Relay Selection in SWIPT-based Energy Harvesting Relay Networks under co-channel Interference

By

Maira Imran

Fall 2016-MS(EE)-8-00000172217

Supervisor

Dr. Syed Ali Hassan

Department of Electrical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree
of Masters of Science in Electrical Engineering (MS EE)

In

School of Electrical Engineering and Computer Science,
National University of Sciences and Technology (NUST),
Islamabad, Pakistan.
(September 2018)

Approval

It is certified that the contents and form of the thesis entitled "**Relay Selection in SWIPT-based Energy Harvesting Relay Networks under co-channel Interference**" submitted by **Maira Imran** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Syed Ali Hassan**

Signature: __________________

Date: __________________

Committee Member 1: **Dr. Sajid Saleem**

Signature: ____________________

Date: ____________________

Committee Member 2: **Dr. Fahd Ahmed khan**

Signature: ____________________

Date: ____________________

Committee Member 3: **Dr Hassaan Khaliq**

Signature: ____________________

Date: ____________________

Abstract

Billions of radio transmitters are currently broadcasting radio frequency (RF) energy around the world. This energy could be harvested to prolong the lifespan of wireless networks. In this work, two approaches are proposed to retrieve the harvested energy from co-channel interference (CCI) signals and infinite capacity rechargeable batteries in a simultaneous wireless information and power transfer (SWIPT) based decode and forward (DF) relaying system. In the first scheme, the DF relays use all the harvested energy to decode the received signal and forward it to the destination node, emptying the battery for next transmission. In the second scheme, relays use only required amount of harvested energy to decode and forward the source signal to the destination, thus making the system energy efficient. A power splitting (PS) technique is espoused in which some portion of received signal is used to decode and the remaining portion is used to forward the signal. Furthermore, the optimum value of power splitting (PS) factor ρ is examined to maximize the system throughput. It is shown that an energy efficient system harvests and keeps more energy in a battery at high signal-to-interference-plus-noise ratio (SINR).

Dedication

I dedicate this thesis to my husband, my parents and my teachers.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Maira Imran**
Signature: ________________

Acknowledgment

First and foremost, I would like to thank Allah Almighty for giving me the opportunity, determination and courage to complete my research. Nothing could have been possible without His blessings.

I would like to express my sincere gratitude to my advisor, Dr. Syed Ali Hassan, without whom not a single page of the thesis would have been possible. I have been extremely fortunate to work under his supervision. His consistency and valuable guidance kept me going throughout this journey for which I am grateful to him. I will never forget his quick feedback and constructive comments which were really inspiring and helpful.

I would also like to thank all my lab mates for being amazing colleagues.

Finally, I give special thanks to my incredible parents and ever supporting husband for their tireless efforts and guidance at every stage of my personal and academic life. I dedicate this thesis to my husband and my parents. Thank you for your endless support and unconditional confidence in me.

Contents

List of Figures **ix**

1 Introduction **1**

1.1 Simultaneous Wireless Information and Power Transfer 1

1.2 Techniques for SWIPT 2

1.2.1 Power Splitting (PS) 2

1.2.2 Time Splitting (TS) 3

1.2.3 Antenna Switching (AS) 4

1.2.4 Spatial Switching (SS) 4

1.3 Relayed Transmissions 5

1.4 Relaying Techniques 5

1.4.1 Amplify and Forward (AF) 5

1.4.2 Decode and Forward (DF) 6

1.4.3 Demodulate and Forward (DMF) 7

1.4.4 Hybrid AF and DF 7

1.5 Thesis Contribution 7

1.6 Thesis Organization 8

2 Background and Literature Review **10**

2.1 Relay Selection in SWIPT 10
2.2 Battery-Aware Relay Selection 12
2.3 Interference Aided Energy Harvesting 13

3 Relay Selection Schemes 15

3.1 Rate Maximization Scheme 15
3.2 System Model 16
3.3 Algorithm for Rate Maximization Scheme 17
3.4 Energy Efficient Scheme 20
3.5 Algorithm for Energy Efficient Scheme 20

4 Simulation Results 23

5 Conclusions and Future Work 43

5.1 Future Work 44

Bibliography 45

List of Figures

1.1 *PS technique of SWIPT* 3

1.2 *TS technique of SWIPT* 3

1.3 *AS technique of SWIPT* 4

1.4 *SS technique of SWIPT* 5

1.5 *AF relaying technique* 6

1.6 *DF relaying technique* 6

3.1 *System Model* 17

3.2 *Algorithm 1* 18

3.3 *Algorithm 2* 22

4.1 *Success probability of different channels using DF path only* . . 24

4.2 *Success probability for N number of relays* 24

4.3 *Success probability for selecting N best links* 25

4.4 *Success probability for selecting best, random and worst SNR link* 26

4.5 *Success probability in the presence of CCI signals* 27

4.6 *Success probability for selecting m out of N relays* 28

4.7 *Success probability for different values of PS factor* ρ 29

4.8 *Success probability for different values of PS factor* ρ 30
4.9 *Rho optimum for different values of SNR* 31
4.10 *Comparison of success probability at fixed value of* ρ *and optimum value of* ρ *at different SNR* 32
4.11 *Comparison of success probability at fixed value of* ρ *and optimum value of* ρ *in Rate Maximization scheme* 33
4.12 *Comparison of success probability at fixed value of* ρ *and optimum value of* ρ *in Energy Efficient scheme* 34
4.13 *Rate Maximization scheme in the presence of co-channel interferer (CCI) signals* 35
4.14 *Energy Efficient scheme in the presence of co-channel interferer (CCI) signals* 36
4.15 *Rate Maximization scheme for N number of relays* 37
4.16 *Battery status at high SNR in Rate Maximization scheme* . . . 38
4.17 *Contour plot for battery status in Rate Maximization scheme* . 39
4.18 *Energy Efficient scheme for N number of relays* 40
4.19 *Battery status at high SNR in Energy Efficient scheme* 41
4.20 *Contour plot for battery status in Energy Efficient scheme* . . 42

Chapter 1

Introduction

This chapter provides a brief introduction about simultaneous wireless information and power transfer (SWIPT) and it's techniques. Relaying techniques are also discussed briefly. After that, thesis contribution is presented and then, thesis organization concludes this chapter.

1.1 Simultaneous Wireless Information and Power Transfer

To meet the growing demand of connecting everything, integrating energy harvesting technologies into communication networks has provided another provision. Solar and wind energy resources are contributing a great deal towards harvesting energy. However, harvesting energy from such sources becomes critical due to their unpredictable and sporadic nature. Another energy harvesting technology, wireless power transfer (WPT) proves to be overcoming these limitations as electromagnetic radiations charge the batteries of nodes in this technology [1].To get further gains in spectral efficiency, latency and managing interference, simultaneous wireless information and power transfer (SWIPT) is a promising solution [2–5]. It exchanges information and harvests energy at the same time, making it effective for ultra low power sensors and biomedical devices [6]. Furthermore, it could also be integrated in millimeter-wave technologies and massive multiple-input multiple-output (MIMO) to overcome fading and path loss effects.

1.2 Techniques for SWIPT

The received signal is split in two distinct parts to achieve SWIPT, one for information decoding and other for energy harvesting as it is not possible for a single signal to simultaneously harvest energy and forward information.

1.2.1 Power Splitting (PS)

SWIPT is achieved in PS technique by splitting the received signal into two streams of different power levels. One is used to decode information and the other stream is used to broadcast information to the destination [7]. This technique is found to be more complex than time switching (TS) technique as the PS factor ρ needs to be optimized, however, it is useful for such applications where one time slot is needed for both harvesting energy and forwarding information as shown in Fig. 1.1.

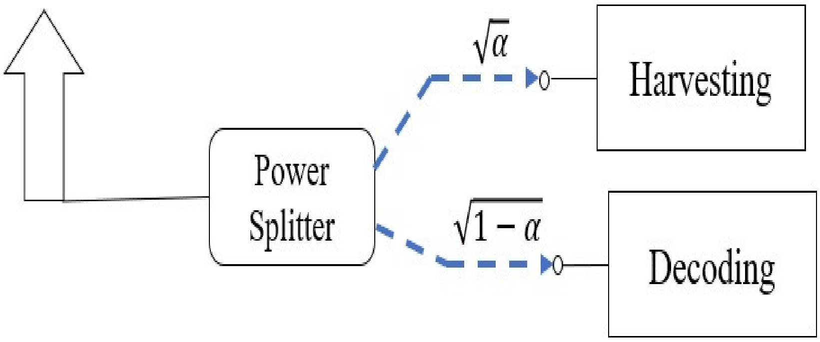

Figure 1.1: *PS technique of SWIPT*

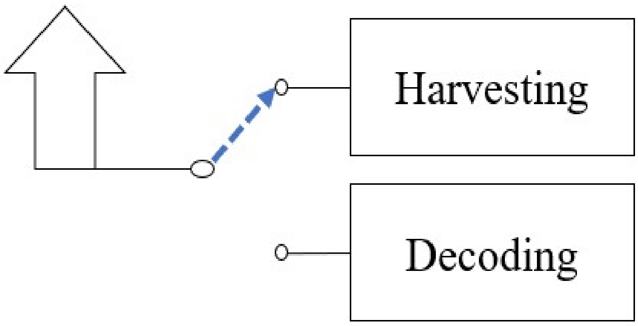

Figure 1.2: *TS technique of SWIPT*

1.2.2 Time Splitting (TS)

In TS technique one time slot is used for both harvesting energy and forwarding information. The received signal is switched between information decoding and energy harvesting in the same time slot [8]. It's hardware implementation is comparatively easy but it requires time synchronization. It can be more clearly seen in Fig. 1.2.

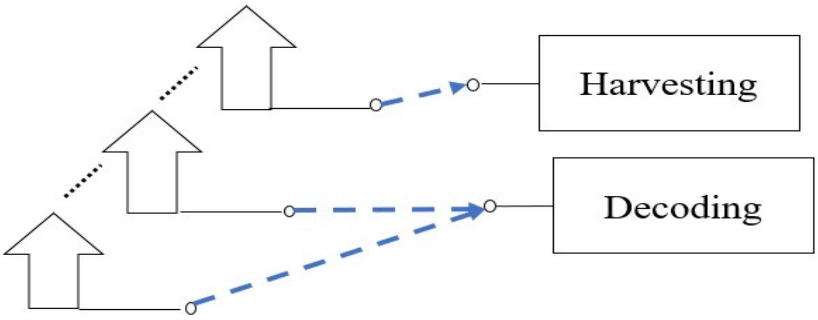

Figure 1.3: *AS technique of SWIPT*

1.2.3 Antenna Switching (AS)

In this technique DC power is generated by antenna arrays. The antennas of received signals are divided into two groups [9]. Energy harvesting is done by one group and information decoding is done by another group as shown in Fig. 1.3. The hardware of AS technique of SWIPT is highly complex. Generalized selection combining (GSC) could be used in low complex AS mechanisms to overcome optimization problem.

1.2.4 Spatial Switching (SS)

SS technique could be implemented in interfering channels. In this technique, the communication link is converted into parallel eigenchannels [10]. Energy or information could be conveyed by these channels. There is a switch at the output of each eigenchannel as shown in Fig. 1.4, that drives to either decoding information or harvesting energy. Optimization problem arises in assignment of eigenchannels and their power allocation.

