PERFORMANCE ANALYSIS OF DSSC BASED RF ENERGY HARVESTING USING 2RRS SCHEME

A thesis submitted by**:**

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Under The Guidance of

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CERTIFICATE

This is to certify that the dissertation entitled **"Performance analysis of DSSC based RF energy harvesting using 2RRS scheme"** submitted by **Urbi Basu** (Examination Roll No: **M4ETC22019**; University Registration No: **154088 of 2020-2021**) of Jadavpur University, Kolkata, is a record of bonafide research work under my supervision and be accepted in partial fulfilment of the requirement for the degree of **MASTER OF ELECTRONICS AND TELE-COMMUNICATION ENGINEERING** of the institute. The research results represented in this thesis are not included in any other paper submitted for the award of any degree to any other university or institute.

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I hereby declare that this thesis titled **"Performance analysis of DSSC based RF energy harvesting using 2RRS scheme"** is an original research work done by me under the guidance of my supervisor. This work has not been submitted previously to any other institute.

All the information has been obtained and presented in accordance with Academic rules and Ethical Code of Conduct of the institute.

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Place: Kolkata ………..……………………………
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ABSTRACT

The use of radio frequency (RF) for energy harvesting (EH) in wireless networks has grown in popularity in recent years. RF can be used for powering *energy-constrained* network nodes as well as to perform data transmission. One of the many flaws that hinder signal transmission in wireless networks is fading. *Cooperative communication* could be used to lessen the effects of channel fading. By use of relaying technique in cooperative communication, data is transmitted from the source to the destination in smaller hops. This enhances the transmission reliability as well as the radio coverage of the wireless network.

A dual hop relay-aided network with wireless energy harvesting is taken into consideration in this thesis. The relays harvest RF energy from the source in order to use it for data transmission. The best relay is chosen for communication assistance within a set transmission block time. Relay selection procedures are crucial to choose the relay that will provide the best network performance at the output. Moreover, an optimization technique is required to handle the trade-off between the energy collected and the received signal quality in a wireless energy harvesting network. In order to address this problem, a comparison of the network performance is done between the existing Partial Relay Selection (PRS) strategy with the proposed Two Round Relay Selection (2RRS)—by utilising Distributed Switch and Stay Combining (DSSC) combining technique at the receiver. The above model with three cooperative relays is simulated using the MATLAB 2015a software. The simulations are done for the two relaying protocols - Amplify and Forward (AF) and Decode and Forward (DF) respectively. The performance of the existing and the proposed relay selection network in terms of outage probability, throughput and spectral efficiency is analysed using the results from the simulations.

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

This chapter provides an introduction to the thesis work. Firstly, the background of this work is presented briefly. Next, based on this background, motivation of work is set. Based on this motivation, the objectives of this thesis work are defined. These objectives are met by following the methodology as mentioned. The major contributions pertinent to this thesis are also listed in this chapter. Finally, the outline of the thesis is summarized for better understanding.

1.2 BACKGROUND

The upcoming generation of wireless networks demand for high-speed connections with quality of service (QoS) standards. A crucial factor in designing such wireless communication systems is energy efficiency. In addition to enabling energy-efficient data transmission, radio frequency (RF) energy transfer and harvesting techniques can be used to power networks that have limited energy resources like “Wireless Sensor Networks” (WSN), “Body Area Networks” (BANs) and “Internet of Things” (IoT) [1]. Conventional energy harvesting sources such as solar, wind, etc. are less dependable than RF energy when sustainability and QoS requirements of a wireless system are considered. Additionally, the infrastructure needed to capture solar, wind, and tidal energy can be rather expensive. RF energy can be a practical source of renewable energy as it is widely used both *indoors* (such as “Wi-Fi” signals from wireless routers) and *outside* (“DTV signal”, “cellular communication signals”). RF- EH is also a more affordable option for powering networks that are situated in dangerous, inaccessible regions. Other than wireless energy harvesting, there are two other wireless energy transfer methods: inductive coupling and magnetic resonance coupling [2]. But both strategies use near-field transmission methods, which renders them useless. RF-EH networks can supply both energy and information in a safe and efficient way through *Simultaneous Wireless Information and Power Transfer (SWIPT)* technique [3]. SWIPT is an affordable method for preserving the functioning of wireless systems without altering the transmitter's hardware.

Cooperative communication has generated a lot of interest as a brand-new paradigm for communication systems. [4]. It uses relays, as intermediary nodes to assist the source, by transmitting its data to the destination. This is particularly important when source to destination connection fails due to any propagation error. Cooperative communication can achieve transmit diversity and hence enable better performance in a wireless system. Utilizing diversity technology significantly boosts the efficiency of wireless communications by providing the signals with a separate fading path during transmission, across the various dimensions like time, frequency, and space etc. [5]. The performance of a cooperative relaying system can be improved by using *relay selection* techniques [6]. In this technique, the single-antenna nodes share their antennas to create a virtual multi-antenna array for the purpose of data transmission. It generates diversity without the need for multiple antennas at any node. Recently, several combination methods have been used in conjunction with relay selection techniques [7]. The receiver at the destination combines the data it has received from the source and the relay to achieve diversity gain. *Relay selection* and *maximum RF energy transfer* are two distinct issues in a relay-aided RF energy harvesting network. However, as these technologies develop, designers are eager to establish the optimal trade-off between them so that the performance of the receiver is not jeopardised.

1.3 MOTIVATION

It is critical to evaluate the output performance of relay-aided RF- Energy Harvesting Network (EHN) as the data sent from the relay node to the destination, may not be always communicated effectively. In addition to this, the system throughput in a "K-relay cooperative system" that uses all "K" relays to forward signal, suffers as "K" increases. This is due to the time-division multiple access time slot allocation per relay. *Distributed spacetime coding*, *full-duplex relay nodes* - that may send and receive data concurrently might be some options to the above problem. Moreover, *dynamic time slot assignment*, and *relay selection* algorithms are also a few of the solutions [8].

Relay selection is the simplest and most practical way of all of these strategies. Numerous relay selection strategies have already been presented in the literature [9-15]. All these models, though theoretically effective, might not hold true in real-world scenarios where relaying links that are experiencing profound fades are suggested as best channels in order to improve service quality. In a RF EHN studied in [9], the source communicated with the AP by using the best relay out of several relays using the optimal relay selection (ORS) strategy. However, since monitoring connectivity across all links can reduce the network lifetime, this technique is not appropriate to implement in resource-constrained wireless networks. Additionally, it necessitates absolute node synchronisation, which is challenging to implement in practice. As a result, the partial relay selection (PRS) strategy has become a viable option, which requires partial information of the channel (the CSI of the first hop) from the source [10]. But in a RF energy harvesting network, the energy harvested at the relay is also of prime importance to determine the network performance. This served as an inspiration to compare the system performance of a suggested 2RRS scheme with the existing PRS scheme in a relay assisted DSSC based RF energy harvesting network.

