= \inf (2v_{11} + v_{31} + u_{13}) \\ \text{s.t. } f v_{11} + (1 - f)v_{31} &\geq (1 - 2r) - (1 - f) \left(1 - \frac{r}{f_1}\right)^+ \\ 0 &\leq v_{11}, v_{31}, u_{13} \leq 1 \end{aligned} \tag{B.1}$$

By using standard linear programming methods as in [72], we get

$$\begin{aligned} d_{\hat{\mathcal{E}}_2}(r) &= \inf_f \frac{2(1 - 2r)}{f} + \left(\frac{3f - 2}{f}\right) \left(1 - \frac{r}{f - \epsilon}\right) \\ \text{s.t. } f &\geq \max \left\{ r + \epsilon, \frac{1 + 2\epsilon}{3} \right\} \end{aligned} \tag{B.2}$$

By taking the first derivative of (B.2) with respect to f and using the fact that $\sqrt{1 - x} \approx 1 - \frac{x}{2}$ for $x \ll 1$, the candidate values of f which minimizes (B.2) can be found as

$$f = \max \left\{ \frac{4}{7} + \frac{9\epsilon}{14}, \frac{1 + 2\epsilon}{3}, r + \epsilon \right\} \tag{B.3}$$

By substituting the optimum value of f in (B.2), we get (5.24), and (5.25) and thus completes the proof. ■

Appendix C

Proofs of Lemmas and Corollaries in Chapter 6

C.1 Proof of Lemma 6.1

The proof follows in principle the one given by Liu *et al.* [117], i.e., we use the notion of removing the conditioning on random variables to arrive at the eventual CDF. The conditional CDF $F_{\Lambda|X,Y}(u)$ is given by

$$\begin{aligned} F_{\Lambda|X,Y}(u) &= \Pr \left[Z < \left(c_2 + \frac{c_1}{Y} \right) (u - X) \right] \\ &= \begin{cases} 1 - e^{-(c_2 + \frac{c_1}{y})(u-x)} & \text{for } u \geq x \\ 0 & \text{for } u < x \end{cases} \end{aligned}$$

For $u \geq x$, removing the conditioning on Y yields

$$F_{\Lambda|X}(u) = \int_0^\infty \left[1 - e^{-(c_2 + \frac{c_1}{y})(u-x)} \right] e^{-y} dy \quad (\text{C.1})$$

$$= 1 - e^{-c_2(u-x)} \int_0^\infty e^{\left[-\frac{4c_1(u-x)}{4y} - y\right]} dy \quad (\text{C.2})$$

By using [137, Eq. (3.324.1)], (C.2) can be evaluated as

$$F_{\Lambda|X}(u) = 1 - e^{-c_2(u-x)} (2\sqrt{c_1(u-x)}) K_1 \left(2\sqrt{c_1(u-x)} \right), \quad (\text{C.3})$$

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where $K_\nu(\cdot)$ is the modified Bessel function of second kind with order ν . Now, by removing the conditioning on X yields

$$F_\Lambda(u) = 1 - e^{-u} - e^{-c_2 u} \int_0^u e^{-(1-c_2)x} (2\sqrt{c_1(u-x)}) K_1\left(2\sqrt{c_1(u-x)}\right) dx \quad (\text{C.4})$$

It is easy to see that there are two solutions to the above problem in (C.4) based on the value of c_2 . Therefore, the CDF has to be computed for both the cases.

Case 1: $c_2 = 1$

By substituting $c_2 = 1$ in (C.4) and upon using [123, Eq.(7.40)] yields

$$F_\Lambda(u) = 1 - e^{-u} - e^{-u} \frac{1}{2c_1} \left[4c_1 u K_2(2\sqrt{c_1 u}) \Big|_{0^+} - 4c_1 u K_2(2\sqrt{c_1 u}) \right], \quad (\text{C.5})$$

further by expanding the K_2 near zero using the small argument expansion [123, Eq.(7.95)] yields,

$$F_\Lambda(u) = 1 - e^{-u} - \frac{1}{c_1} e^{-u} [1 - 2c_1 u K_2(2\sqrt{c_1 u})] \quad (\text{C.6})$$

Finally by substituting $u = \lambda$, we get the CDF for this case:

$$F_\Lambda(\lambda) = 1 - e^{-\lambda} \left(1 + \frac{1}{c_1} - 2\lambda K_2(2\sqrt{c_1 \lambda}) \right) \quad (\text{C.7})$$

Case 2: $0 < c_2 < 1$

By setting $v = 2\sqrt{c_1(u-x)}$, and after some algebraic manipulation, (C.4) can be rewritten as

$$F_\Lambda(u) = 1 - e^{-u} - \frac{e^{-u}}{2c_1} \int_{2\sqrt{c_1 u}}^0 e^{\frac{1-c_2}{4c_1} v^2} v^2 K_1(v) dv \quad (\text{C.8})$$

By denoting $\bar{c} = \frac{1-c_2}{4c_1}$, and upon expanding $e^{\bar{c}v^2}$ using Taylor series, (C.8) can be rewritten as:

$$F_\Lambda(u) = 1 - e^{-u} - \frac{e^{-u}}{2c_1} \sum_{m=0}^{\infty} \frac{(\bar{c})^m}{m!} \int_{2\sqrt{c_1 u}}^0 v^{2m+2} K_1(v) dv \quad (\text{C.9})$$