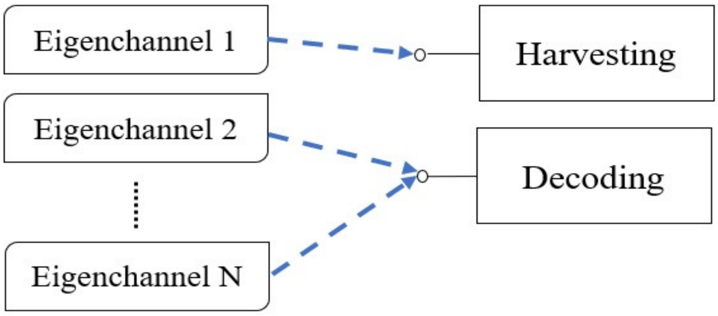

Figure 1.4: *SS technique of SWIPT*

1.3 Relayed Transmissions

Relaying plays an important role in wireless communications as it promises to improve the quality of a wireless channel. It is easy to implement and it increases connectivity. It is robust to changing channel conditions which is not the case with the direct link transmissions.

1.4 Relaying Techniques

Relays work on different techniques based on their ability to forward the received signal [11].

1.4.1 Amplify and Forward (AF)

In AF relaying technique, noise signal is also amplified along with the information signal as shown in Fig. 1.5 [12]. Large amount of analog needs to be stored in it, so it is difficult to be implemented in TDMA systems. The signal quality is however degraded at low SNR due to noise amplification.

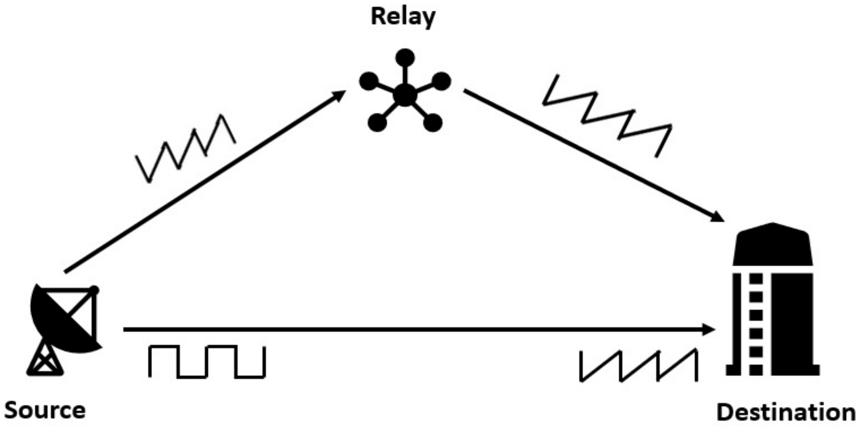

Figure 1.5: *AF relaying technique*

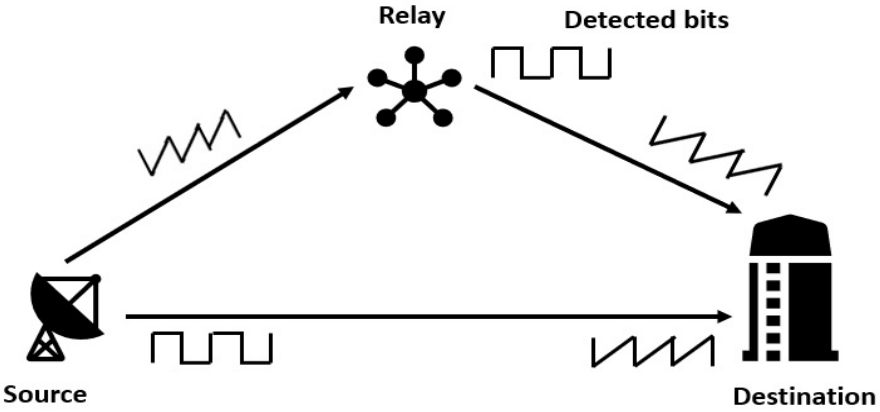

Figure 1.6: *DF relaying technique*

1.4.2 Decode and Forward (DF)

In DF relaying technique, received signal is forwarded only when the relay is able to decode it [13]. SNR threshold and error count checks the detected bits. Noise is removed in this technique as shown in Fig. 1.6 DF relaying finds its applications in wireless sensor networks, wireless ad-hoc networks and vehicle-to-vehicle communication.

1.4.3 Demodulate and Forward (DMF)

In this technique the received signal is first demodulated by relay and then is forwarded to the destination [14]. The signal is demodulated without detecting it. This technique is comparatively less complex than DF relaying as the signal is demodulated as received.

1.4.4 Hybrid AF and DF

This technique switches between AF and DF based on the channel condition [15]. If the channel condition is good, message signal is decoded and original bits are received at the destination. However, for poor channel condition, noise is amplified along with the message signal and is received at the destination node.

1.5 Thesis Contribution

The main contributions of this thesis can be listed as:

- In this thesis, we propose two novel approaches for relay selection in SWIPT-based energy harvesting co-operative network under infinite capacity rechargeable batteries and co-channel interference (CCI).

- The first proposed approach is focused on rate maximization irrespective of the battery status. Energy is being harvested from both the co-channel interferer (CCI) signal and PS factor ρ. The harvested energy is then used to forward the received signal to the destination consuming all of the battery power.

- The second proposed approach focuses on the battery status at high SNR thus making the system energy efficient as it consumes only required amount of energy. The remaining energy energy at the end of each transmission is consumed by the second transmission. Rate is however compromised in this scheme at high SNR.

- Another significant contribution of this work is finding the optimum value of PS factor ρ that maximizes the success probability of the system.

- A comparison of optimum value of PS factor is made with fixed value retaining highest success probability in the presence of batteries and CCI signals. Rho optimum is proved to be a more suitable PS factor to meet system requirements.

1.6 Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 presents the background and existing literature on the relay selection techniques in the presence of CCI and rechargeable batteries. In chapter 3, two schemes, rate maximization scheme and energy efficient scheme are proposed along with their system model and algorithms. Chapter 4 presents the simulation results and performance evaluation for the proposed schemes. Chapter 5 generalizes the conclusion drawn from the above frameworks along with the concluding remarks.

Chapter 2

Background and Literature Review

This chapter presents the background and literature review on the relay selection schemes in a SWIPT-based system. It discusses the effects of CCI signals and batteries in communication networks. It also discusses energy harvesting from CCI signals.

2.1 Relay Selection in SWIPT

To meet the growing demand of wireless users and to overcome the fading, path loss and transmission limitations, various relay selection schemes have been proposed based on channel-state information (CSI), signal-to-noise-plus-interference ratio (SINR) and other network conditions. A simple SWIPT-based cooperative network is analyzed in [16]. Simultaneously transmitting data improves the bandwidth efficiency of a network. This simultaneous transmission is termed as two-way relaying. This two-way relaying is analyzed for co-operative communications in [17]. Single relay selection (SRS) [18] and multi relay selection (MRS) [19] schemes have already been discussed based on channel-state information (CSI). Optimal relay selection (ORS) scheme maximizes the end to end SNR of all the users [20]. Several existing works used partial relay selection (PRS) scheme to prolong the life-time of relay node by selecting a single link based on the first-hop channel state information (CSI) only. A considerable amount of work on fair relay selection scheme in a general fading environment has been addressed in [21]. Dual relay co-operative approach is investigated in [22] for wireless networks. A detailed comparative study of different relay selection schemes has been carried out in [23, 24] and the references therein. We focus on finding out the outage probability of a system to evaluate our system performance. In previous works, outage probability of a DF system in Nakagami environment has been analyzed in [25]. Shadowed Nakagami fading channel for co-operative communication has been observed in a SWIPT-based system in [26]. Mostly in relay selection we do not consider direct link due to path loss and fading but in previous works, direct links have been exploited in SWIPT-based networks [27]. Each modulation scheme has its own impact on a system. SWIPT-based systems are analyzed under different modulation schemes as in [28]. Game theory is basically a study of mathematical modeling. SWIPT-based system is also modeled under game theoretic approach in [29].

2.2 Battery-Aware Relay Selection

Energy harvesting (EH) from sustainable energy resources is an unfold solution to enable green wireless networks. This energy is collected from various external power sources including radio frequency (RF) radiations, solar radiations, wind power, thermoelectric effects and so forth. When traditional relays are replaced by such EH relays they prove to provide green signal to wireless communications. This harvested energy, received by the receiver is then converted to DC current and is then consumed by the relays. So EH has drawn tremendous attention in wireless communications.

EH in simple relay selection scheme based on CSI and current available energy was inspected in [30]. EH in network operations and their improved performance is investigated in [31]. Finite energy storage is another parameter that is integrated with the relay selection for cooperative relays in a SWIPT-based system [32]. Energy could also be stored in non-linear models, these models are analyzed in [33]. Energy harvesting in fading environment is yet another artifact [34]. Energy harvested from such resources in wireless networks could be stored in batteries to be used by next transmitted signals. Such a battery-aware relay selection scheme is investigated in [35]. Relay selection technique MRS is merged with energy harvesting from batteries in [36].

Security is an important factor to be considered in every aspect including communication networks. To secure an untrusted relay system, relay selection scheme in the presence of energy harvesting form RF signals is investigated in [37]. Since power allocation is equally important when energy is being harvested in wireless and ad hoc networks. Such performance is evaluated in [38]. Power allocation along with incremental decode and forward system is modeled in [39]. Batteries integrated in amplify and forward co-operative system is modeled in [40]. This model focuses on maximizing the lifetime of network.

2.3 Interference Aided Energy Harvesting

Interference is existent almost everywhere, so in order to bring it into service, we can harvest energy from co-channel interferer (CCI) signals and store it in battery to be used in next transmission or could be used in the same transmission. Either ways relays may sometimes need to replenish energy from various sources, CCI signals could serve as a new source of power storage. Interference is analyzed in multi-hop networks in [41]. A survey has been made to harvest energy by exploiting interference is done in [42]. Relays harvest energy from these CCI signals, store it into batteries and then use it to forward the transmitted signal. Decode and forward relays harvesting energy from CCI signals only is inspected in [43]. Energy harvesting from CCI signals is multi-hop co-operative relaying is explained in [44]. Radio frequency (RF) based energy harvesting is analyzed in [45] for decode and forward (DF) relaying systems. Many other sources along with CCI signals could also be integrated in wireless network to store more energy. Power allocation becomes an important factor when energy is being harvested from various sources. This power allocation has been discussed in [46]. Co-operative systems could be made energy efficient by right power allocation and energy harvesting. Energy efficiency is implemented in such systems in [47]. This energy efficiency is then merged with relay selection in multi-hop device to device D2D networks in [48]. Game theoretic approach is applied in energy efficient hybrid networks to analyze resource allocation in [49]. A survey of relay selection scheme in ad hoc networks has been conducted in [50].

As energy is being harvested from interferer. Previous works show that this interferer could be anything even the signal itself too. The work done in [51] shows how energy is being harvested by self-interference. Electromagnetic interference induced in human body could also act as interference from which energy is harvested as in [52] and the references therein. Energy is accumulated in multiple input multiple output MIMO relaying against co-channel interference in [53]. RF Energy harvesting from CCI signals in D2D communication in analyzed in [54].

Chapter 3

Relay Selection Schemes

In this chapter, we present two relay selection schemes. First one focuses on maximizing rate of the system irrespective of the battery status at any value of SNR. Second one focuses on overall energy of the system thus making an energy efficient system.

3.1 Rate Maximization Scheme

In rate maximization scheme, system focuses on maximizing the overall rate of the system at each value of SNR. System efficiency is not the factor taken into account in this scheme. It's system model is presented and the algorithm is explained. The main focus of this algorithm is to maximize the overall rate of the system by using optimum value of PS factor ρ. This ρ is obtained by keeping a condition to achieve some percentage of success. Simulations have shown that this optimum value in the presence of batteries and CCI outperforms rate maximization scheme by a huge margin.