1.4 OBJECTIVE

The performance of a wireless channel at the physical layer is measured by bit-error-rate (BER), outage probability, throughput, spectral efficiency etc. The objective of this thesis work is to analyse the performance of a relay-aided RF energy harvesting network employing *Distributed Switch and Stay Combining (DSSC)* technique at the receiver under the proposed relay selection strategy - *Two Round Relay Selection* (2RRS) and compare its system performance with the existing *Partial Relay Selection (PRS)* strategy.

1.5 METHODOLOGY

A *dual-hop full duplex* network having a single source and destination and three relays has been considered. RF energy is harvested by the relays in accordance with the *Power Splitting Ratio (PSR) protocol.* The *DSSC* combining technique is used at the receiver. The source-relay link, relay-destination link and the source-destination link are modelled as *independent flat Rayleigh fading channels.* The *Two Round Relay Selection (2RRS)* strategy is used to choose the best energy-efficient relay for the communication. Another existing relay selection approach, *Partial Relay Selection (PRS)*, is used and compared to gauge its performance. The relay selected for consideration employs both *AF* and *DF* relaying individually. The performance of the above model has been analysed with respect to outage probability, throughput and spectral efficiency of the network.

1.6 CONTRIBUTIONS

The major contributions to this work are as follows:

- A relay selection strategy "*Two Round Relay Selection (2RRS)"* has been devised to select the best relay for the proposed system model. The strategy selects the best energy-efficient relay for the communication thorough a two round relay selection. The relays which are selected in the first round are only applicable for further selection. The further inclusion of DSSC technique at the receiver is also taken into account while selecting the best relay.

- Another existing relay selection approach, *Partial Relay Selection (PRS)* has been used and compared with the 2RRS scheme to gauge its performance. The relays selected for consideration, employs both *AF* and *DF* relaying individually.

- The impact of full duplex relaying on the system's spectral performance has also been studied by simulating the above system model for both full -duplex and half-duplex mode of relay operation.

1.7 OUTLINE

The organization of this thesis is as follows:

- Chapter 2 presents the detailed literature survey of related works in wireless energy harvesting networks with cooperative relays. The various relay selection schemes that are used previously are also discussed.
- Chapter 3 presents a brief theoretical background needed for the understanding of the proposed system model. It explains the concept of "DSSC" and its basic operation. This chapter also discusses the relay section techniques in detail.
- Chapter 4 discusses the proposed system model of a full duplex dual hop relay-aided RF energy harvesting network based on DSSC technique. This chapter also discusses the two relay selection strategies that has been used for evaluating system performance-the proposed 2 RRS and existing PRS.
- Chapter 5 presents the simulations of the proposed work that has been carried out and based on the presented results, a comparative analysis between the 2 RRS based DSSC and PRS based DSSC is done.
- Finally, the thesis is concluded in Chapter 6. Some of the related works that can be performed in the future is also considered.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

A literature review on relay-aided RF Energy Harvesting Network is presented in this chapter. A brief description of the architecture of RF Energy Harvesting Network (RF-EHN) is presented followed by the existing works in literature on the RF-EH protocols. An overview of the prevalent work on cooperative relay schemes used in RF EHN is also studied.

2.2 ARCHITECTURE OF A RF ENERGY HARVESTING NETWORK

The primary components of an RF-Energy harvesting Network (EHN), as described by the authors of [1], are RF energy sources, information gateways, and network nodes/devices. Figures 2.1 and 2.2 depict the architecture of an infrastructure-based and an infrastructure-less RF-EHN respectively [1].

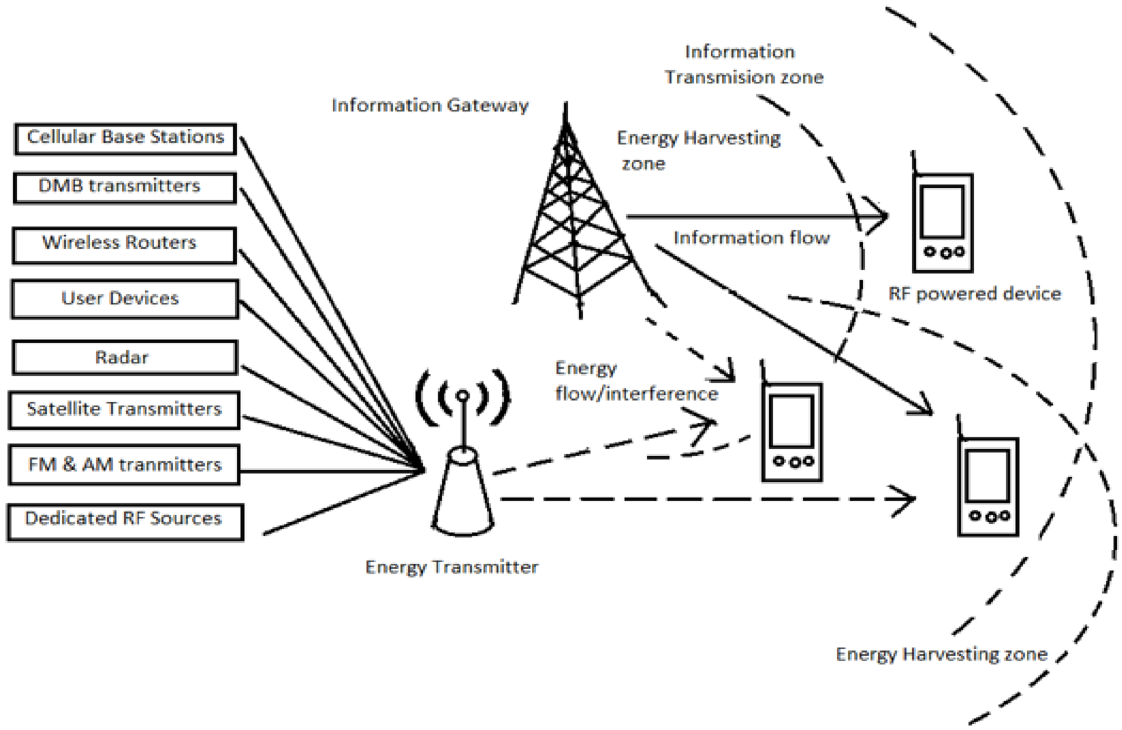


Figure 2.1: An infrastructure-based architecture of RF- EHN [1]