The following identity [138] is needed to evaluate the integral in (C.9)

$$\int x^n K_1(x) dx = \left[G_{1,3}^{2,1} \left(\frac{x}{2}, \frac{1}{2} \middle| \begin{matrix} 1 \\ \frac{n}{2}, \frac{n+2}{2}, 0 \end{matrix} \right) \right] + \text{constant} \quad (\text{C.10})$$

where $G(\cdot)$ is the Meijer-G function [123]. Upon using (C.10), the CDF in (C.9) can be evaluated as

$$F_\Lambda(u) = 1 - e^{-u} - \frac{e^{-u}}{2c_1} \sum_{m=0}^{\infty} \frac{(\bar{c})^m}{m!} 2^{2m+1} \left[G_{1,3}^{2,1} \left(\sqrt{c_1}u, \frac{1}{2} \middle| \begin{matrix} 1 \\ m+1, m+2, 0 \end{matrix} \right) \right] \quad (\text{C.11})$$

Finally, by substituting $u = \lambda$, and after some algebraic manipulation, we get

$$F_\Lambda(\lambda) = 1 - e^{-\lambda} \left(1 + \frac{1}{c_1} \sum_{m=0}^{\infty} \frac{(\bar{c})^m}{m!} 2^{2m} \left[G_{1,3}^{2,1} \left(\sqrt{c_1}\lambda, \frac{1}{2} \middle| \begin{matrix} 1 \\ m+1, m+2, 0 \end{matrix} \right) \right] \right) \quad (\text{C.12})$$

By using (C.7), (C.12), we get (6.21) and which completes the proof. ■

C.2 Proof of Corollary 6.1

As the outage probability of AF protocol is composed of two cases based on the value of c_2 , the diversity order also consists of two parts, which are detailed below:

Case 1: $c_2 = 1$

By denoting $x = (2\sqrt{c_1\zeta_3})$, the outage probability (6.22) for this case can be rewritten as

$$P_{out}^{AF} = 1 - e^{-\zeta_3} \left(1 + \frac{1}{c_1} + B_2(x) \right), \quad (\text{C.13})$$

where $B_2(x) = -\frac{1}{2c_1} x^2 K_2(x)$. By using the derivative for modified Bessel function of the second kind [138], the derivative of (C.13) can be evaluated

as

$$\frac{dP_{out}^{AF}(r, \gamma)}{d\gamma} = e^{-\zeta_3} \cdot \frac{d\zeta_3}{d\gamma} \left[1 + \frac{1}{c_1} - 2\zeta_3 K_2 \left(2\sqrt{c_1\zeta_3} \right) - 2\sqrt{c_1\zeta_3} K_1 \left(2\sqrt{c_1\zeta_3} \right) \right], \quad (C.14)$$

where $\frac{\partial \zeta_3}{\partial \gamma} = -\frac{\zeta_3}{\gamma}$. Consequently, by substituting (C.14) in (6.12), yields the desired result given in (6.23).

Case 2: $0 < c_2 < 1$

Upon using the derivative of Meijer-G function [138], the derivative of outage probability (6.22) for this case can be evaluated as:

$$\begin{aligned} \frac{dP_{out}^{AF}(r, \gamma)}{d\gamma} = & e^{-\zeta_3} \cdot \frac{d\zeta_3}{d\gamma} \left(1 + \frac{1}{c_1} \sum_{m=0}^{\infty} \frac{(\bar{c})^m}{m!} 2^{2m} \right. \\ & \left. \left[G_{1,3}^{2,1} \left(\sqrt{c_1\zeta_3}, \frac{1}{2} \middle| \begin{matrix} 1 \\ m+1, m+2, 0 \end{matrix} \right) \right] \right) \\ & - e^{-\zeta_3} \cdot \frac{d\zeta_3}{d\gamma} \left(2\sqrt{c_1\zeta_3} \sum_{m=0}^{\infty} \frac{(4\bar{c}c_1\zeta_3)^m}{m!} K_1 \left(2\sqrt{c_1\zeta_3} \right) \right), \end{aligned} \quad (C.15)$$

where $\bar{c} = \frac{1-c_2}{4c_1}$. After some algebraic manipulations, (C.15) can be rewritten

as

$$\frac{dP_{out}^{AF}(r, \gamma)}{d\gamma} = e^{-\zeta_3} \cdot \frac{d\zeta_3}{d\gamma} \left(1 + \sum_{m=0}^{\infty} \frac{(4\bar{c})^m}{m!} \left[\frac{1}{c_1} G(\sqrt{c_1\zeta_3}) - (c_1\zeta_3)^m B_1(2\sqrt{c_1\zeta_3}) \right] \right), \quad (C.16)$$

where $B_1(x) = xK_1(x)$, and $G(x) = G_{1,3}^{2,1} \left(x, \frac{1}{2} \middle| \begin{matrix} 1 \\ m+1, m+2, 0 \end{matrix} \right)$.