3.2 System Model

Consider a source-destination pair with N decode-and-forward (DF) relays which are integrated to accelerate information transmission of the source to the destination node. No direct link is assumed because of attenuation and path loss. These DF relays are armed with separate information and energy receivers to easily switch between information forwarding (IF) and energy harvesting (EH) mode. Each of these relays are also equipped with finite-capacity rechargeable batteries in which they can collect energy to be used in the following or next transmission to assist the transmission. Moreover, each of these relays are prone to L CCI signals where L=$\{1,2...L\}$. In this work, source and destination are represented by subscript-S and subscript-D respectively. Each relay is denoted by R_u where u=$\{1,2...N\}$ as shown in Fig. 3.1. Rayleigh fading channel is assumed for each S-R_u link and each R_u-D link. Here h_N is the channel co-efficient between each S-R_u link and g_N is the channel co-efficient between each R_u-D link where N=$\{1,2...N\}$.

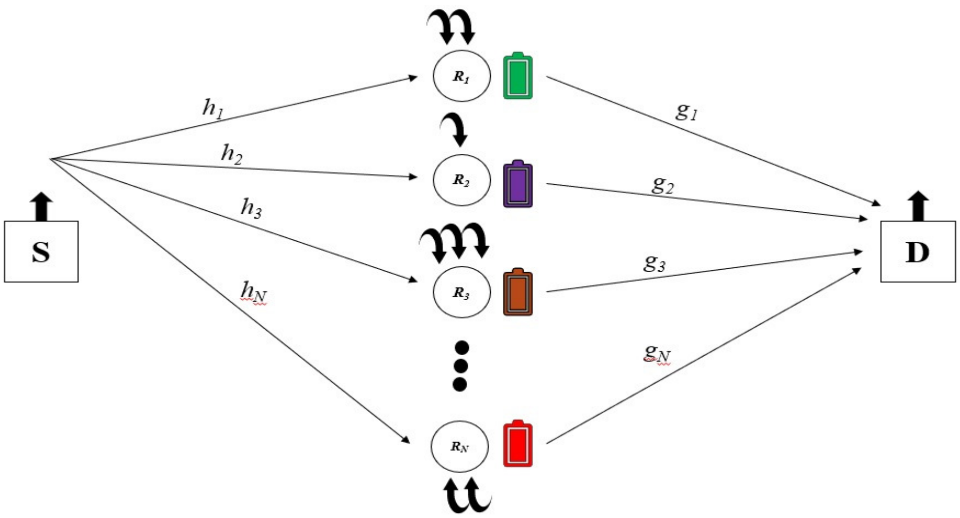

Figure 3.1: *System Model*

3.3 Algorithm for Rate Maximization Scheme

Let P_t denote the transmitted power broad-casted by source S and x denote the transmitted symbol. The signal received at u-th relay is then given by

$$Y_u = \sqrt{P_t} h_u x + \sqrt{P_I} x \sum_{l=1}^{L} \beta_{l,u} + n \tag{3.1}$$

where P_I is the power of CCI signals and β_l, u is the channel co-efficient between l^{th} relay to u^{th} interferer. Additive white Gaussian noise is denoted by n with zero mean and variance N_o.

As SWIPT-based system is used in PS technique, a PS factor will divide the received signal into two parts. Rho ρ times received signal Y_u will be used to decode information and $(1-\rho)$ times Y_u will be used to forward the transmitted signal. This model works based on algorithm 1.

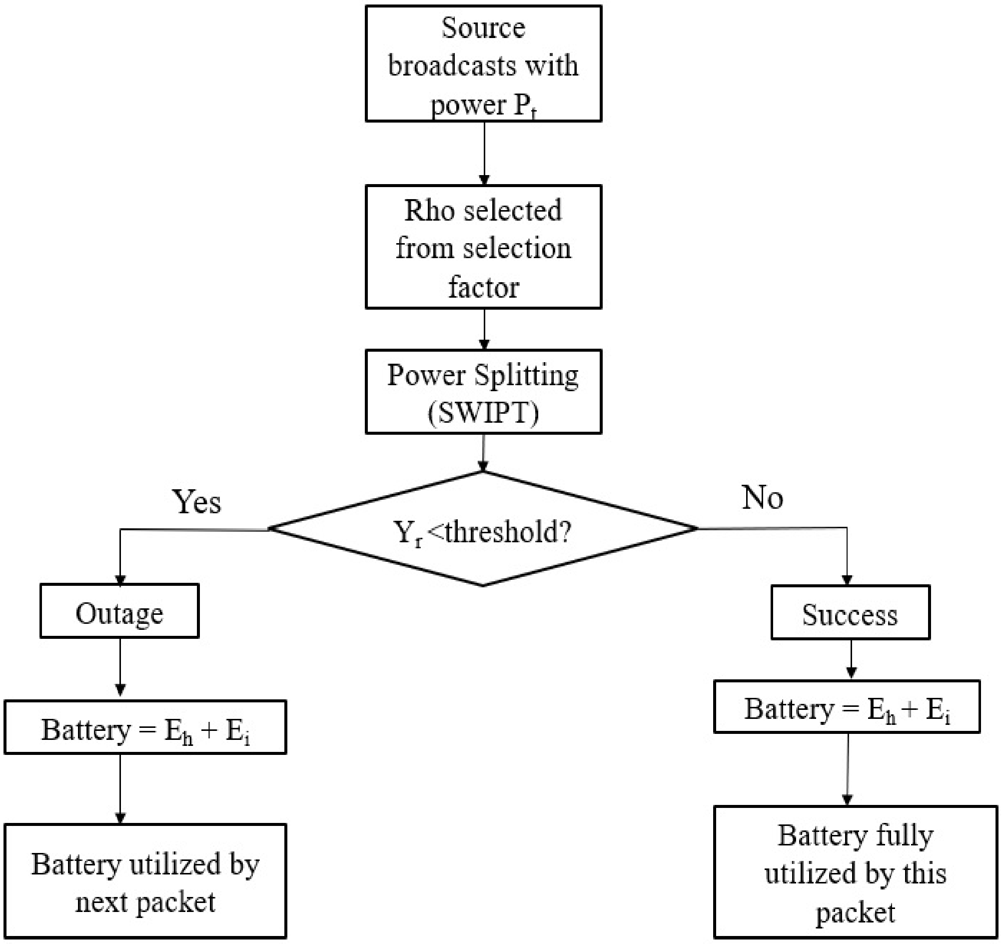

Figure 3.2: *Algorithm 1*

As energy is harvested ρ times, this ρ selection is another factor. We have obtained optimum value of rho against the condition given by (3.2).

$$(\rho)Y_u > Threshold \tag{3.2}$$

This value of PS factor then forwards the information and harvests energy and this amount of energy harvested is given by (3.3).

$$E_h = \eta(1-\rho)(\frac{1}{2}P_t|h_u|^2 + \frac{1}{2}P_I\sum_{l=1}^{L}|\beta_{l,u}|^2) \tag{3.3}$$

where $0 < \eta < 1$ denotes energy conversion efficiency, $|h_u|^2$ denotes the channel power gain between S and R_u and $|\beta_{l,u}|^2$ denotes the channel power gain between l^{th} interferer and u^{th} relay.

In rate maximization scheme,each relay will be able to decode and forward the transmitted signal if the condition given by (3.2) is satisfied. Based on that success and outage will be defined. This scheme focuses on maximizing rate of the system consuming all of the battery power in forwarding transmitted signal and the battery is emptied for the next packet. It is filled by harvesting energy from CCI signals and PS factor ρ and is then utilized when meets the threshold. The signal received at destination is then given by

$$Y_d = \sqrt{E_h} h_d x + n \tag{3.4}$$

where h_d is the channel co-efficient between R_u and D. The final success is then inspected by

$$Y_d > Threshold \tag{3.5}$$

3.4 Energy Efficient Scheme

The main focus of this scheme is to make the system energy efficient. Rate is compromised at high SNR but we have energy in batteries. This is done by defining the minimum amount of energy needed to forward received signal. When only that amount is consumed, remaining energy remains in battery to be used by other transmissions. The minimum amount of energy required is given by

$$P_r > Threshold/g_n \tag{3.6}$$

3.5 Algorithm for Energy Efficient Scheme

Main algorithm running behind energy efficient scheme is explained in Fig. 3.3. This algorithm continues from Fig. 3.2 and changes from (3.2). At the success of this condition, only required amount of battery energy given by (3.6) is consumed for transmission and remaining amount is used by the next transmissions. However, in case when outage is interpreted, battery only harvests energy from CCI signals and PS factor ρ. That energy is then consumed by the next transmissions. (3.6) plays an important role in energy efficient scheme as even after success is outlined, battery status is checked if that required amount is present or not. Success is obtained based on the battery status, outage is expected after first success based on the current amount of energy in battery. Final success is then defined at destination, same as that in rate maximization scheme.

This scheme is found effective at high SNR. As with the rate maximization scheme, at high SNR batteries have very low power which effect the next transmissions as the battery first harvests enough energy from CCI signals and ρ and then uses that energy to forward the signals. But in this scheme we have enough battery power at high SNR, rate is however compromised as the system is energy efficient.

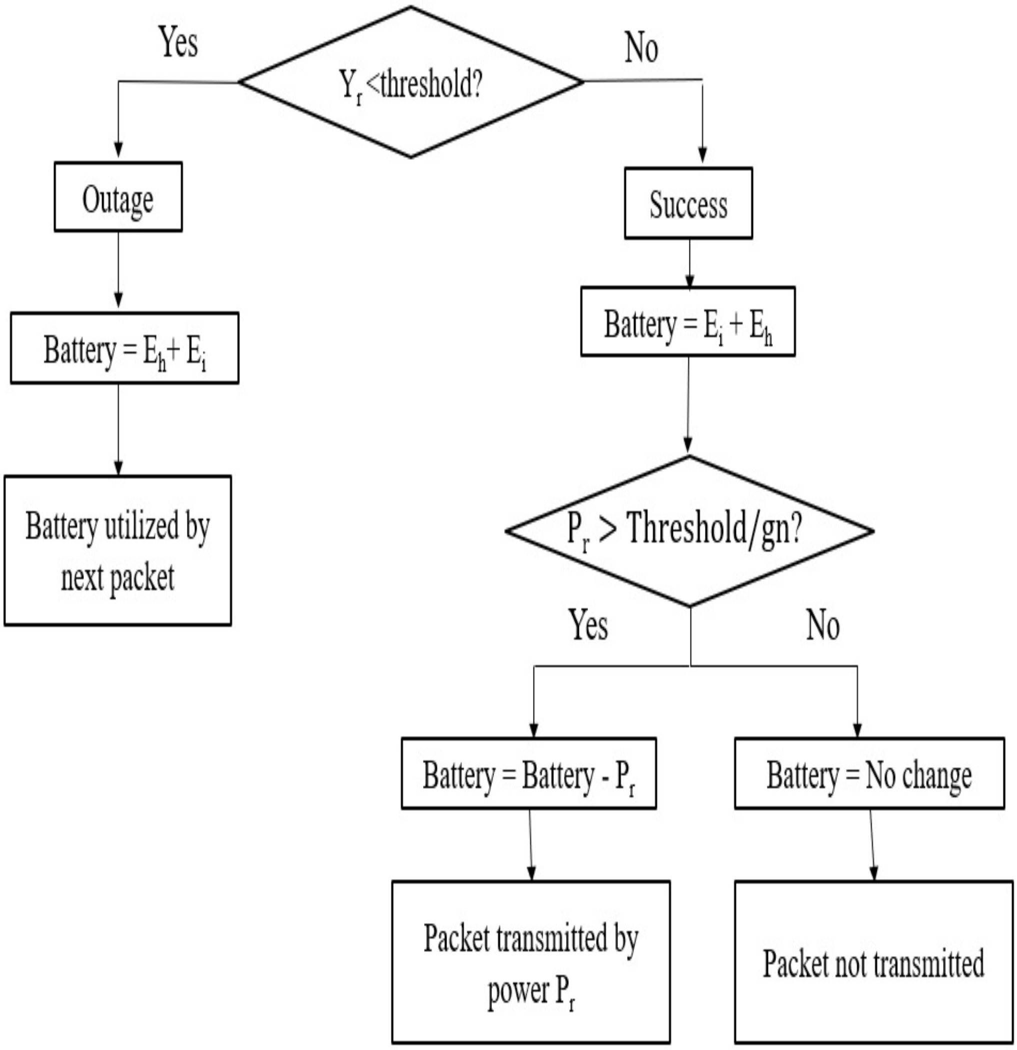

Figure 3.3: *Algorithm 2*

Chapter 4

Simulation Results

We consider a S-D link with N relays to assist communication. Two different schemes are applied on this model. First one focuses on rate maximization of the system and second one focuses on energy efficiency. In simulations, we have used energy efficiency parameter η 0.5.