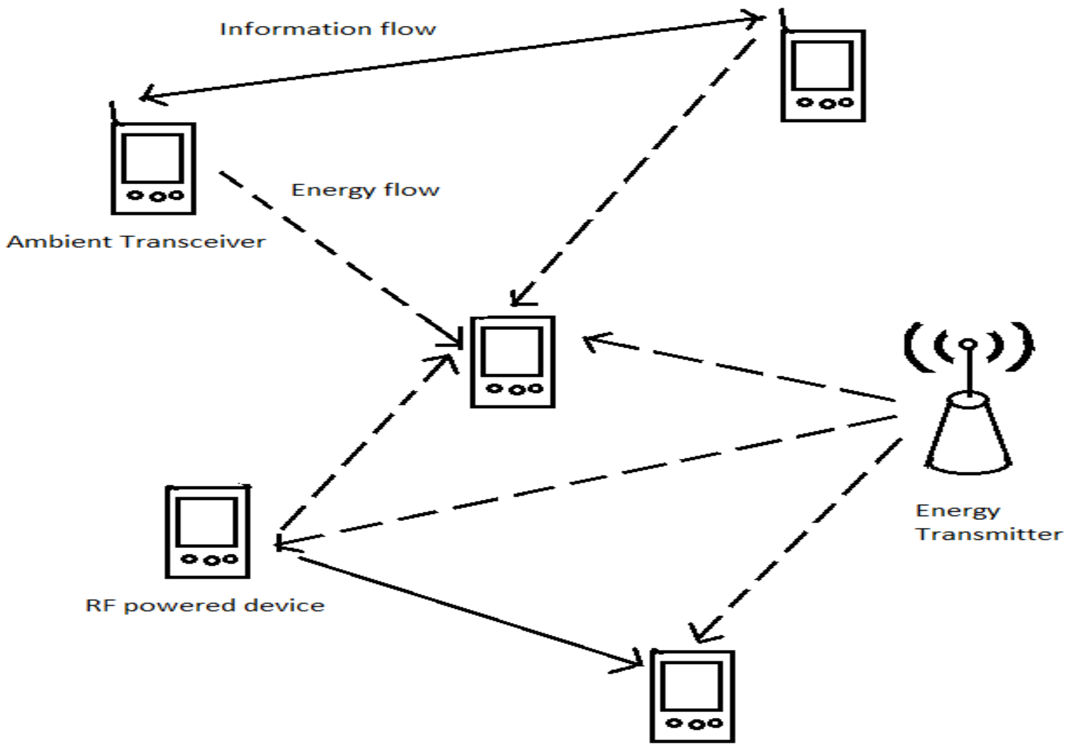


Figure 2.2: An infrastructure-less architecture of RF- EHN[1]

The base stations, wireless routers serve as the *information gateways*. They interact with *network nodes*, which are end user devices. The information gateway occasionally serves as an *RF energy source* apart from the ambient indoor and outdoor RF sources (TV towers. Wi-Fi access points,). There can also be dedicated energy source like the RF energy transmitters.

The information transmission zone is larger than the energy harvesting zone which are depicted by the dotted circles in Fig. 2.1. The reason for this is that the energy harvester node requires more operating power than the information decoding node.

The two common techniques for controlling incoming energy at the power management unit of a network node are "*harvest-use*" and "*harvest-store-use*" [12]. In the *harvest-use* approach, the network node is instantly powered by the harvested energy. On the other hand, if the network node's power consumption is lower than the harvested energy, the *harvest-store-use* approach is applied. [2]

2.3 RELAY OPERATION POLICIES BASED ON RECEIVER DESIGN IN RF- ENERGY HARVESTING NETWORK

Information processing and energy harvesting cannot be done in the same circuit at the same time. As a result, two distinct receiver designs were suggested based on how the received signal was processed for information decoding and energy harvesting [3]. In the first design, a *Time Switching (TS)* structure was considered [11], where the signal was allotted two separate time slots for transmitting power and information respectively.

In contrast to [11], the signal was split into two streams using a power ratio for energy harvesting and data decoding in *Power Splitting (PS)* structure [12]. The transmission block time of *TS* and power ratio of *PS* were adjusted to get the best performance in information and energy transfer.

The *Time Splitting-based Relaying* (TSR) protocol was described by the authors in [13]. A block diagram of a relay receiver using TSR protocol has been shown in Figure 2.3 [13]. In this protocol, the entire "transmission block time" was split in two parts by a fraction, "α" one for the relay to gather energy from the source signal and the remaining block time for information transfer. The possible throughput at the receiver was determined by the time-splitting factor. However, one major drawback of this protocol was the accompanying hardware complexity and power amplification caused by variations in transmit power.

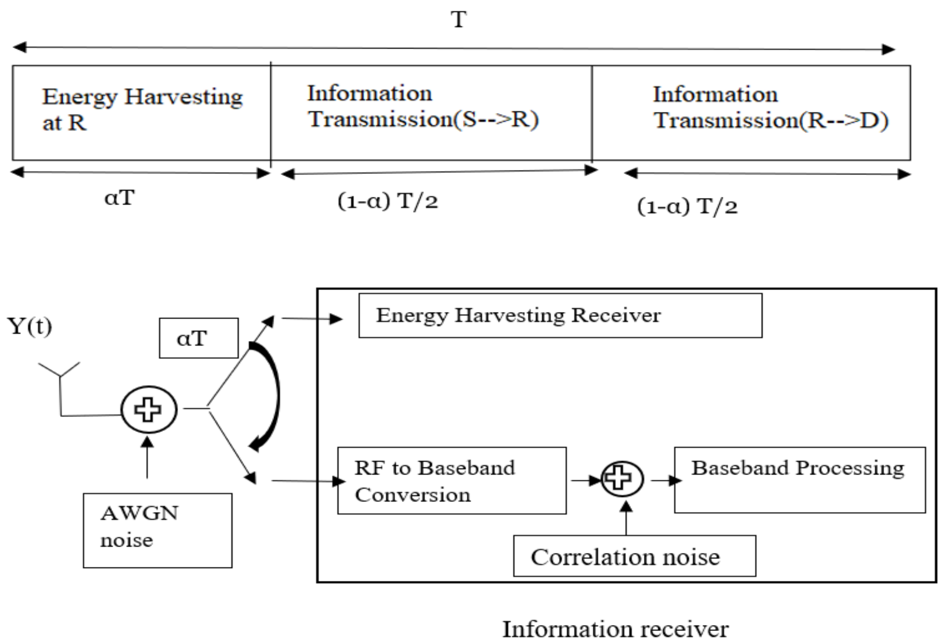


Figure 2.3: Block diagram of a relay receiver using TSR protocol [13]

The *Power Splitting-based Relaying* (PSR) technique was described by the authors in [14]. In *PSR* protocol, the processing power of the receiver was divided into two parts in contrast to division of the transmission block time in TSR protocol. Here, the "power splitting ratio (ρ)" utilised to capture energy at the relay, determined the *throughput* at the destination. Figure. 2.4 [12] depicts the block diagram of a communication system utilising the *PSR* protocol, where "P" stands for the received signal power at the relay and "T" for the entire transmission block time.