Consequently, by substituting (C.16) in (6.12), yields the result given in (6.23). This completes the proof of Corollary 6.1. ■

C.3 Proof of Lemma 6.2

In this section, we compute the CDF of $F_\Lambda(\lambda)$ with $\Lambda = X + cYZ$. As in the proof of Lemma 6.1, for $u \geq x$, removing the conditioning on Y yields

$$F_{\Lambda|X}(u) = 1 - \int_0^\infty e^{-\frac{u-x}{cy} - y} dy \quad (\text{C.17})$$

By using the table of integrals [137, Eq. (3.324.1)], (C.17) can be evaluated as

$$F_{\Lambda|X}(u) = 1 - 2\sqrt{\left(\frac{u-x}{c}\right)} K_1\left(2\sqrt{\left(\frac{u-x}{c}\right)}\right) \quad (\text{C.18})$$

Next, removing the conditioning on X gives

$$F_\Lambda(u) = \int_0^u \left[1 - 2\sqrt{\left(\frac{u-x}{c}\right)} K_1\left(2\sqrt{\left(\frac{u-x}{c}\right)}\right) \right] e^{-x} dx$$

By setting $v = 2\sqrt{\frac{u-x}{c}}$, and upon using [137, Eq. (5.52.1)] yields

$$F_\Lambda(u) = 1 - e^{-u} - \frac{c}{2} \left[\frac{4u}{c} K_2\left(2\sqrt{\frac{u}{c}}\right) \Big|_{0+} - \frac{4u}{c} K_2\left(2\sqrt{\frac{u}{c}}\right) \right] \quad (\text{C.19})$$

By expanding the modified Bessel function of the second kind K_2 near zero using the small argument expansion [123, Eq.(7.95)] yields the following:

$$F_\Lambda(u) = 1 - c - e^{-u} + 2u K_2\left(2\sqrt{\frac{u}{c}}\right) \quad (\text{C.20})$$

Finally, by substituting $u = \lambda$, we get the desired result in (6.30). This completes the proof of Lemma 6.2 ■

C.4 Proof of Corollary 6.4

In this section, the closed-form expression for the finite-SNR diversity order of EH-based DF protocol has been derived. First, as in Appendix C.2, by using the derivative for modified Bessel function of the second kind [138], the derivative of (6.31) has been evaluated below:

$$\frac{dP_{out}^{DF}(r, \gamma)}{d\gamma} = e^{-\zeta_3} \frac{d\zeta_3}{d\gamma} + e^{-\zeta_1} \frac{d\zeta_1}{d\gamma} \left(\kappa - 2\zeta_3 K_2\left(2\sqrt{\frac{\zeta_3}{\kappa}}\right) \right)$$

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$$- e^{-\zeta_1} \frac{d\zeta_3}{d\gamma} \left(2\sqrt{\frac{\zeta_3}{\kappa}} K_1 \left(2\sqrt{\frac{\zeta_3}{\kappa}} \right) \right), \quad (\text{C.21})$$

where $\frac{\partial \zeta_i}{\partial \gamma} = -\frac{\zeta_i}{\gamma}, \forall i \in \{1, 2\}$. Consequently, by substituting (C.21) in (6.12), we get the desired result given in (6.38). This completes the proof of Corollary 6.4 ■

List of Publications

The following is a list of publications by the author during his Ph.D. candidature.

Journal papers

1. **Rao, Yepuri Sudhakara**, A. S. Madhukumar, and Rajendra Prasad Sirigina. “Wireless Energy Harvesting Based Relaying: A Finite-SNR Diversity-Multiplexing Tradeoff Perspective”, IEEE Transactions on Green Communications and Networking (2019)
2. **Rao, Yepuri Sudhakara**, A. S. Madhukumar, and Rajendra Prasad Sirigina. “RF Energy Harvesting Based Multiple Access Relay Systems: A DMT Perspective”, IEEE Access (2018)
3. **Rao, Yepuri Sudhakara**, A. S. Madhukumar, and Rajendra Prasad Sirigina. “Limited Feedback Assisted Dynamic Decode-and-Forward Relaying for Multiple Access Relay Channel”, Wireless Personal Communications (2018): 1-16.
4. **Rao, Yepuri Sudhakara**, Rajendra Prasad Sirigina, and A. S. Madhukumar. “On the DMT of RF Energy Harvesting-Based Dynamic Decode-and-Forward Relaying.” IEEE Communications Letters 21.1 (2017): 200-203.

Conference papers

1. **Rao, Yepuri Sudhakara**, and A. S. Madhukumar, and Rajendra Prasad Sirigina. “On wireless energy harvesting based relaying for interference limited user: A DMT perspective”, IEEE Globecom Workshops, Abu Dhabi, United Arab Emirates, 2018, pp. 1-6.
2. **Rao, Yepuri Sudhakara**, A. S. Madhukumar, and Rajendra Prasad Sirigina. “RF energy harvesting based relays: Non-orthogonal AF Vs dynamic DF.” 20th International Symposium on Wireless Personal Multimedia Communications (WPMC), IEEE, 2017.
3. **Rao, Yepuri Sudhakara**, and A. S. Madhukumar. “Optimal algorithms for energy harvesting based systems with circuit power considerations.” Region 10 Conference (TENCON), IEEE, 2016.
4. **Rao, Yepuri Sudhakara**, and A. S. Madhukumar., “On optimal transmission policies for non-ideal energy harvesting communication system,” Proc. Smart Wireless Communications Conference (Smartcom’2014), Singapore, October, 2014.

Bibliography

- [1] A. S. Andrae and T. Edler, “On global electricity usage of communication technology: trends to 2030,” *Challenges*, vol. 6, no. 1, pp. 117–157, 2015.
- [2] M.-L. Ku, W. Li, Y. Chen, and K. R. Liu, “Advances in energy harvesting communications: Past, present, and future challenges,” *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1384–1412, 2016.
- [3] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, “Wireless networks with RF energy harvesting: A contemporary survey,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 757–789, 2015.
- [4] R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, May 2013.
- [5] J. Xu and R. Zhang, “Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 2, pp. 322–332, 2014.
- [6] Y. Jing and S. Ulukus, “Optimal packet scheduling in an energy harvesting communication system,” *IEEE Transactions on Communications*, vol. 60, no. 1, pp. 220–230, 2012.
- [7] Y. He, X. Cheng, W. Peng, and G. L. Stuber, “A survey of energy harvesting communications: models and offline optimal policies,” *IEEE Communications Magazine*, vol. 53, no. 6, pp. 79–85, 2015.