Fig. 4.1 presents the success probability against each value of SNR for different fading channels. Nakagami channel with shape parameter $m = 1$ becomes Rayleigh fading channel and it can be clearly seen in the figure. It is found to give lowest success probability because of absence of light-of-sight (LoS) component. Nakagami with $m = 4$ has highest LoS component and so it results in highest success probability.

Success probability for N number of relays is shown in Fig. 4.2. The result sums up that increasing number of relays in a S-D system assisted by N relays results in increased success probability of the system. This is because the message signal is transmitted by more number of relays, so at least one of them can guarantee success however this is not the case with only one relay in the system.

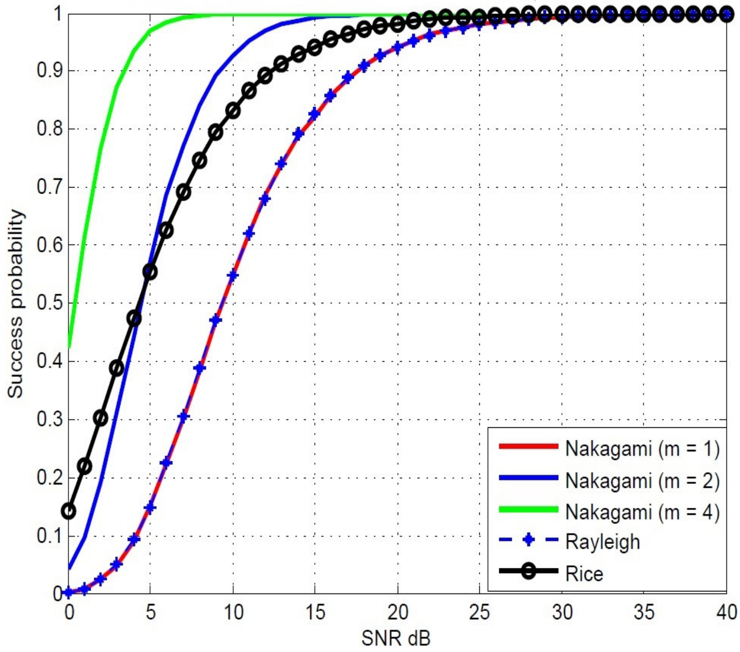

Figure 4.1: *Success probability of different channels using DF path only*

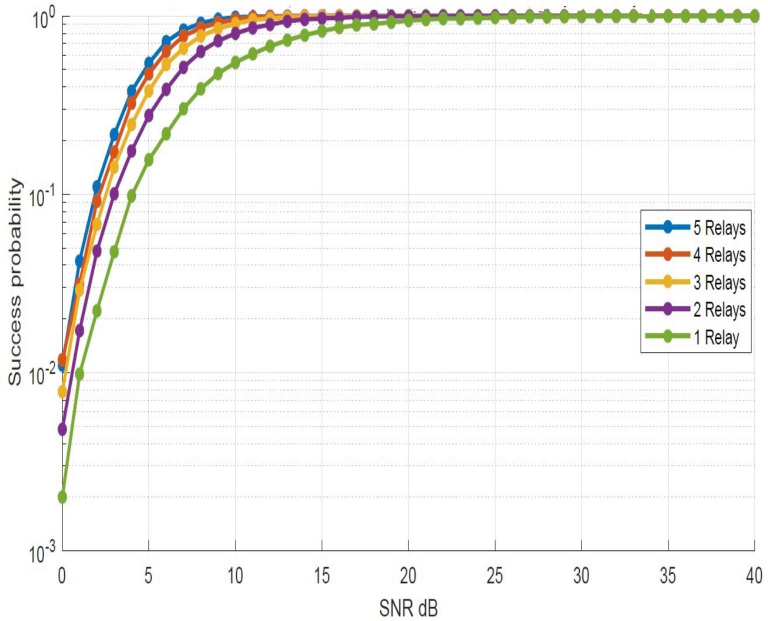

Figure 4.2: *Success probability for N number of relays*

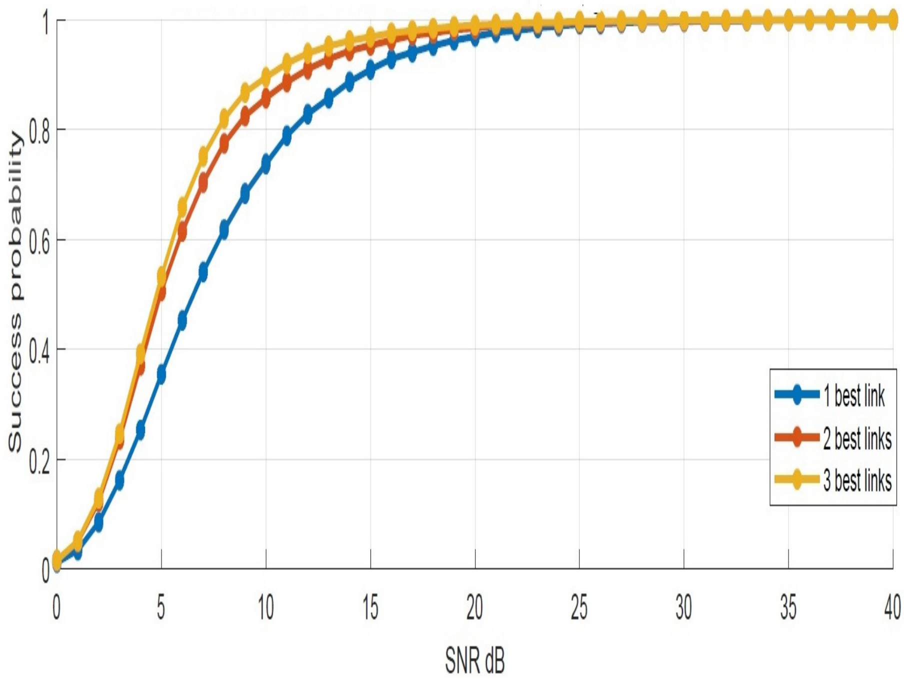

Figure 4.3: *Success probability for selecting N best links*

Fig. 4.3 presents success probability while selecting N number of relays. This means that one message signal is transmitted by selecting N relays at a time. Here we can see that selecting more relays to transmit one message increases the success probability of system but it is cost-effective so we need to look for other solutions.

Here all these relays are forwarding message by a diversity technique maximum ratio combining (MRC) at the destination node. In MRC each signal branch is multiplied by a weight factor that is proportional to amplitude of the signal [55]. Weak signals are attenuated and strong signals are further amplified. Here, SNR of all the forwarding relays are added up and the combined signal is checked at the destination node to affirm final success.

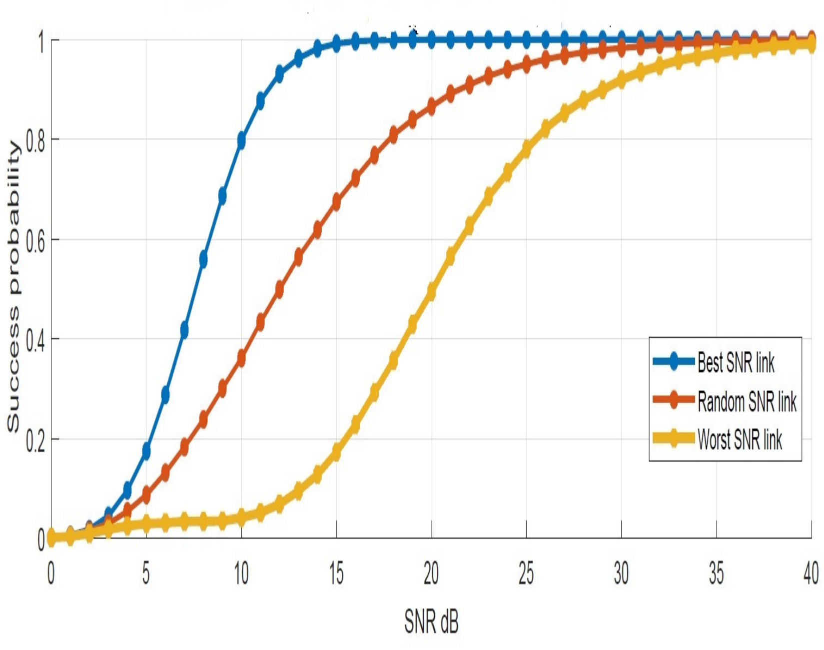

Figure 4.4: *Success probability for selecting best, random and worst SNR link*

In Fig. 4.4 Best SNR link is compared to worst SNR link and some random SNR link out of N relays. Resulting plot proves that the best SNR link provides a promising solution to improve the success probability of system. This is because if the channel is not good, ho much ever energy will be present in the battery, message would not be transmitted and outage will be observed. Remarkable differences between the links can be noticed from Fig. 4.4.

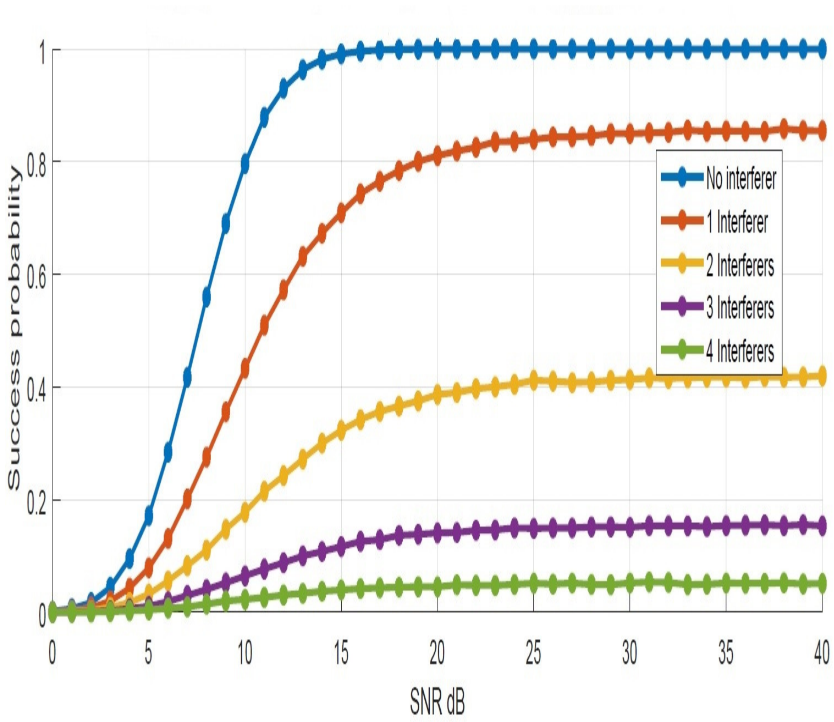

Figure 4.5: *Success probability in the presence of CCI signals*

In Fig. 4.5 CCI signals are introduced to a simple *S*-*D* system. Here we can see that in the absence of CCI signal, system is least in outage. As soon as the CCI signals start adding and increasing in number, system starts behaving in a poor manner. Success probability reaches down close to zero in the presence of four CCI signals. This shows that CCI signals are incorporating in system and effecting in an uncooperative way. These signals could be made to cooperate with the system by harvesting their energy and utilizing in the transmissions.