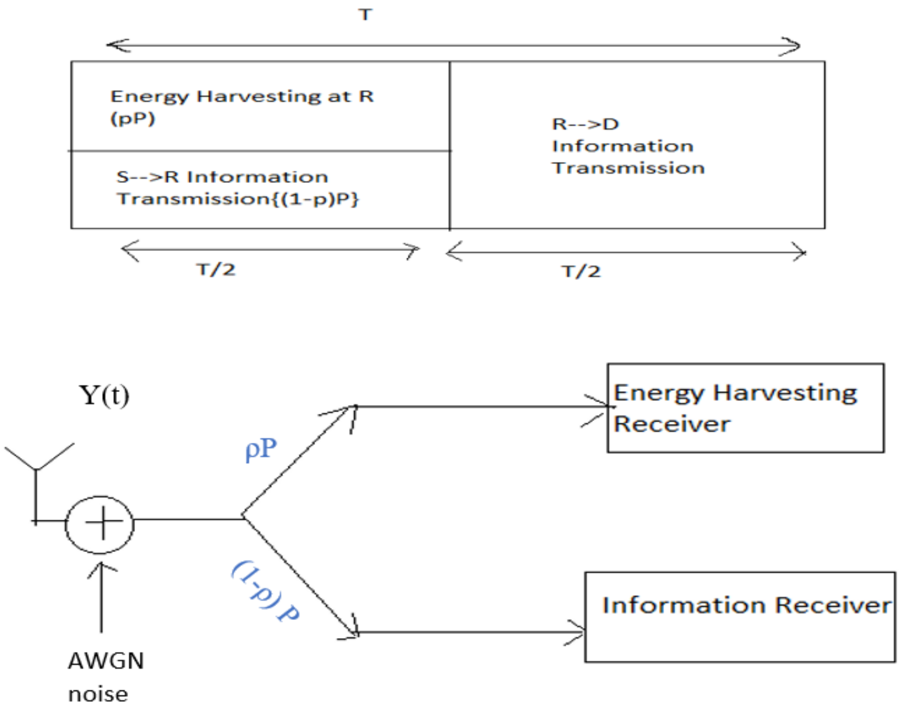


Figure 2.4 : Block diagram of a relay receiver using PSR protocol [14]

In [15], the authors presented two relaying protocols -*Time Switching Relaying (TSR*) and *Power Splitting (PSR)* for an RF-EHN relay node based on the corresponding power-splitting and time-splitting receiver designs [11-12]. The protocols were examined individually under the conditions of *delay-tolerant* and *delay-limited* situations, and analytical formulations for ergodic capacity and outage probability were obtained. The *time-switching* based relaying approach was found to perform better than PSR at high transmission rates and relatively low SNR values.

2.4 COOPERATIVE RELAYING IN RF-EHN

Two major obstacles to overcome while developing a wireless communication network are fading and attenuation. The use of *diversity* technology greatly enhances wireless communications performance by providing the signals with a separate fading path during transmission. Modern wireless transceivers can benefit from spatial diversity by being equipped with several antennas due to recent advancement in the theory of *multiple-input multiple-output (MIMO)* systems [16]. However, it is impracticable to have numerous antennas on a single terminal since wireless devices are expensive and limited in size for many applications, such as wireless sensor networks and cellular phones. The simplest and most effective solution in such situations is to create a virtual *MIMO* environment where nodes can cooperate and share their antennas through distributed transmission and signal processing. This can be accomplished by *Cooperative Communications*. The ground-breaking article on the relay channel written in 1979 by Thomas M. Cover and Abbas A. El Gamal is thought to be the pioneering work for *cooperative communication* as shown in Figure 2.5[17].

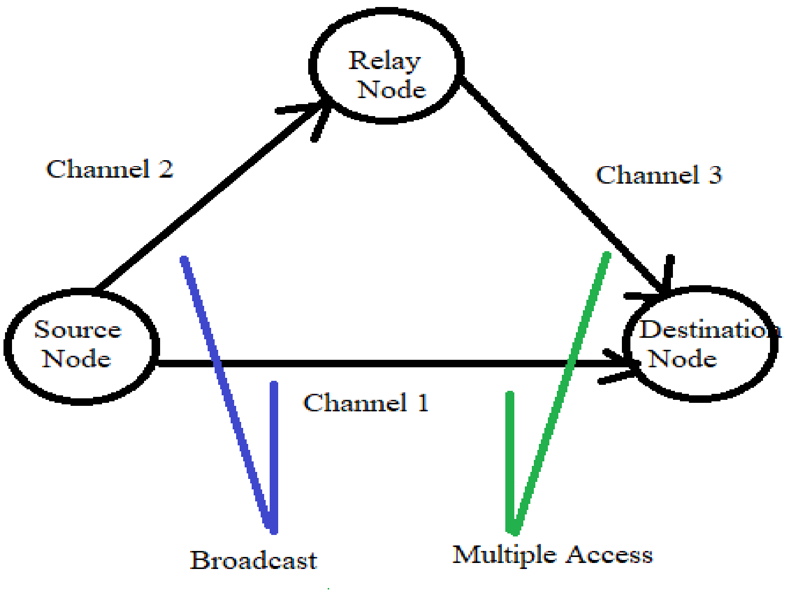


Figure 2.5: System model for relay-based communication [17]

Relaying transmission is one of the more modern methods for achieving spatial diversity. *Cooperative relaying* approaches [8], [10-15], [18] can aid in overcoming fading and attenuation in multi-hop relay networks. It makes use of intermediary relay nodes, which enhances the effectiveness and dependability of the network. As a result, it is especially well suited for use in energy-constrained networks like RF-EHNs [9].

Most research initiatives for cooperative relaying in RF-EHNs aim to increase performance gain on the physical layer, MAC layer, and network layer (for example, relay selection, relay operation policy, and power allocation) [19]. These cooperative relaying design problems get trickier for insufficient CSI. It is also necessary to consider the status of the energy (such as the energy reserve and prospective RF energy).

2.4.1 Relaying Protocols in RF-EHN

Research on relaying protocols in RF-EHN primarily takes into account a three-node cooperative relaying network design, where the three nodes are a source node for information transmission, a relay node, and a destination node for receiving the information. One or more of these nodes may additionally perform RF energy harvesting. All data transmitted from the source passes through the relay node before being forwarded to the destination. The two major methods used by relay nodes are the *Amplify-and-Forward (AF)* [20] and *Decode-and-Forward (DF)* [21] protocols. According to the authors of [21], *DF* system was more practicable and affordable in energy-constrained networks than *AF* scheme as the *AF* system required high peak power levels.

For both *AF* and *DF* RF-EHNs, an adaptive *time switching* protocol was proposed in [22] based on *time-switching* architecture. The main concept was to modify the energy harvesting time length at the relay node by accounting for the available gathered energy and the channel state of the source to relay link. By taking into account the "harvest-store-use'' scheme, the authors devised two different switching protocols such as *continuous* and *discrete* time. For both scenarios, analytical equations for the throughput were derived. It was determined that the "discrete adaptive time-switching" protocol outperformed the "continuous time-switching" strategy at comparatively high SNR values. However, because relay nodes could only use fixed transmit power, it was deemed ineffective.

The *time-switching* receiver architecture served as the foundation for the *greedy switching policy* as developed by the researchers in [23]. The concept was to allow the relay node to transmit while information was also delivered using the energy saved. Based on the *Markov chain model*, the *outage probability* for the relay node was expressed in closed-form. They came to the conclusion that, over a wide range of SNR, the *greedy switching policy's outage probability* performance was approximately equal to the "genie-aided approach" (that includes a priori information about the relay node such as the energy status and the channel coefficients).

The majority of relaying protocols, as has been studied above, were created for two-hop relay networks. It necessitates the development of new operational guidelines for *multi-hop* relay networks. The new regulations must also provide methods for addressing co-channel interference. In [24], a "harvest-then-cooperate" (*HTC*)protocol was discussed. Prior to scheduling the source and relay for information transmission in the uplink, the protocol arranges the source and relay for energy harvesting. The approximate closed-form expression was derived for the average throughput using *Rayleigh* fading. According to the simulations, their suggested methodology performs better than the conventional protocol used in [23].