-
- [8] 5G-PPP, “5g vision (the next generation of communication networks and services),” *The 5G infrastructure public private partnership [Available Online at: <https://5g-ppp.eu/wpcontent/uploads/2015/02/5G-Vision-Brochure-v1.pdf>]*, 2015.
- [9] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks,” in *Proceedings of the 33rd annual Hawaii international conference on System sciences*. IEEE, 2000, pp. 10–pp.
- [10] T. Van Dam and K. Langendoen, “An adaptive energy-efficient MAC protocol for wireless sensor networks,” in *Proceedings of the 1st international conference on Embedded networked sensor systems*. ACM, 2003, pp. 171–180.
- [11] A. El-Hoiydi and J.-D. Decotignie, “Wisemac: an ultra low power mac protocol for the downlink of infrastructure wireless sensor networks,” in *Proceedings of Ninth International Symposium on Computers and Communications*, vol. 1. IEEE, 2004, pp. 244–251.
- [12] Z. Zhou, S. Zhou, J.-H. Cui, and S. Cui, “Energy-efficient cooperative communication based on power control and selective relay in wireless sensor networks,” in *IEEE Military Communications Conference (MILCOM 2007)*. IEEE, 2007, pp. 1–7.
- [13] G. Y. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, “Energy-efficient wireless communications: tutorial, survey, and open issues,” *IEEE Wireless Communications*, vol. 18, no. 6, 2011.
- [14] T. Rault, A. Bouabdallah, and Y. Challal, “Energy efficiency in wireless sensor networks: A top-down survey,” *Computer Networks*, vol. 67, pp. 104–122, 2014.

-
- [15] M. Peng, K. Zhang, J. Jiang, J. Wang, and W. Wang, "Energy-efficient resource assignment and power allocation in heterogeneous cloud radio access networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 11, pp. 5275–5287, 2015.
- [16] S. Buzzi, I. Chih-Lin, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A survey of energy-efficient techniques for 5G networks and challenges ahead," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 697–709, 2016.
- [17] K. Tutuncuoglu and Yener, "Optimum transmission policies for battery limited energy harvesting nodes," *IEEE Transactions on Wireless Communications*, vol. 11, no. 3, pp. 1180–1189, 2012.
- [18] C. Alippi and C. Galperti, "An adaptive system for optimal solar energy harvesting in wireless sensor network nodes," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 55, no. 6, pp. 1742–1750, 2008.
- [19] Y. K. Tan and S. K. Panda, "Self-autonomous wireless sensor nodes with wind energy harvesting for remote sensing of wind-driven wildfire spread," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 4, pp. 1367–1377, 2011.
- [20] Ö. Zorlu, E. T. Topal, and H. Kulah, "A vibration-based electromagnetic energy harvester using mechanical frequency up-conversion method," *IEEE Sensors Journal*, vol. 11, no. 2, pp. 481–488, 2011.
- [21] V. Leonov, T. Torfs, P. Fiorini, and C. Van Hoof, "Thermoelectric converters of human warmth for self-powered wireless sensor nodes," *IEEE Sensors Journal*, vol. 7, no. 5, pp. 650–657, 2007.
- [22] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. Leung, and

-
- Y. L. Guan, “Wireless energy harvesting for the internet of things,” *IEEE Communications Magazine*, vol. 53, no. 6, pp. 102–108, 2015.
- [23] N. Zhao, F. R. Yu, and V. C. Leung, “Wireless energy harvesting in interference alignment networks,” *IEEE Communications Magazine*, vol. 53, no. 6, pp. 72–78, 2015.
- [24] X. Huang and N. Ansari, “Energy sharing within EH-enabled wireless communication networks,” *IEEE Wireless Communications*, vol. 22, no. 3, pp. 144–149, 2015.
- [25] J. Xu, L. Duan, and R. Zhang, “Cost-aware green cellular networks with energy and communication cooperation,” *IEEE Communications Magazine*, vol. 53, no. 5, pp. 257–263, 2015.
- [26] O. Galinina, K. Mikhaylov, K. Huang, S. Andreev, and Y. Koucheryavy, “Wirelessly powered urban crowd sensing over wearables: Trading energy for data,” *IEEE Wireless Communications*, vol. 25, no. 2, pp. 140–149, 2018.
- [27] E. Telatar, “Capacity of multi-antenna gaussian channels,” *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–595, Nov./Dec. 1999.
- [28] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless personal communications*, vol. 6, no. 3, pp. 311–335, Mar. 1998.
- [29] L. Zheng and D. N. C. Tse, “Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels,” *IEEE Transactions on Information Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.
- [30] P. Viswanath, D. N. C. Tse, and V. Anantharam, “Asymptotically optimal water-filling in vector multiple-access channels,” *IEEE Transactions on Information Theory*, vol. 47, no. 1, pp. 241–267, 2001.