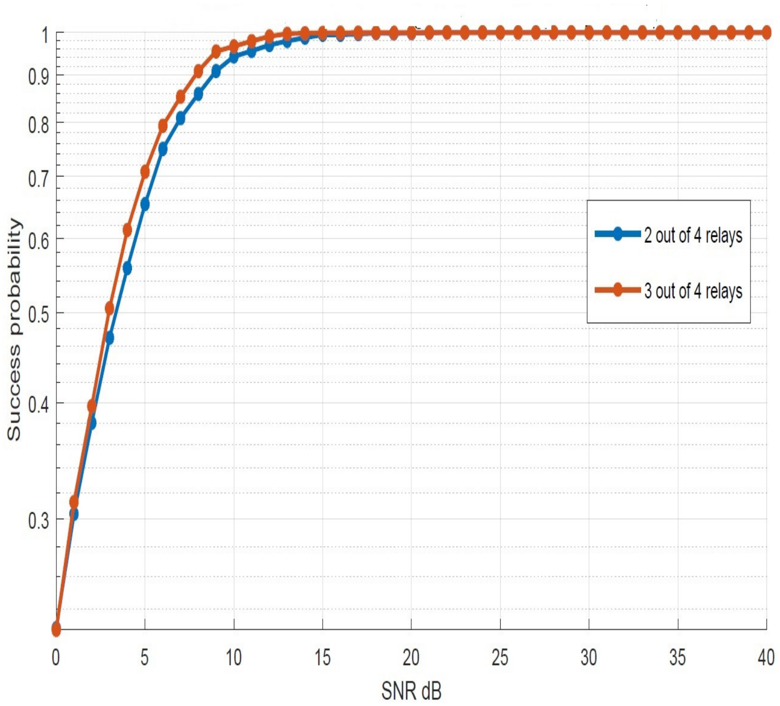

Figure 4.6: *Success probability for selecting m out of N relays*

Fig. 4.6 shows the results of selecting m out of N relays to forward the message signal. These relays are selected irrespective of the message size. Message is itself divided among the prescribed number of relays for a particular system. Fig. 4.6 shows that increasing m increases the overall success probability of the system. The reason here again is that if more relays will be forwarding the message, chance of outage probability will be less.

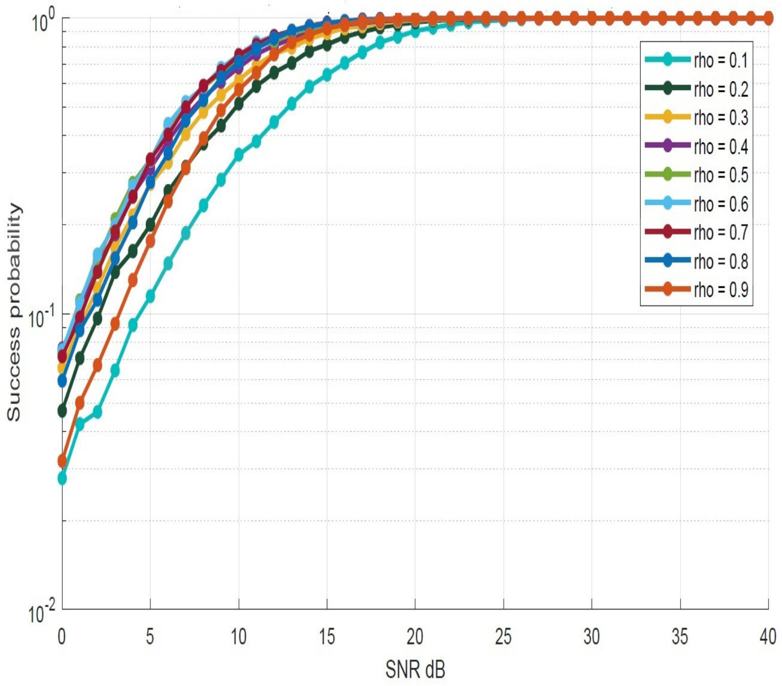

Figure 4.7: *Success probability for different values of PS factor* ρ

Fig. 4.7 shows the results of different values of PS factor ρ. ρ could be any value to be used in wireless system as it is dividing the received signal in IF and EH mode. For a simple system in the absence of CCI signals and rechargeable batteries, the received signal is used for IF and EH based on the values of ρ as in Fig. 4.7. Worst performance is observed for ρ=0.1 and best one is observed for ρ=0.5. ρ=0.9 is observed to give average performance. These results are more clearly described in Fig. 4.8.

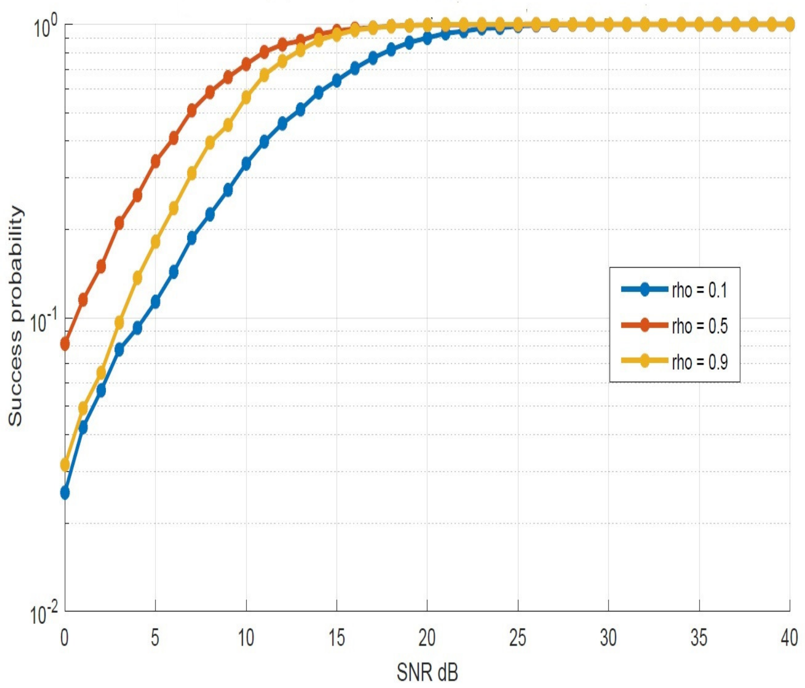

Figure 4.8: *Success probability for different values of PS factor ρ*

Clear results of PS factor ρ are shown in Fig. 4.8.As $\rho = 0.5$ is observed to give best success probability, rest of the comparisons with fixed ρ are made with the value $\rho = 0.5$.

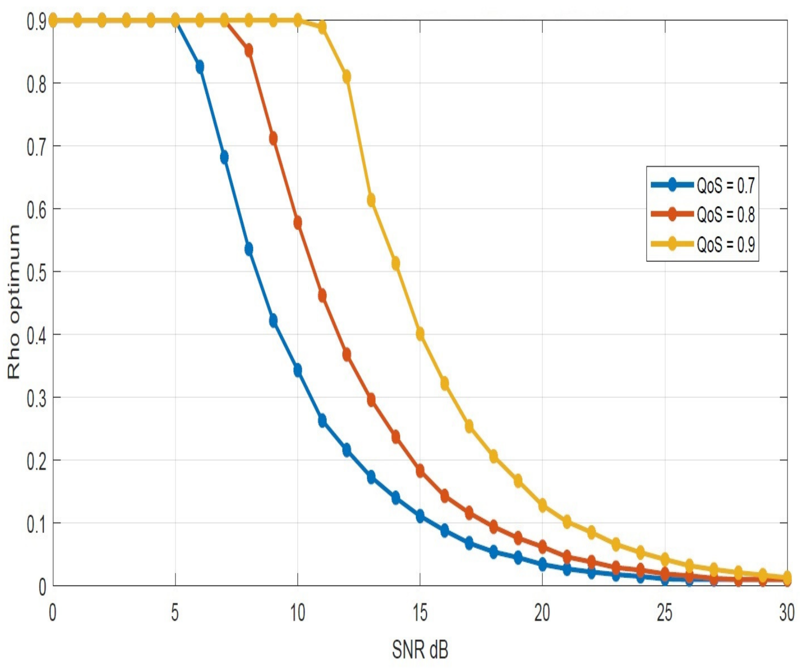

Figure 4.9: *Rho optimum for different values of SNR*

Fig. 4.9 shows the value of rho optimum obtained at each value of SNR to pledge success probability 70%, 80% and 90% respectively. This plot acts like a table from where optimum value of PS factor ρ for a particular SNR could be read to get any percent of success probability. This value of ρ divides the received power in such a way between IF and EH mode that it guarantees a particular success.

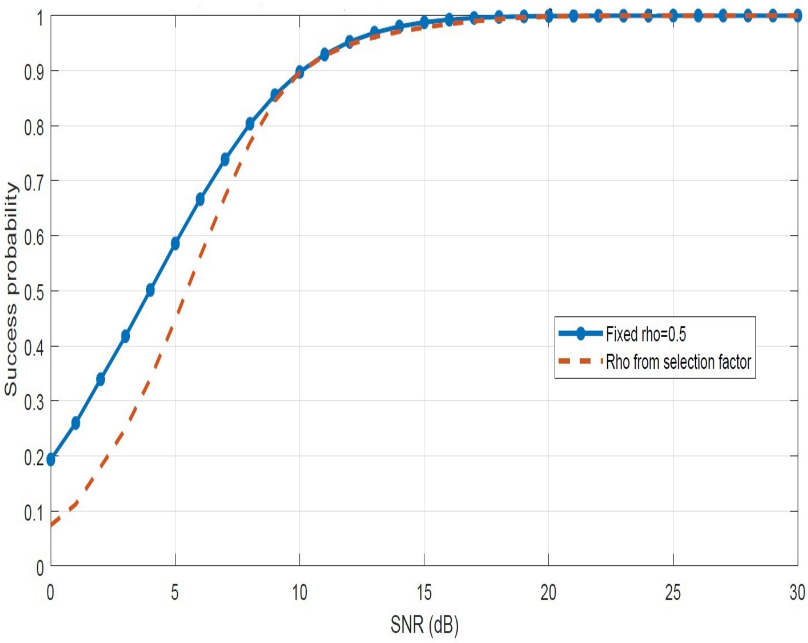

Figure 4.10: *Comparison of success probability at fixed value of* ρ *and optimum value of* ρ *at different SNR*

Fig. 4.10 compares the success probability for fixed value of $\rho = 0.5$ as it is observed to give best results. Plot shows that optimum value of ρ lowers its performance at low SNR. Here making use of batteries and CCI signals and harvesting energy from them will rise this curve at low SNR resulting in good performance. It would be more clear by seeing the forthcoming plots.