2.4.2 RELAY SELECTION STRATEGIES IN RF-EHN

Relay selection is important to realize cooperative relaying in practice. The nodes located between sender and receiver must agree in a distributed manner as to which of them will act as relay. Relay selection strategies for cooperative communications focuses on facilitating the transmission of information from the source to the destination, when there may be more than one relay [25].

To combat fading and system outages, relay selection algorithms were first described in the literature [26]. *Partial Relay Selection* (PRS) and *Opportunistic Relay Selection* (ORS) are two of the most widely used relay selection schemes. These two strategies achieved higher cooperative diversity gains [27].

A dual-hop DF cooperative network was taken into account by the authors of [28]. For information decoding and forwarding at the best relay, the relays harvested RF energy during the initial step. The two widely used relay selection algorithms, *ORS* and *PRS*, were used in the system model to reduce outages and increase diversity gains. To analyse the outage performance for both the *ORS* and *PRS* methods, they presupposed independent *Rayleigh* fading channels. The *ORS* method was demonstrated to be superior to the *PRS* scheme, but on the other hand, the cooperative overhead increased as well.

One of the main problems in the relay selection process of *a SWIPT* RF-Energy Harvesting Networks is that the optimal relay for information transmission may not be the same as the relay having the strongest channel for the purpose of energy harvesting [29]. As a result, there is a trade-off between information and energy transfer efficiency.

The authors in [30] examined three relay selection strategies ("time sharing selection'', "threshold-checking selection'', and "weighted difference selection scheme'') amongst two available relays in a Rayleigh fading network with a distinct information receiver and energy harvester. During the *time-sharing selection*, the source node changed between the relays with the highest SNR at various times during. The relay having the greatest RF energy harvesting rate was selected by the source node during the *threshold-checking process.* The *weighted* *difference selection* algorithm selected the optimal relay, based on the importance of information transmission and energy transfer. The authors came to the conclusion that using a threshold checking option yields superior capacity results for a particular RF energy harvesting need. In contrast, when the normalised average SNR per link is more than 5 dB, the *time-sharing selection* performs better in terms of *outage probability*. However, each transmission session calls for knowledge of the entire *CSI* for both selection strategies.

The authors of [31] took into account the problem of selecting the diversity-optimal relay in RF-EHN. The authors came to the conclusion that, as compared to a traditional network, the max-min criterion causes a loss of diversity gains in the system model under consideration. This is explained by the fact that in the max-min criterion, both the source to relay connection and the relay to destination link have equal precedence. The source-relay channels, however, are more significant in RF-EHNs than the relay-destination link. This is because the dependability of reception and the amount of power gathered at the relay are both greatly influenced by the source to relay link. The authors as a result devised a greedy scheduling technique. The best source-relay channel conditions are first scheduled by the algorithm for the sources. The information is then forwarded to the destinations with the best relay-destination link conditions. Even though the greedy scheduling technique fully maximised diversity gain, it could only be applied to *delay-tolerant networks*.

In [32], the authors explored a new class of partial relay selection networks, with “switch-and-stay partial relay selection method” where each transmission time slot was occupied by a single relay from a pair of cooperating DF relays in order to enhance the functionality of the dual-hop relaying network with partial relay selection (DRPRS). These networks increase the spectral efficiency of the system while utilising the direct source-destination link to provide spatial diversity.

2.5 COMBINING TECHNIQUES IN RELAYING NETWORK

Switch and Stay Combining (SSC) diversity approach had been researched by the authors in [33]. In [34], the authors investigated *SSCSR* in terms of outage probability, bit error probability, and spectral efficiency. The authors came to the conclusion that SSCSR outperformed conventional selection relay schemes and incremental relaying schemes in terms of performance at high SNRs.

The distributed SSC and relay selection combination (DSCSR) was proposed by the authors in [35]. It has been suggested that *distributed switch and stay combining (DSSC)* is a useful method for achieving spatial diversity in a distributed setting with minimal processing complexity. In each transmission time, the destination compares the received SNR with a predetermined constant switching threshold to determine the active branch. A branch-switching occurs if the received SNR is less than the switching threshold. The findings demonstrated that bit error probability of the suggested model is lower when compared to partial relay selection networks with selection combining.

In [36], the authors used the DSSC technique at the receiver's end to examine the outage performance for the system with two energy harvesting full duplex relays with the assumption that all relevant channels are available with perfect CSI. The results showed reduction in quantization errors when compared to systems not using DSSC.

In [37], the authors integrated *DSSC* with PRS into a *full-duplex* dual hop relaying system, where three-relay nodes with limited energy supply transmit information to the destination by wirelessly harvesting energy from the source. The found that the DSSC -PRS system gave better performance compared to PRS systems without DSSC. This effective method decreased the implementation and hardware complexity at the destination while simultaneously enhancing the performance of full-duplex relaying systems. DSSC technique may be used in situations when there are hardware limitations at the destination or when the direct link from source to destination is experiencing deep fade.

2.6 OUTCOME

A survey of the literature on relay-aided RF energy harvesting networks was presented in this chapter. A general overview of cooperative relaying in RF energy harvesting networks was provided along with a detailed discussion of two important relaying protocols - *Amplify-and-Forward (AF)* and *Decode-and-Forward (DF)* that support cooperative communication. *Power-energy* trade-off is one of the main issues in relay-aided RF energy harvesting communication network design. Selecting the right relay is one of the solutions to the aforementioned issue. Numerous relay selection procedures have been studied in section 2.4.2. *Diversity* gain can also be attained by using the "*Distributed Switch and Stay Combining (DSSC)*" technique at the receiver in addition to relay operation and relay selection. This idea is relatively new, yet it has been shown to be successful by providing the best communication performance. The review is concluded with an examination of this method and existing literature on the subject.

CHAPTER 3

THEORETICAL BACKGROUND

3.1 OVERVIEW

An outline of the theoretical foundation for the proposed work has been provided in this chapter. A brief discussion of channel impairments in wireless networks is followed by the study of various cooperative relaying terminologies and the relaying standards used for RF Energy Harvesting. The discussion is concluded with a study of the various combining techniques utilised in cooperative communication networks.

3.2 CHANNEL IMPAIRMENTS IN A RF EHN

In a wireless network, the power density of RF waves reduces as is absorbed and diffracted on the path from the transmitter to the receiver, which is known as path loss. Path loss can also be influenced by atmospheric elements like dry or humid air. The *Friis' equation*, which is presented in Equation (3.1) [38] below, can be used to describe the path-loss between two non-isotropic antennas with gains -"G_R" and "G_T" respectively, and corresponding effective areas - "A_R"and "A_T".

$$\frac{P_T}{P_R} = \frac{(4\pi)^2(d)^2}{G_R G_T \lambda} = \frac{(\lambda d)^2}{A_R A_T} = \frac{(cd)^2}{f^2 A_R A_T} \tag{3.1}$$

In a mobile environment where one or both the source and the destination are moving, the relative positioning of various barriers that block the direct line of sight (LOS) changes with time, leading to complex transmission effects. This alters the received signal's amplitude, phase, and angle, commonly referred to as multipath fading. There are various types of fading and several statistical models are suggested to study its effect [39]. The *Rayleigh fading* model [40] can be applied when there are several paths between transmitters and receivers but no dominant line of sight (LoS) path. It assumes that random fluctuations in the channel strength follow a Rayleigh distribution. In the proposed work, Rayleigh fading is considered for all the wireless network channels. Equation (3.2) can be used to calculate the probability density function for a random variable "x" that follows the Rayleigh distribution, where "σ" is the distribution's scaling parameter [40].