-
- [31] W. Yu and J. M. Cioffi, "Sum capacity of gaussian vector broadcast channels," *IEEE Transactions on Information Theory*, vol. 50, no. 9, pp. 1875–1892, 2004.
- [32] S. Vishwanath, N. Jindal, and A. Goldsmith, "Duality, achievable rates, and sum-rate capacity of Gaussian MIMO broadcast channels," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2658–2668, 2003.
- [33] H. Weingarten, Y. Steinberg, and S. S. Shamai, "The capacity region of the gaussian multiple-input multiple-output broadcast channel," *IEEE Transactions on Information Theory*, vol. 52, no. 9, pp. 3936–3964, 2006.
- [34] D. N. C. Tse, P. Viswanath, and L. Zheng, "Diversity-multiplexing tradeoff in multiple-access channels," *IEEE Transactions Information Theory*, vol. 50, no. 9, pp. 1859–1874, 2004.
- [35] E. C. Van Der Meulen, "Three-terminal communication channels," *Advances in applied Probability*, vol. 3, no. 1, pp. 120–154, 1971.
- [36] T. Cover and A. E. Gamal, "Capacity theorems for the relay channel," *IEEE Transactions on Information Theory*, vol. 25, no. 5, pp. 572–584, 1979.
- [37] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415–2425, Oct 2003.
- [38] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, Dec 2004.
- [39] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE communications Magazine*, vol. 42, no. 10, pp. 74–80, 2004.

-
- [40] Q. Li, R. Q. Hu, Y. Qian, and G. Wu, "Cooperative communications for wireless networks: techniques and applications in LTE-advanced systems," *IEEE Wireless Communications*, vol. 19, no. 2, pp. 22–29, 2012.
- [41] S. O. Gharan, A. Bayesteh, and A. K. Khandani, "On the diversity–multiplexing tradeoff in multiple-relay network," *IEEE Transactions on Information Theory*, vol. 55, no. 12, pp. 5423–5444, 2009.
- [42] M. Yuksel and E. Erkip, "Multiple-Antenna Cooperative Wireless Systems: A Diversity Multiplexing Tradeoff Perspective," *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3371–3393, Oct 2007.
- [43] R. P. Sirigina and A. Madhukumar, "On the symbol error rate and diversity gain region of the relay-assisted Z-channel," *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 1965–1978, 2016.
- [44] R. Tannious and A. Nosratinia, "Spectrally-efficient relay selection with limited feedback," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 8, pp. 1419–1428, 2008.
- [45] A. Benjebbour, Y. Saito, Y. Kishiyama, A. Li, A. Harada, and T. Nakamura, "Concept and practical considerations of non-orthogonal multiple access (noma) for future radio access," in *Proceedings of International Symposium on Intelligent Signal Processing and Communication Systems*. IEEE, 2013, pp. 770–774.
- [46] K. Azarian, H. E. Gamal, and P. Schniter, "On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels," *IEEE Transactions on Information Theory*, vol. 51, no. 12, pp. 4152–4172, Dec 2005.
- [47] D. Chen, K. Azarian, and J. N. Laneman, "A case for amplify-forward

-
- relaying in the block-fading multiple-access channel,” *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3728–3733, Aug 2008.
- [48] D. J. Love, R. W. Heath, V. K. Lau, D. Gesbert, B. D. Rao, and M. Andrews, “An overview of limited feedback in wireless communication systems,” *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 8, 2008.
- [49] Y. Wu, “Achievable rate regions for cooperative relay broadcast channels with rate-limited feedback,” in *IEEE International Symposium on Information Theory (ISIT)*. IEEE, 2016, pp. 1660–1664.
- [50] R. Q. Hu and Y. Qian, “An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems,” *IEEE Communications Magazine*, vol. 52, no. 5, pp. 94–101, 2014.
- [51] H. Chen, Y. Li, J. L. Rebelatto, B. F. Uchoa-Filho, and B. Vucetic, “Harvest-then-cooperate: Wireless-powered cooperative communications,” *IEEE Transactions on Signal Processing*, vol. 63, no. 7, pp. 1700–1711, Apr 2015.
- [52] Y. Gu and S. Aissa, “Rf-based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6425–6434, Nov 2015.
- [53] Y. Liu, “Wireless information and power transfer for multirelay-assisted cooperative communication,” *IEEE Communications letters*, vol. 20, no. 4, pp. 784–787, April 2016.
- [54] R. Narasimhan, “Finite-SNR diversity performance of rate-adaptive MIMO systems,” in *IEEE Global Telecommunications Conference*, vol. 3, Nov 2005, pp. 5 pp.–.
- [55] A. Goldsmith, *Wireless Communications*. Cambridge university press, 2005.