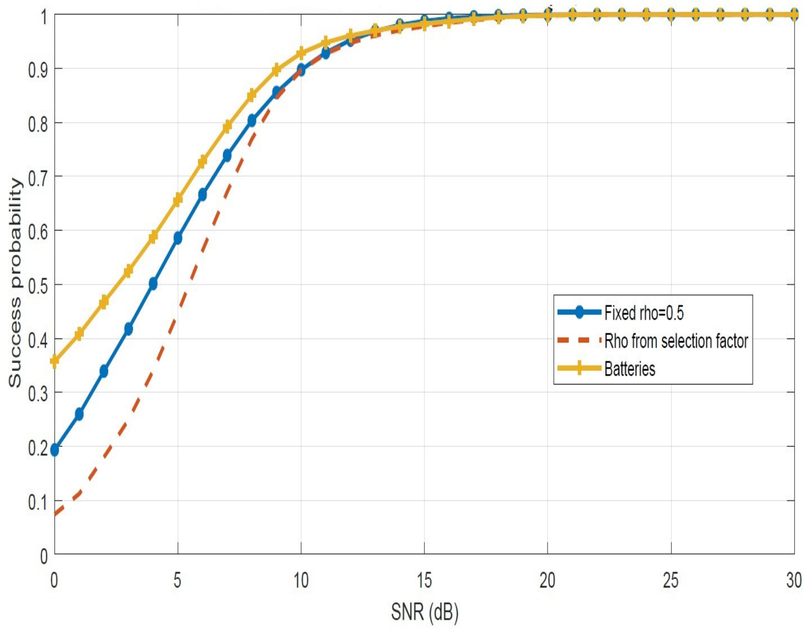

Figure 4.11: *Comparison of success probability at fixed value of ρ and optimum value of ρ in Rate Maximization scheme*

Here we see that when batteries are integrated to the system, our success probability at low SNR is improved. Here these batteries are storing energy only from PS factor ρ. While forwarding the received signal, batteries make use of their full energies stored and thus they are empty for the next transmission and starts harvesting till they meet the forwarding criteria. Here if somehow battery stores more energy than required, even then all of it will be consumed by the forwarding signal. Energy efficient scheme is the solution to it as it only uses energy as required by relay to forward the received signal.

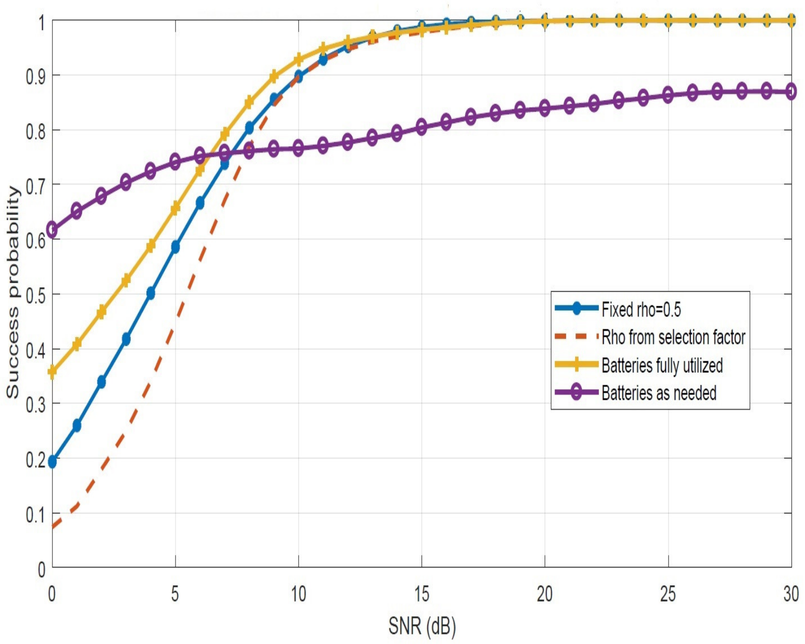

Figure 4.12: *Comparison of success probability at fixed value of ρ and optimum value of ρ in Energy Efficient scheme*

Fig. 4.12 shows that at low SNR, performance is further improved and more success probability is obtained. But rate is compromised here which is not the case with Rate Maximization scheme shown in Fig. 4.11. This system however is energy efficient at high SNR as only required amount of energy is utilized to forward the information signal and the rest is stored in battery for the next transmissions. Battery status at high SNR is monitored in the imminent graphs.

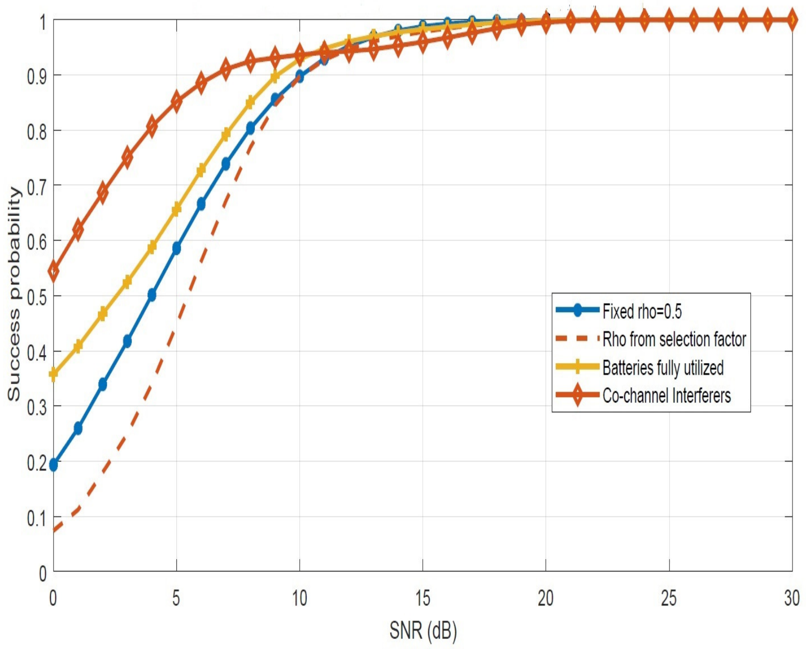

Figure 4.13: *Rate Maximization scheme in the presence of co-channel interferer (CCI) signals*

We have already monitored the presence of batteries being utilized in both the schemes. Now in Fig. 4.13 batteries will store energy from CCI signals as well and utilize that energy based on the scheme used. Here in Rate Maximization scheme, batteries are forwarding information with more power as more power is stored in batteries and they are utilizing all of it. So we see an overall enhanced performance of the system. Batteries will however be emptied for next transmissions again.

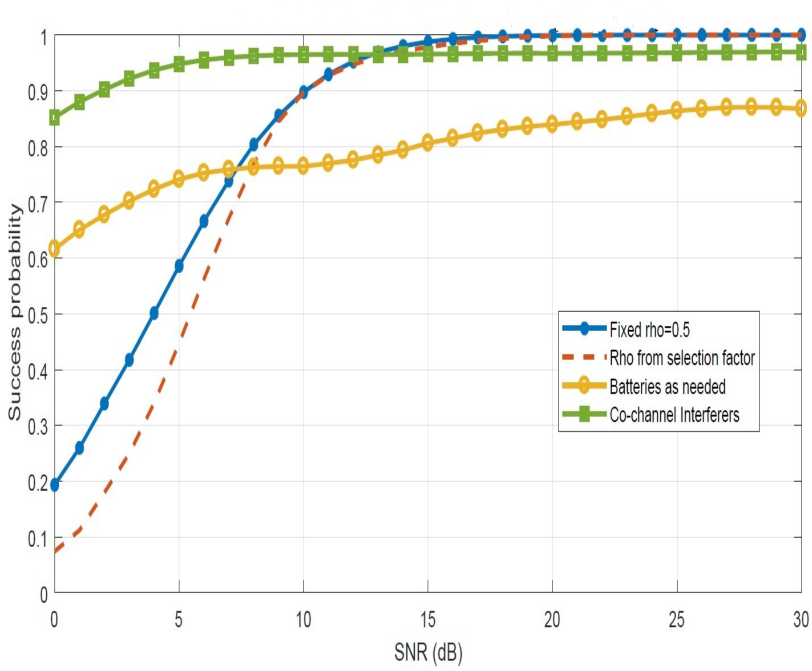

Figure 4.14: *Energy Efficient scheme in the presence of co-channel interferer (CCI) signals*

Energy Efficient scheme is also observed to improve the system performance by harvesting energy from CCI signals but at high SNR, success probability is still lower than that of Rate Maximization scheme. Batteries, however will have energy at high SNR making system energy efficient.

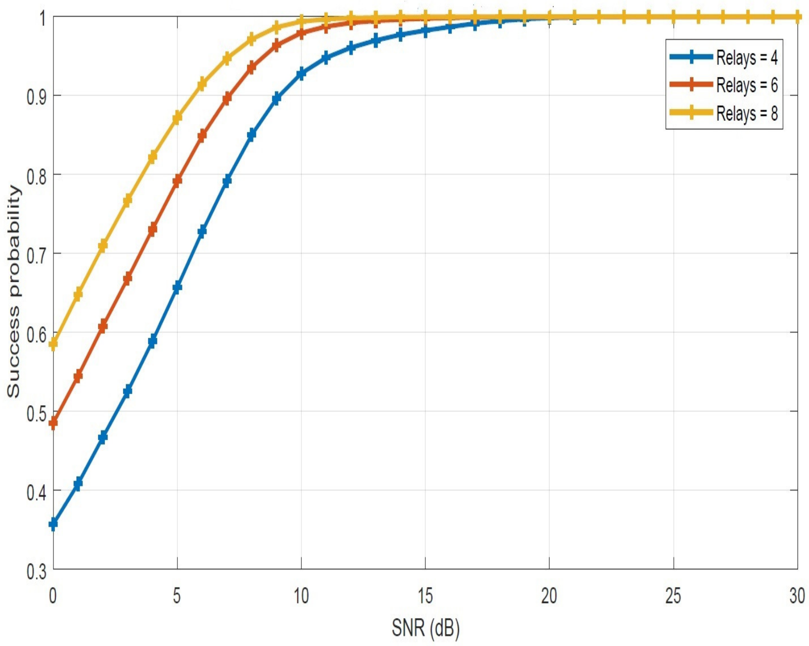

Figure 4.15: *Rate Maximization scheme for N number of relays*

Fig. 4.15 shows that increasing number of relays in Rate Maximization scheme, increases the overall success probability of system considering the fact that at least one link among them will ensure success. This at the same time decreases the battery power by consuming all of it for one transmission. Fig. 4.16 and Fig. 4.17 shows the battery status of this scheme at high SNR.