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{(2\sigma^2)}}, x \geq 0 \tag{3.2}$$

3.3 RELAYING PROTOCOLS FOR RF ENERGY HARVESTING IN A COOPERATIVE NETWORK

Use of relays in communication networks can be one of the ways to combat fading by providing spatial diversity. Cooperative relaying enables source nodes to transmit data to their intended destinations through shorter hops employed in the network. This increases the network's effectiveness. However, the relays might not have a permanent power source, which limits their performance. As a result, RF energy harvesting is carried out at the relays, which not only provides energy but also allows transmission of data across the relay using the harvested power. Two protocols are commonly used for RF energy harvesting in cooperative relay networks, depending on the receiver architecture: 1) *Time Switching Relaying (TSR) protocol* based on the "Time-switching-receiver architecture" and 2) *Power Splitting Relaying (PSR)* protocol, based on the "Power-splitting-receiver architecture" [15]. A schematic representation of a cooperative network with full *duplex* RF energy harvesting relays using "TSR" protocol with time splitting ratio "α", has been shown in Figure 3.1 [15].

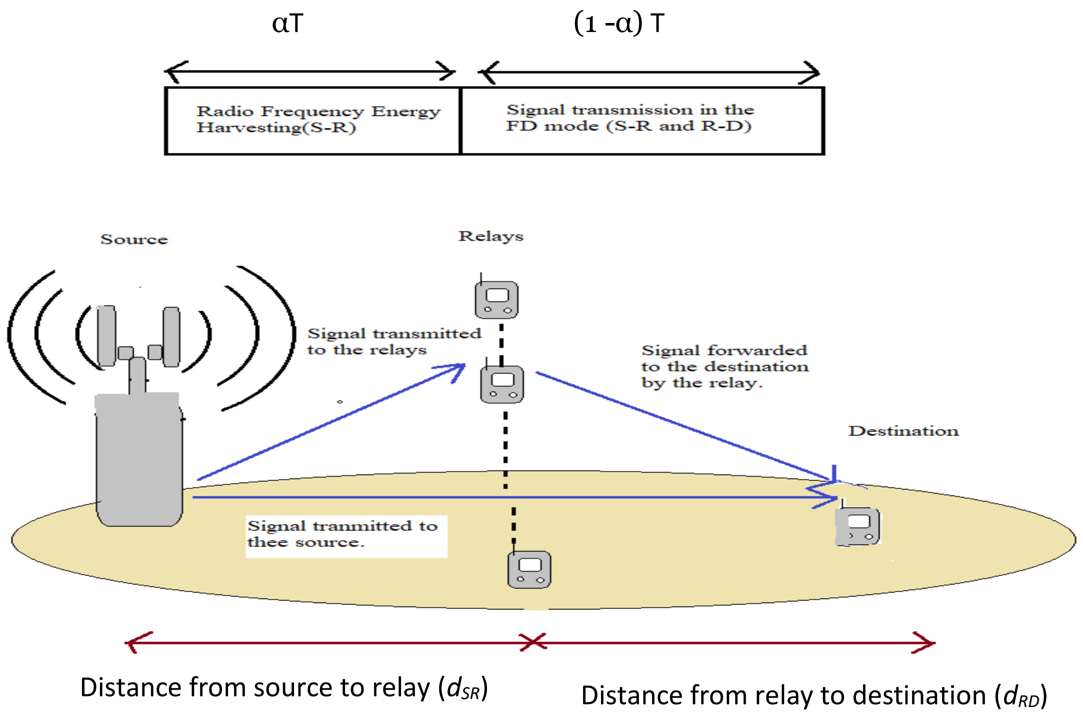


Figure 3.1: A full duplex relay-aided RF energy harvesting network [28]

3.3.1 TIME SWITCHING RELAYING (TSR) PROTOCOL

The "transmission slot-structure" for the *TSR* protocol, which is employed at the relay node to harvest energy and process data, has been shown in Figure 3.2 [13]. Here, the relay uses "α" fraction of the total time-slot ("T") to capture RF energy followed by source to relay communication during the next half of the remaining time "(1- α) T". In the final time-slot, communication from relay to destination takes place utilizing the harvested power.

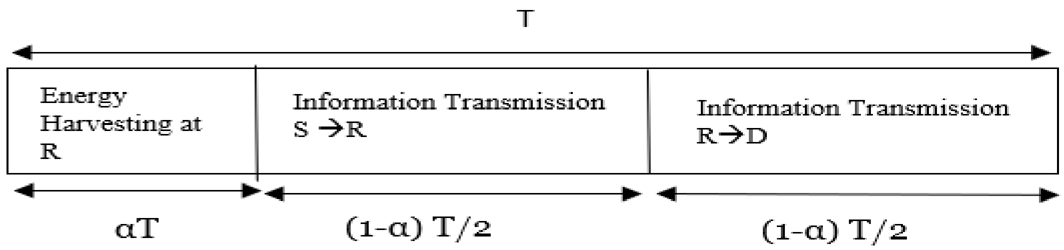


Figure 3.2: Time switching relaying (TSR) protocol [27]

The energy harvested (E_{TSR}) at the relay using TSR protocol and the corresponding transmission power (P_{TSR}) can be given by equations (3.3) and (3.4) respectively [13], where "η" is the energy conversion efficiency and "P_S" is the source transmit power.

$$E_{TSR}= \frac{\eta P|h|^2}{d^m}\alpha T \quad (3.3)$$

$$P_{TSR}= \frac{E_{TSR}}{(1-\alpha)T/2} = \frac{2\eta P_S|h|^2\alpha}{d^m(1-\alpha)} \quad (3.4)$$

3.3.2 POWER SPLITTING RELAYING (PSR) PROTOCOL

The PS receiver is used at the relay in order to perform this protocol. As seen in Figure 3.3[14], in this protocol, the receiver divides its power "P" according to the power splitting ratio "ρ", where some of the source power "ρP" is used for harvesting RF energy and the remaining power – ["(1- ρ)P"] is used for decoding the received data.