-
- [56] Q. Zhang, J. Jia, and J. Zhang, “Cooperative relay to improve diversity in cognitive radio networks,” *IEEE Communications Magazine*, vol. 47, no. 2, pp. 111–117, 2009.
- [57] Y. Liao, L. Song, Z. Han, and Y. Li, “Full duplex cognitive radio: a new design paradigm for enhancing spectrum usage,” *IEEE Communications Magazine*, vol. 53, no. 5, pp. 138–145, 2015.
- [58] J. Sydir and R. Taori, “An evolved cellular system architecture incorporating relay stations,” *IEEE Communications Magazine*, vol. 47, no. 6, pp. 115–121, 2009.
- [59] B. Timus, J. Hultell, and M. Nilson, “Techno-economical viability of deployment strategies for cellular-relaying networks,” in *VTC Spring 2008-IEEE Vehicular Technology Conference*. IEEE, 2008, pp. 2259–2263.
- [60] N. V. Shende, Ö. Gürbüz, and E. Erkip, “Half-duplex or full-duplex communications: Degrees of freedom analysis under self-interference,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 1081–1093, 2018.
- [61] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge university press, 2005.
- [62] Y. Zhao, R. Adve, and T. J. Lim, “Improving Amplify-and-Forward Relay Networks: Optimal Power Allocation versus Selection,” in *IEEE International Symposium Information Theory*, July 2006, pp. 1234–1238.
- [63] S. Simoens, O. Muñoz-Medina, J. Vidal, and A. Del Coso, “Compress-and-forward cooperative MIMO relaying with full channel state information,” *IEEE Transactions on Signal Processing*, vol. 58, no. 2, pp. 781–791, 2010.
- [64] N. Tesla, “Apparatus for transmitting electrical energy.” *US Patent 1,119,732*, Dec. 1, 1914.

-
- [65] C.-S. Wang, G. A. Covic, and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," *IEEE Transactions on industrial electronics*, vol. 51, no. 1, pp. 148–157, 2004.
 - [66] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *American Association for the Advancement of Science*, vol. 317, no. 5834, pp. 83–86, 2007.
 - [67] Wireless Power Consortium(WPC), "The Qi wireless power transfer system," Part 1 and 2: Interface Definition," *Wireless Power Consortium(WPC)*, Version 1.2.2., 2016a.
 - [68] L. R. Varshney, "Transporting information and energy simultaneously," in *Proceedings IEEE Symposium on Information Theory*, July 2008, pp. 1612–1616.
 - [69] P. Popovski, A. M. Fouladgar, and O. Simeone, "Interactive joint transfer of energy and information," *IEEE Transactions on Communications*, vol. 61, no. 5, pp. 2086–2097, 2013.
 - [70] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Transactions on Communications*, vol. 61, no. 11, pp. 4754–4767, November 2013.
 - [71] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Throughput and ergodic capacity of wireless energy harvesting based DF relaying network," in *IEEE International Conference on Communications (ICC)*, June 2014, pp. 4066–4071.
 - [72] Y. S. Rao, R. P. Sirigina, and A. Madhukumar, "On the DMT of RF energy harvesting-based dynamic decode-and-forward relaying," *IEEE Communications letters*, vol. 21, no. 1, pp. 200–203, 2017.

-
- [73] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622–3636, July 2013.
- [74] —, "Wireless-powered relays in cooperative communications: Time-switching relaying protocols and throughput analysis," *IEEE Transactions on Communications*, vol. 63, no. 5, pp. 1607–1622, 2015.
- [75] T. Li, P. Fan, and K. B. Letaief, "Outage probability of energy harvesting relay-aided cooperative networks over rayleigh fading channel," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 2, pp. 972–978, 2016.
- [76] I. Krikidis, S. Sasaki, S. Timotheou, and Z. Ding, "A Low Complexity Antenna Switching for Joint Wireless Information and Energy Transfer in MIMO Relay Channels," *IEEE Transactions on Communications*, vol. 62, no. 5, pp. 1577–1587, May 2014.
- [77] Y. Chen, R. Shi, W. Feng, and N. Ge, "AF relaying with energy harvesting source and relay," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 1, pp. 874–879, 2017.
- [78] S. Modem and S. Prakriya, "Optimization of links with a battery-assisted time-switching wireless energy harvesting relay," *IEEE Systems Journal*, 2017.
- [79] X. Di, K. Xiong, P. Fan, and H.-C. Yang, "Simultaneous wireless information and power transfer in cooperative relay networks with rateless codes," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 2981–2996, Apr. 2017.
- [80] J. Castura and Y. Mao, "Rateless coding over fading channels," *IEEE communications letters*, vol. 10, no. 1, pp. 46–48, 2006.

-
- [81] M. R. Aref, “Information flow in relay networks,” Ph.D. dissertation, Stanford university, 1981.
- [82] P. Gupta and P. Kumar, “Towards an information theory of large networks: an achievable rate region,” *IEEE Transactions on Information Theory*, vol. 49, no. 8, pp. 1877–1894, 2003.
- [83] L.-L. Xie and P. R. Kumar, “Multisource, multideestination, multirelay wireless networks,” *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3586–3595, 2007.
- [84] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *IEEE Transactions on Information Theory*, vol. 51, no. 9, pp. 3037–3063, Sept 2005.
- [85] J. N. Laneman, “Cooperative diversity in wireless networks: Algorithms and architectures,” Ph.D. dissertation, Massachusetts Institute of Technology, 2002.
- [86] F. Oggier and B. Hassibi, “An algebraic coding scheme for wireless relay networks with multiple-antenna nodes,” *IEEE Transactions on Signal processing*, vol. 56, no. 7, pp. 2957–2966, 2008.
- [87] Y. Jing and B. Hassibi, “Distributed space-time coding in wireless relay networks,” *IEEE Transactions on Wireless Communications*, vol. 5, no. 12, pp. 3524–3536, Dec 2006.
- [88] Y. Jing and H. Jafarkhani, “Distributed differential space-time coding for wireless relay networks,” *IEEE Transactions on Communications*, vol. 56, no. 7, 2008.
- [89] —, “Relay power allocation in distributed space-time coded networks with channel statistical information,” *IEEE Transactions on Wireless Communications*, vol. 10, no. 2, pp. 443–449, 2011.