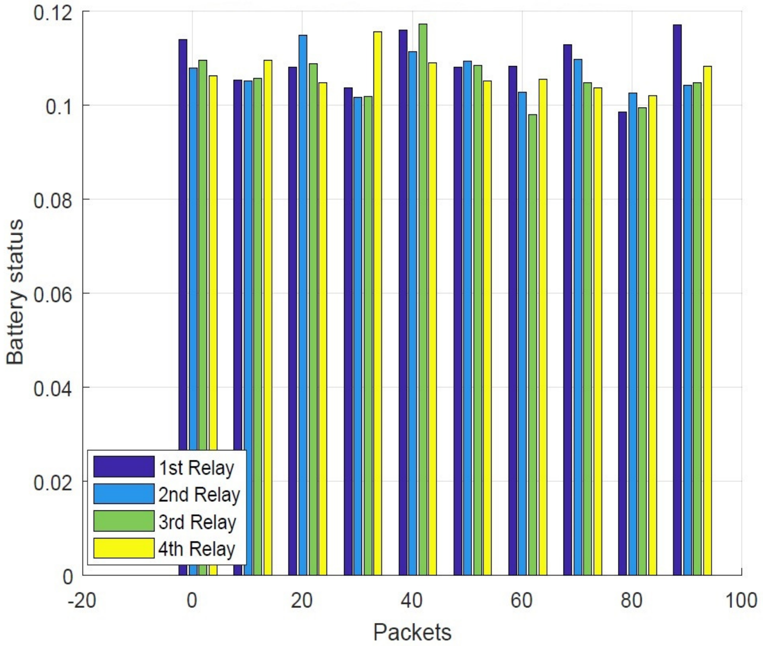

Figure 4.16: *Battery status at high SNR in Rate Maximization scheme*

Fig. 4.16 shows the battery status of Rate Maximization scheme at high SNR. We can see that even when 100 packets are sent, battery status at each relay is around 0.1W, which is very less at the moment. It would be further cleared by seeing the contour in Fig. 4.17

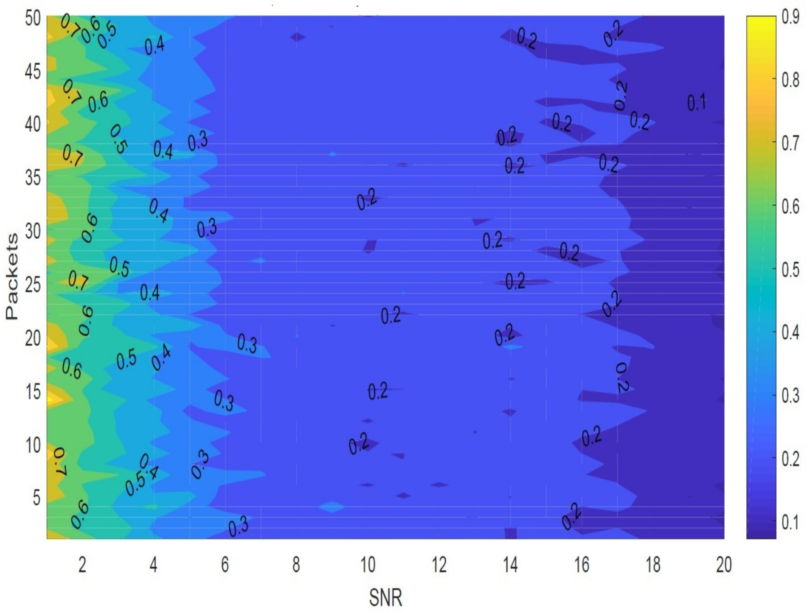

Figure 4.17: *Contour plot for battery status in Rate Maximization scheme*

Fig. 4.17 shows the contour plot for battery status of Rate Maximization scheme. It can be seen from the plot that at high SNR battery power is around 0.1W because all of it is consumed in transmitting the received signal and there is almost no energy left in the battery at high SNR. At this point battery will harvest energy in the upcoming transmissions and will forward the message signal once enough energy is present to forward.

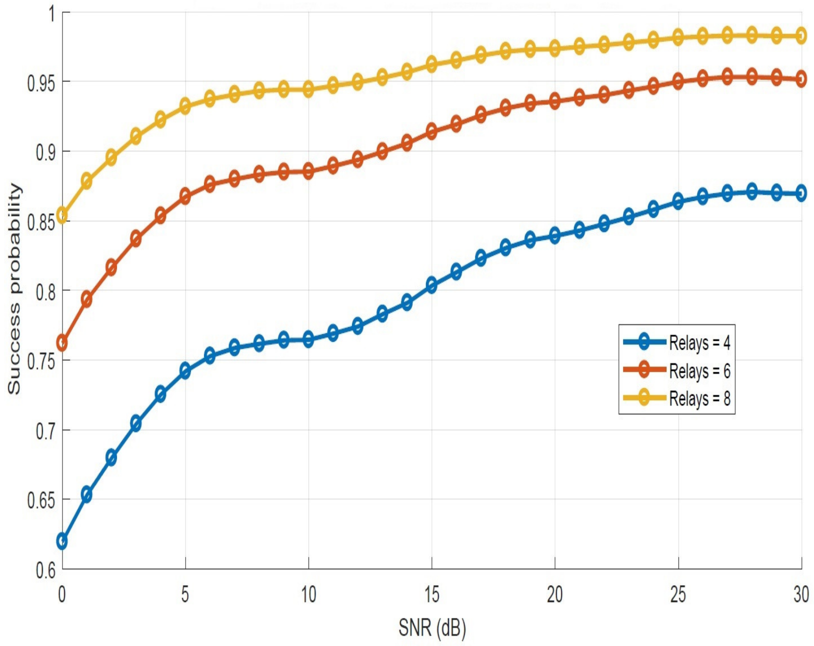

Figure 4.18: *Energy Efficient scheme for N number of relays*

Fig. 4.18 shows that increasing number of relays in Energy Efficient scheme, increases the overall success probability of system. However in this scheme batteries have maximum power for upcoming transmissions even at high SNR as they are only consuming the required part for transmission. Fig. 4.19 and Fig. 4.20 shows the battery status of this scheme at high SNR.

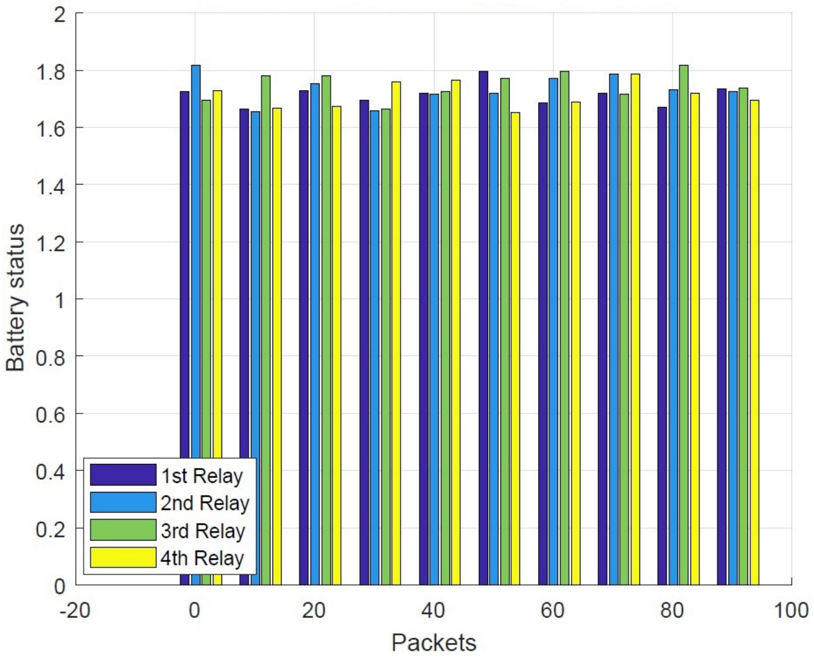

Figure 4.19: *Battery status at high SNR in Energy Efficient scheme*

Fig. 4.19 shows the battery status of Energy Efficient scheme at high SNR. We can see that even when 100 packets are sent, battery status at each relay is around 2W. It would be further cleared by seeing the contour in Fig. 4.20

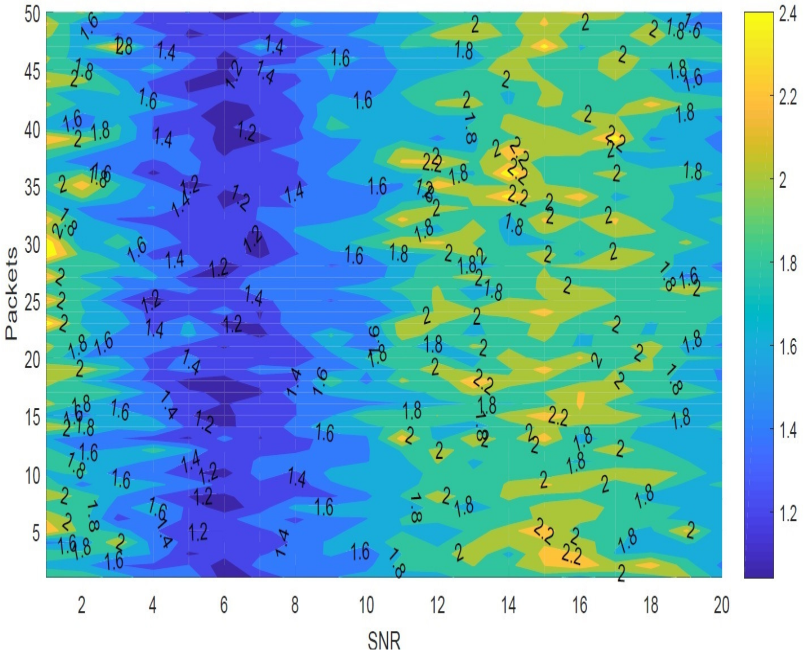

Figure 4.20: *Contour plot for battery status in Energy Efficient scheme*

Fig. 4.20 shows the contour plot for battery status of Energy Efficient scheme. It can be seen from the plot that at high SNR battery power is around 2W because only required amount of it is consumed in transmitting the message signal and the remaining energy is preserved in battery for next transmissions. System will keep harvesting energy and forwarding information simultaneously.

Chapter 5

Conclusions and Future Work

In this thesis, we discussed and analyzed promising technologies for harvesting energy from CCI signals and ρ in a SWIPT-based wireless system. This work proposed two schemes, first one maximizes data rates and the second one makes the system energy efficient. This thesis can be concluded as

- Chapter 3 discusses rate maximization scheme, where overall rate of the system is focused. Rate maximization find its many applications in today's world of communications. For such systems, this scheme is a promising solution.
- In chapter 4, energy efficient scheme is discussed which focuses on the energy efficiency of the system irrespective of the rate. It is useful in cases where system is focused and not the rate. The drawback of this algorithm is that it is likely that for a particular node, channel condition is quite good but battery do not have enough power to transmit. We will be facing outage in this case till battery power reaches the required

level.

5.1 Future Work

- In the future, we intend to further explore the concept used in energy efficient scheme. As MRC is incorporated at the destination node, we focus on assigning good weights to the nodes whose channel condition is good so that we can have success out of them as well.
- We also aspire to design the system more energy efficient by harvesting energy from various other factors including shadowing and path loss. Self interference can also be utilized to harvest energy.
- By adding specific distances we aim to make our model more worthy of. It can help by setting different parameters as per distances of S-R and R-D.

Bibliography

[1] P. A. Asokan and I. Mamatha, “A novel approach to wireless power transfer,” in *2017 International Conference on Technological Advancements in Power and Energy (TAP Energy)*, pp. 1–6, Dec 2017.

[2] N. Zhao, F. Hu, Z. Li, and Y. Gao, “Simultaneous wireless information and power transfer strategies in relaying network with direct link to maximize throughput,” *IEEE Transactions on Vehicular Technology*, pp. 1–1, 2018.

[3] S. H. Chae, C. Jeong, and S. H. Lim, “Simultaneous wireless information and power transfer for internet of things sensor networks,” *IEEE Internet of Things Journal*, pp. 1–1, 2018.

[4] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, “Simultaneous wireless information and power transfer in modern communication systems,” *IEEE Communications Magazine*, vol. 52, pp. 104–110, Nov 2014.

[5] T. Perera, D. Jayakody, S. De, and M. A. Ivanov, “A survey on simultaneous wireless information and power transfer,” in *Journal of Physics: Conference Series*, vol. 803, p. 012113, IOP Publishing, 2017.