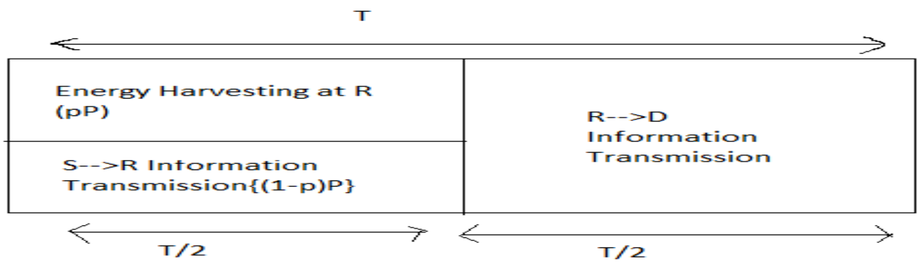


Figure 3.3: Power Splitting Relaying (PSR) protocol [28]

The harvested energy (E_{PSR}) and transmit power (P_{PSR}) of a relay using PSR protocol, can be calculated using the equations (3.5) and (3.6) respectively [14].

$$E_{PSR} = \frac{\eta P|h|^2}{d^m}\left(\frac{T}{2}\right) \tag{3.5}$$

$$P_{PSR} = \frac{E_{PSR}}{T/2} = \frac{\eta P|h|^2}{d^m} \tag{3.6}$$

3.4 METHODS FOR RELAYING IN A COOPERATIVE RF ENERGY HARVESTING NETWORK

Depending on the channel conditions, the location of the users in relation to one another, and the complexity of the transceiver, various relaying techniques may be employed to encourage user cooperation. These protocols specify how data is processed by relays before it is transmitted to the final location. Two basic relaying protocols (DF and AF) have been used in the simulations of the proposed work. Both the protocols have been discussed below.

3.4.1 AMPLIFY AND FORWARD (AF) PROTOCOL

This is a simple cooperative signalling strategy, introduced and evaluated by Laneman et al. [20]. In this relaying technique, the signal from the source is amplified at the relay before being sent to the target. Figure 3.4 [20] shows a schematic of a three-node relay network using the AF protocol.

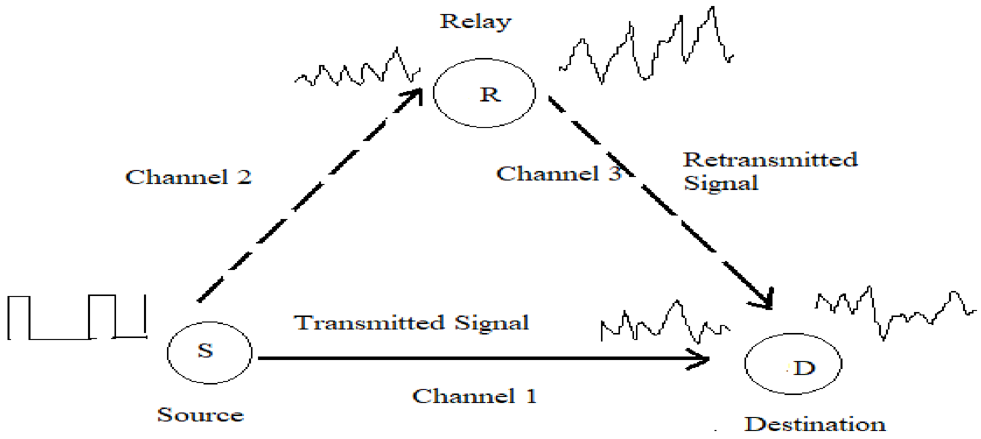


Figure 3.4: Amplify and Forward (AF) Protocol [20]

The fundamental disadvantage of this strategy is that both the signal and the noise get amplified at the relay. Thus, this protocol is used only when the time delay of the relay in decoding and encoding the message should be minimum or when the relay has limited computing resources.

The block-wise amplification of the received signal "y_R" in AF protocol can be modelled as-multiplication of the signal with an "*amplification factor (β)"*, that normalises the received power The received power at the relay is given by equation (3.7). The *amplification factor* " β" can be calculated by equation (3.8) based on the assumption that a complete estimation of the channel parameters is possible at the relay [20].

$$E[|y_R^2|] = E\left[\left|h_{s,R}\right|^2\right] E[|x_s|^2] + E\left[\left|z_{s,R}\right|^2\right] = \left|h_{s,R}\right|^2 \xi + 2\sigma_{s,R}^2 \tag{3.7}$$

$$\beta = \sqrt{\frac{\xi}{\left|\mathrm{h_{s,r}}\right|^2 \xi + 2\sigma_{s,r}^2}} \tag{3.8}$$

3.4.2 DECODE AND FORWARD (DF) PROTOCOL

This strategy was implemented in the work of Sendris et al. [21]. Using this technique, the relay station decodes the received signal from the source node, decodes it, before sending it to the destination station. A schematic of a three-node network using *DF* protocol is shown in Figure 3.5 [21].

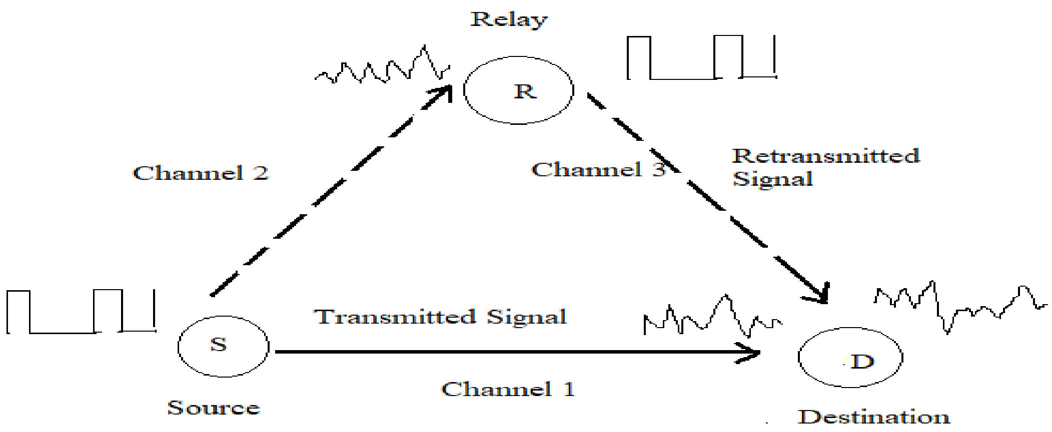


Figure 3.5: Decode and Forward (DF) Protocol [21]

The relay use checksum method along with error-correcting codes to detect and correct any errors present in the received signal. It is frequently used as a data processing tool at the relay due to the fact that the transmitted signal doesn't contain amplified noise, as was the problem in AF protocol. But on the downside, the relay needs both processing time and bandwidth to perform the decoding operation successfully. Another approach processes the signal by decoding and re-encoding it symbol by symbol in order to avoid the delay brought on by decoding. This approach can also be used when the relay has insufficient computing power or it needs to communicate sensitive data.

3.5 MODES OF RELAY -COMMUNICATION IN A COOPERATIVE RF ENERGY HARVESTING NETWORK

Relays at present mainly use half-duplex communication for data transmission, which prevents them from broadcasting and receiving data simultaneously on the same frequency. However, this relaying method does not offer complete spectrum efficiency. Full-duplex relaying was proposed as a solution [11], which can make greater use of the available frequency spectrum. It allows the relays to conduct uplink and downlink communications simultaneously throughout the whole frequency range. However, in full-duplex transmission, the nearby antennas' self-interference can reduce the quality of the received signal. To combat it, self-interference cancelling (SIC) methods are needed. Recent improvements in digital self-interference cancelling (SIC) systems have experimentally substantiated the viability of full-duplex communications [12]. With full-duplex communication, throughput, latency, and spectrum efficiency can all be increased.