-
- [90] G. Scutari and S. Barbarossa, “Distributed space-time coding for regenerative relay networks,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 5, pp. 2387–2399, 2005.
 - [91] S. Atapattu, H. Jiang, J. Evans, and C. Tellambura, “Time-switching energy harvesting in relay networks,” in *IEEE International Conference on Communications (ICC)*. IEEE, 2015, pp. 5416–5421.
 - [92] D. S. Michalopoulos, H. A. Suraweera, and R. Schober, “Relay selection for simultaneous information transmission and wireless energy transfer: A tradeoff perspective,” *IEEE journal on Selected Areas in Communications*, vol. 33, no. 8, pp. 1578–1594, 2015.
 - [93] I. Krikidis, “Simultaneous information and energy transfer in large-scale networks with/without relaying,” *IEEE Transactions on Communications*, vol. 62, no. 3, pp. 900–912, 2014.
 - [94] G. Kramer and A. J. van Wijngaarden, “On the white Gaussian multiple-access relay channel,” in *IEEE International Symposium on Information Theory*. IEEE, 2000, p. 40.
 - [95] L. Sankaranarayanan, G. Kramer, and N. B. Mandayam, “Capacity theorems for the multiple-access relay channel,” in *Proceedings 42nd Annu. Allerton Conference Communications, Control, and Computing*, 2004, pp. 1782–1791.
 - [96] L. Sankar, G. Kramer, and N. B. Mandayam, “Offset encoding for multiple-access relay channels,” *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3814–3821, 2007.
 - [97] K. Azarian, H. E. Gamal, and P. Schniter, “On the optimality of the ARQ-DDF protocol,” *IEEE Transactions on Information Theory*, vol. 54, no. 4, pp. 1718–1724, April 2008.

-
- [98] M. Abouelseoud and A. Nosratinia, “Opportunistic wireless relay networks: diversity-multiplexing tradeoff,” *IEEE Transactions on Information Theory*, vol. 57, no. 10, pp. 6514–6538, 2011.
- [99] K. Tutuncuoglu and A. Yener, “Cooperative energy harvesting communications with relaying and energy sharing,” in *IEEE Information Theory Workshop (ITW)*,. IEEE, 2013, pp. 1–5.
- [100] A. Rajaram, D. N. K. Jayakody, K. Srinivasan, B. Chen, and V. Sharma, “Opportunistic-harvesting: RF wireless power transfer scheme for multiple access relays system,” *IEEE Access*, vol. 5, pp. 16 084–16 099, 2017.
- [101] O. Sahin and E. Erkip, “Achievable rates for the gaussian interference relay channel,” in *Global Telecommunications Conference (GLOBECOM’07)*. IEEE, 2007, pp. 1627–1631.
- [102] A. Carleial, “Interference channels,” *IEEE Transactions on Information Theory*, vol. 24, no. 1, pp. 60–70, 1978.
- [103] I. Maric, R. Dabora, and A. Goldsmith, “On the capacity of the interference channel with a relay,” in *IEEE International Symposium on Information Theory*. IEEE, 2008, pp. 554–558.
- [104] I. Maric, R. D. Yates, and G. Kramer, “Capacity of interference channels with partial transmitter cooperation,” *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3536–3548, 2007.
- [105] D. Zahavi and R. Dabora, “On the sum-rate capacity of the phase fading z-interference channel with a relay in the weak interference regime,” in *IEEE International Symposium on Information Theory*, 2013, pp. 2414–2418.
- [106] D. Zahavi, L. Zhang, I. Maric, R. Dabora, A. J. Goldsmith, and S. Cui, “Diversity-multiplexing tradeoff for the interference channel with a relay,” *IEEE Transactions on Information Theory*, vol. 61, no. 2, pp. 963–982, 2015.

-
- [107] D. Zahavi and R. Dabora, “On cooperation and interference in the weak interference regime,” *IEEE Transactions on Information Theory*, vol. 63, no. 6, pp. 3894–3922, 2017.
- [108] G. Zhu, C. Zhong, H. A. Suraweera, G. K. Karagiannidis, Z. Zhang, and T. A. Tsiftsis, “Wireless information and power transfer in relay systems with multiple antennas and interference,” *IEEE Transactions on Communications*, vol. 63, no. 4, pp. 1400–1418, 2015.
- [109] Y. Chen, “Energy-harvesting af relaying in the presence of interference and nakagami- m fading,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 2, pp. 1008–1017, 2016.
- [110] B. Medepally and N. B. Mehta, “Voluntary energy harvesting relays and selection in cooperative wireless networks,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3543–3553, 2010.
- [111] M. S. Nafea, K. G. Seddik, M. Nafe, and H. E. Gamal, “On the diversity gain region of the Z-interference channels,” in *IEEE International conference on Communications (ICC 2012)*, June 2012, pp. 2392–2397.
- [112] C. Helmberg, F. Rendl, R. J. Vanderbei, and H. Wolkowicz, “An interior-point method for semidefinite programming,” *SIAM Journal on Optimization*, vol. 6, no. 2, pp. 342–361, 1996.
- [113] R. P. Sirigina and A. Madhukumar, “On the diversity gain region of the dynamic decode-and-forward relay-assisted Z-channel,” *Wireless Networks*, pp. 1–13, Aug 2016.
- [114] J. Lee, D. Toumpakaris, and W. Yu, “Interference mitigation via joint detection,” *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 6, pp. 1172–1184, 2011.