[6] J. Yan and C. Zhang, "Energy-aware relay selections for simultaneous wireless information and power transfer," in *2017 23rd Asia-Pacific Conference on Communications (APCC)*, pp. 1–6, Dec 2017.

[7] H. Liu, Y. Peng, D. Wang, X. Ma, Y. Yang, Y. Wu, and C. Zhang, "On optimizing power allocation and power splitting for miso swipt systems with heterogeneous users," in *2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, pp. 577–582, May 2017.

[8] A. A. Al-habob, A. M. Salhab, S. A. Zummo, and M. S. Alouini, "A modified time-switching relaying protocol for multi-destination relay networks with swipt," in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, April 2018.

[9] Z. Zhou, M. Peng, Z. Zhao, and Y. Li, "Joint power splitting and antenna selection in energy harvesting relay channels," *IEEE Signal Processing Letters*, vol. 22, pp. 823–827, July 2015.

[10] D. Mishra and G. C. Alexandropoulos, "Jointly optimal spatial channel assignment and power allocation for mimo swipt systems," *IEEE Wireless Communications Letters*, vol. 7, pp. 214–217, April 2018.

[11] A. Ali, A. Ejaz, M. Jabbar, K. Hameed, Z. Mushtaq, T. Akhter, and A. Haider, "Performance analysis of af, df and dtf relaying techniques for enhanced cooperative communication," in *2016 Sixth International Conference on Innovative Computing Technology (INTECH)*, pp. 594–599, Aug 2016.

[12] S. S. Ikki, M. Uysal, and M. H. Ahmed, "Performance analysis of incremental-best-relay amplify-and-forward technique," in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, pp. 1–6, IEEE, 2009.

[13] Q. F. Zhou, Y. Li, F. C. M. Lau, and B. Vucetic, "Decode-and-forward two-way relaying with network coding and opportunistic relay selection," *IEEE Transactions on Communications*, vol. 58, pp. 3070–3076, November 2010.

[14] T. W. Yune, D. Kim, and G. H. Im, "Opportunistic network-coded cooperative transmission with demodulate-and-forward protocol in wireless channels," *IEEE Transactions on Communications*, vol. 59, pp. 1791–1795, July 2011.

[15] B. Can, H. Yomo, and E. D. Carvalho, "Hybrid forwarding scheme for cooperative relaying in ofdm based networks," in *2006 IEEE International Conference on Communications*, vol. 10, pp. 4520–4525, June 2006.

[16] R. I. Ansari, S. A. Hassan, and C. Chrysostomou, "A swipt-based device-to-device cooperative network," in *2017 24th International Conference on Telecommunications (ICT)*, pp. 1–5, May 2017.

[17] A. Mukherjee, T. Acharya, and M. R. A. Khandaker, "Outage analysis for swipt-enabled two-way cognitive cooperative communications," *IEEE Transactions on Vehicular Technology*, pp. 1–1, 2018.

[18] M. M. Eddaghel, U. N. Mannai, and J. A. Chambers, "Outage probability analysis of a multi-path cooperative communication scheme based on single relay selection," in *The 5th International Conference on Communications, Computers and Applications (MIC-CCA2012)*, pp. 107–111, Oct 2012.

[19] H. He, K. Xiao, and D. Fu, "A multi-relay selection scheme in the df cooperative network composed of the battery-operated relays," pp. 606–610, May 2017.

[20] S. Atapattu, Y. Jing, H. Jiang, and C. Tellambura, "Relay selection and performance analysis in multiple-user networks," *IEEE Journal on Selected Areas in Communications*, vol. 31, pp. 1517–1529, August 2013.

[21] M. Sadeghi and A. M. Rabiei, "A fair relay selection scheme for a df cooperative network with spatially random relays," *IEEE Transactions on Vehicular Technology*, vol. 66, pp. 11098–11107, Dec 2017.

[22] S. A. Hassan, G. Y. Li, P. S. S. Wang, and M. W. Green, "A full rate dual relay cooperative approach for wireless systems," *Journal of Communications and Networks*, vol. 12, pp. 442–448, Oct 2010.

[23] N. Jain, A. Dongariya, and A. Verma, "Comparative study of different types of relay selection scheme for cooperative wireless communication," in *2017 International Conference on Information, Communication, Instrumentation and Control (ICICIC)*, pp. 1–4, Aug 2017.

[24] H. A. Zhao, “Relays selection with power allocation in relay networks,” in *2015 4th International Conference on Computer Science and Network Technology (ICCSNT)*, vol. 01, pp. 1270–1273, Dec 2015.

[25] F. Nawaz, S. A. Hassan, S. Aissa, and S. Saleem, “Outage probability for a decode-and-forward swipt relaying system in nakagami fading,” *Internet Technology Letters*, vol. 1, no. 1, p. e13, 2018.

[26] Y. Feng, V. C. M. Leung, and F. Ji, “Performance study for swipt cooperative communication systems in shadowed nakagami fading channels,” *IEEE Transactions on Wireless Communications*, vol. 17, pp. 1199–1211, Feb 2018.

[27] N. T. Do, D. B. da Costa, T. Q. Duong, V. N. Q. Bao, and B. An, “Exploiting direct links in multiuser multirelay swipt cooperative networks with opportunistic scheduling,” *IEEE Transactions on Wireless Communications*, vol. 16, pp. 5410–5427, Aug 2017.

[28] L. Mohjazi, S. Muhaidat, M. Dianati, and M. Al-Qutayri, “Outage probability and throughput of swipt relay networks with differential modulation,” in *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*, pp. 1–6, Sept 2017.

[29] H. H. Chen, Y. Li, Y. Jiang, Y. Ma, and B. Vucetic, “Distributed power splitting for swipt in relay interference channels using game theory,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 1, pp. 410–420, 2015.

[30] M. Pejanovi-Djurii and E. Koan, "Relaying techniques for cooperative communication systems," in *2011 19thTelecommunications Forum (TELFOR) Proceedings of Papers*, pp. 418–424, Nov 2011.

[31] P. Mahadevan, P. Sharma, S. Banerjee, and P. Ranganathan, "Energy aware network operations," in *IEEE INFOCOM Workshops 2009*, pp. 1–6, April 2009.

[32] K. H. Liu, "Performance analysis of relay selection for cooperative relays based on wireless power transfer with finite energy storage," *IEEE Transactions on Vehicular Technology*, vol. 65, pp. 5110–5121, July 2016.

[33] H. V. Tran, G. Kaddoum, and K. T. Truong, "Resource allocation in swipt networks under a non-linear energy harvesting model: Power efficiency, user fairness, and channel non-reciprocity," *IEEE Transactions on Vehicular Technology*, pp. 1–1, 2018.

[34] J. M. Kang, I. M. Kim, and D. I. Kim, "Joint optimal mode switching and power adaptation for nonlinear energy harvesting swipt system over fading channel," *IEEE Transactions on Communications*, vol. 66, pp. 1817–1832, April 2018.

[35] Y. Lee and K. Liu, "Battery-aware relay selection for energy harvesting cooperative networks," *CoRR*, vol. abs/1408.4218, 2014.

[36] H. He, K. Xiao, and D. Fu, "A multi-relay selection scheme in the df cooperative network composed of the battery-operated relays," in *2017 IEEE 9th International Conference on Communication Software and Networks (ICCSN)*, pp. 606–610, May 2017.

[37] A. Mabrouk, A. E. Shafie, K. Tourki, and N. Al-Dhahir, “An-aided relay-selection scheme for securing untrusted rf-eh relay systems,” *IEEE Transactions on Green Communications and Networking*, vol. 1, pp. 481–493, Dec 2017.

[38] C. K. Toh, H. Cobb, and D. A. Scott, “Performance evaluation of battery-life-aware routing schemes for wireless ad hoc networks,” in *ICC 2001. IEEE International Conference on Communications. Conference Record (Cat. No.01CH37240)*, vol. 9, pp. 2824–2829 vol.9, 2001.

[39] G. Brante, R. D. Souza, and L. Vandendorpe, “Battery-aware energy efficiency of incremental decode-and-forward with relay selection,” in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1108–1112, April 2012.

[40] W. j. Huang, Y. w. P. Hong, and C. c. J. Kuo, “Lifetime maximization for amplify-and-forward cooperative networks,” *IEEE Transactions on Wireless Communications*, vol. 7, pp. 1800–1805, May 2008.

[41] Q. Shafi and S. A. Hassan, “Interference analysis in cooperative multi-hop networks subject to multiple flows,” in *2014 IFIP Wireless Days (WD)*, pp. 1–6, Nov 2014.

[42] N. Zhao, S. Zhang, F. R. Yu, Y. Chen, A. Nallanathan, and V. C. M. Leung, “Exploiting interference for energy harvesting: A survey, research issues, and challenges,” *IEEE Access*, vol. 5, pp. 10403–10421, 2017.

[43] Y. Gu and S. Assa, "Interference aided energy harvesting in decode-and-forward relaying systems," in *2014 IEEE International Conference on Communications (ICC)*, pp. 5378–5382, June 2014.

[44] E. Chen, M. Xia, D. B. da Costa, and S. Assa, "Multi-hop cooperative relaying with energy harvesting from cochannel interferences," *IEEE Communications Letters*, vol. 21, pp. 1199–1202, May 2017.

[45] Y. Gu and S. Assa, "Rf-based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 6425–6434, Nov 2015.

[46] U. Saleem, S. Jangsher, H. K. Qureshi, and S. A. Hassan, "Joint subcarrier and power allocation in the energy-harvesting-aided d2d communication," *IEEE Transactions on Industrial Informatics*, vol. 14, pp. 2608–2617, June 2018.

[47] S. H. Kabir, M. S. Omar, S. A. Raza, M. Hussain, and S. A. Hassan, "Demonstration and implementation of energy efficiency in cooperative networks," in *2015 International Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 1341–1346, Aug 2015.

[48] R. I. Ansari, S. A. Hassan, and C. Chrysostomou, "Energy efficient relay selection in multi-hop d2d networks," in *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 620–625, Sept 2016.

[49] H. Munir, S. A. Hassan, H. Pervaiz, Q. Ni, and L. Musavian, "Energy efficient resource allocation in 5g hybrid heterogeneous networks:

A game theoretic approach," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, pp. 1–5, Sept 2016.

[50] S. Abdulhadi, M. Jaseemuddin, and A. Anpalagan, "A survey of distributed relay selection schemes in cooperative wireless ad hoc networks," *Wireless Personal Communications*, vol. 63, no. 4, pp. 917–935, 2012.

[51] H. Tang, X. Xie, and J. Chen, "X-duplex relay with self-interference signal energy harvesting and its hybrid mode selection method," in *2018 27th Wireless and Optical Communication Conference (WOCC)*, pp. 1–6, April 2018.

[52] C. H. Hyoung, J. H. Hwang, J. H. Lee, S. W. Kang, and Y. T. Kim, "Energy harvesting from electromagnetic interference induced in the human body," *Electronics Letters*, vol. 52, no. 22, pp. 1881–1883, 2016.

[53] Y. Gu, H. Chen, Y. Li, and B. Vucetic, "Exploiting energy accumulation against co-channel interference in wireless energy harvesting mimo relaying," in *2016 19th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, pp. 227–232, Nov 2016.

[54] T. X. Doan, T. M. Hoang, T. Q. Duong, and H. Q. Ngo, "Energy harvesting-based d2d communications in the presence of interference and ambient rf sources," *IEEE Access*, vol. 5, pp. 5224–5234, 2017.

[55] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1451–1458, Oct 1998.