-
- [115] R. P. Sirigina and A. Madhukumar, “Interference mitigation in Z-channel and relay-assisted Z-channel: a diversity gain region perspective,” *Wireless Networks*, vol. 23, no. 1, pp. 51–63, 2017.
 - [116] E. Stauffer, O. Oyman, R. Narasimhan, and A. Paulraj, “Finite-SNR diversity-multiplexing tradeoffs in fading relay channels,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, 2007.
 - [117] Y. Liu, P. Dharmawansa, M. R. McKay, and K. B. Letaief, “Finite-SNR diversity-multiplexing trade-off of dual hop multiple-relay channels,” *IEEE Transactions on Communications*, vol. 60, no. 5, pp. 1451–1463, 2012.
 - [118] A. El Falou, W. Hamouda, C. Langlais, C. A. Nour, and C. Douillard, “Finite-SNR diversity-multiplexing tradeoff for Rayleigh MIMO channels,” *IEEE Communications letters*, vol. 17, no. 4, pp. 753–756, 2013.
 - [119] Z. Chen, B. Xia, and H. Liu, “Wireless information and power transfer in two-way amplify-and-forward relaying channels,” in *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Dec 2014, pp. 168–172.
 - [120] S. rao Yepuri, R. P. Sirigina, and A. Madhukumar, “On the DMT of RF energy harvesting based dynamic decode-and-forward relaying,” *IEEE Communications letters*, 2016.
 - [121] Y. S. Rao, A. Madhukumar, and R. P. Sirigina, “RF energy harvesting based relays: Non-orthogonal AF Vs dynamic DF,” in *20th International Symposium on Wireless Personal Multimedia Communications (WPMC)*. IEEE, 2017, pp. 506–510.
 - [122] R. Narasimhan, “Finite-SNR diversity-multiplexing tradeoff for correlated rayleigh and rician mimo channels,” *IEEE Transactions on Information Theory*, vol. 52, no. 9, pp. 3965–3979, 2006.

-
- [123] L. C. Andrews, *Special functions of mathematics for engineers*. McGraw-Hill New York, 1992.
- [124] Y. S. Rao, A. S. Madhukumar, and R. P. Sirigina, “RF energy harvesting based multiple access relay systems: A DMT perspective,” *IEEE Access*, pp. 1–12, 2018.
- [125] X. Lin, M. Tao, Y. Xu, and R. Wang, “Outage probability and finite-SNR diversity-multiplexing tradeoff for two-way relay fading channels,” *IEEE Transactions on Vehicular Technology*, vol. 62, no. 7, pp. 3123–3136, 2013.
- [126] E. Uysal-Biyikoglu, B. Prabhakar, and A. El Gamal, “Energy-efficient packet transmission over a wireless link,” *IEEE/ACM Transactions on Networking (TON)*, vol. 10, no. 4, pp. 487–499, 2002.
- [127] W. Chen, M. J. Neely, and U. Mitra, “Energy-efficient transmissions with individual packet delay constraints,” *IEEE Transactions on Information Theory*, vol. 54, no. 5, pp. 2090–2109, May 2008.
- [128] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus, and A. Yener, “Transmission with energy harvesting nodes in fading wireless channels: Optimal policies,” *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1732–1743, 2011.
- [129] S. Verdú, “On channel capacity per unit cost,” *IEEE Transactions on Information Theory*, vol. 36, no. 5, pp. 1019–1030, 1990.
- [130] P. Youssef-Massaad, L. Zheng, and M. Médard, “Bursty transmission and glue pouring: on wireless channels with overhead costs,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 5188–5194, 2008.
- [131] A. Chandrakasan, R. Min, M. Bhardwaj, S. Cho, and A. Wang, “Power aware wireless microsensor systems,” in *Proceedings of the 28th European Solid-State Circuits Conference , (ESSCIRC 2002)*. IEEE, 2002, pp. 47–54.

-
- [132] B. H. Calhoun, D. C. Daly, N. Verma, D. F. Finchelstein, D. D. Wentzloff, A. Wang, S.-H. Cho, and A. P. Chandrakasan, "Design considerations for ultra-low energy wireless microsensor nodes," *IEEE Transactions on Computers*, vol. 54, no. 6, pp. 727–740, Jun 2005.
- [133] S. Nedeveschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall, "Reducing network energy consumption via sleeping and rate-adaptation." in *NsDI*, vol. 8, 2008, pp. 323–336.
- [134] R. M. Corless, G. H. Gonnet, D. E. Hare, D. J. Jeffrey, and D. E. Knuth, "On the LambertW function," *Advances in Computational mathematics*, vol. 5, no. 1, pp. 329–359, 1996.
- [135] B. Clerckx and E. Bayguzina, "Waveform design for wireless power transfer," *IEEE Transactions on Signal Processing*, vol. 64, no. 23, pp. 6313–6328, Dec 2016.
- [136] Y. Huang and B. Clerckx, "Waveform design for wireless power transfer with limited feedback," *IEEE Transactions on Wireless Communications*, vol. 17, no. 1, pp. 415–429, Jan 2018.
- [137] A. Jeffrey, D. Zwillinger, I. Gradshteyn, and I. Ryzhik, "3-4 - Definite Integrals of Elementary Functions," in *Table of Integrals, Series, and Products (Seventh Edition)*. Academic Press, 2007, pp. 247 – 617. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/B9780080471112500133>
- [138] W. R. Inc., "Mathematica, Version 11.3," champaign, IL, 2018.