In the proposed work, the relay node employs full-duplex technology to carry out data transmission to the destination and energy harvesting from the source signal concurrently. This can decrease delay time of the network while also enhancing the spectral efficiency.

3.6 Relay Selection Schemes

Selection of relay in a cooperative network is important for improving the performance of the network. Relay selection can result in less energy loss and higher throughput. There are several relay-selection schemes. Based on the selection criterion, they can be divided into two groups [30-38]:

3.6.1. Opportunistic Relay Selection

This relay selection scheme can be broadly classified as follows:

1 Selection of relay based on CSI measurement

This strategy [30] selects the best relay (“R_B”) among the "N" relays based on the channel status of the “2N” channels. This selection technique logs the channel state information for each relay using the *RTS/CTS* signal. After estimating the channel status information, each relay starts a timer equal to the inverse of the estimated values. The relay node which gives the highest value is selected as the best relay for the communication purpose. Subsequently, the selected relay sends a request to other relays for accessing the channel in order to avoid the "hidden node problem”.

The disadvantage of this scheme is the complexity associated with estimating the status of the “2N” channels for large values of “N”. In a wireless channel, the channel conditions are always changing due to fading. As a result, it may not be possible to estimate accurate CSI for all the channels at a particular time.

II Performance based relay selection

In this method [31], estimates of the delay, energy efficiency, etc. are used to choose the best relay.

- In Step-I, the transmitter transmits the desired relay performance value.
- Step-II entails the computation of data regarding the state and performance level of the channel at relaying nodes.

However, the performance of this strategy is limited due to overhead estimates.

III Threshold-dependent Relay selection

The selection algorithm [32] operates as follows:

- In Step-I, the received signal quality is evaluated, and compared with a predetermined threshold for delay, throughput, or BER. Only those relays whose performance estimates are above the threshold value are selected.

- In Step-II, the relaying nodes that have the lowest SNR values for transmitter-to-relay and relay-to-receiver channels is selected.

This strategy may not be an optimal solution in some cases [33]. For instance, if "M" numbers of relay nodes are selected in the first step; the available channels for performance evaluation in the next step is "2*M". The relaying operation would not be able to react to changes in the channel as the threshold level was already chosen.

IV Adaptive relay selection

The relay selection process is done by comparing the power of the received signal to the predetermined threshold value. Relay selection is performed iff strength drops below a predetermined level [37].

3.6.2. RANDOM RELAY SELECTION

In this selection strategy, all the relay nodes have equal chances of selection. This selection occurs randomly and is not dependant on the information of the channels. This is a fair optimizing technique and has been shown to be effective in resource constrained networks [38-39]. The disadvantage of this strategy is that, due to random selection, the relays may not provide optimal performance.

3.7 COMBINING TECHNIQUES IN COOPERATIVE NETWORKS

In wireless communication, the received signals can be combined using several combining techniques to create a stronger signal. [40-45]. In the proposed work, we have used DSSC technique at the receiver, which is based on the SSC technique. Both the combining techniques have been discussed below.

For a single relay network, the received signal at destination ($y_D[n]$) can be given by equation (3.9) [40] where the signal received from the source and the relay are denoted by $y_{SD}[n]$ and $y_{RD}[n]$ respectively.

$$y_D[n] = y_{SD}[n] + y_{RD}[n] \tag{3.9}$$

3.7.1 SWITCH AND STAY COMBINING (SSC)

SSC is an effective combining technique which weighs the signals from the two diversity branches-direct branch ("S"- "D") and the relaying branch ("S"- "R"- "D") based on their corresponding Signal-to-Noise ratio (SNR). This method selects the signal with the highest SNR by alternating between signals from two branches based on their immediate received signal-to-noise ratio (SNR).

SSC has drawn a lot of interest, and numerous research projects have looked into how well this technique performs [38]. The working of this technique can be explained by the equation (3.10) [39]:

$$y_D[n] = \begin{cases} y_{SD}[n] & \left(\frac{\text{SNR}_{\text{SD}}}{\text{SNR}_{SRD}} > 10\right) \\ y_{SD}[n] + y_{SRD}[n] & \left(0.1 \le \frac{\text{SNR}_{SD}}{\text{SNR}_{SRD}} \le 10\right) \\ y_{SRD}[n] & \left(\frac{\text{SNR}_{\text{SD}}}{\text{SNR}_{SRD}} < 0.1\right) \end{cases} \tag{3.10}$$

3.7.2 DISTRIBUTED SWITCH AND STAY COMBINING (DSSC)

This method can be compared to a "virtual *SSC* system" with the direct branch ("S"- "D") and the relaying branch ("S"- "R"- "D") acting as the two input branches [37]. The destination determines the active branch for each transmission period by comparing it's received SNR with a *switching threshold* ("k"). If the received SNR is less than "k", a branch-switching takes place. It is possible to determine the SNR of a relay link using AF by sending a known sequence in each block. But when the relay link employs the DF protocol in a multi- hop network, the receiver accepts the latest CSI for each of the hops. In order to assess SNR, it is assumed that the relay will send some additional data to the destination concerning the quality of the unseen hops.

<u>Estimation of SNR using AF relaying:</u>

The received signal at the relay for the *AF* protocol is given by, equation (3.11).[38]

$$y_{r,d} = h_{r,d}x_r + z_{r,d} = h_{r,d}\beta\left(h_{s,r}x_s + z_{s,r}\right) \times z_{r,d} \tag{3.11}$$

Therefore, received power is calculated as in equation (3.12) [39]

$$E\left[\left|y_{r,d}\right|^2\right] = \beta^2\left|h_{r,d}\right|^2\left(\left|h_{s,r}\right|^2\xi + 2\sigma_{s,r}^2\right) + 2\sigma_{r,d}^2 \tag{3.12}$$

The SNR of a single relay- link can be estimated by, the following equation (3.13);

$$SNR = \frac{\beta^2 |h_{s,r}|^2 |h_{r,d}|^2 \xi}{\beta^2 |h_{r,d}|^2 2\sigma_{s,r}^2 + 2\sigma_{r,d}^2} \quad (3.13)$$

Estimation of SNR using *DF* relaying:

The BER of the link must first be computed and then converted to an equivalent SNR in order to calculate the SNR using *DF* relaying. The BER of a single relay-link and the corresponding SNR for a *BPSK* modulated *Rayleigh* faded signal could be determined by the equations (3.14) and (3.15) respectively,[40]:

$$\text{BER}_{s,r,d} = \text{BER}_{s,r}\left(1 - \text{BER}_{r,d}\right) + \left(1 - \text{BER}_{s,r}\right)\text{BER}_{r,d} \quad (3.14)$$

$$SNR = \frac{1}{2}\left[Q^{-1}(BER)\right]^2 \quad (3.15)$$

In this thesis, we have considered a *dual hop* system. The branch switching process, for a dual hop network can be expresses as in equation (3.16) where "$\gamma_{\text{DF}}^{\text{e2e,R}_B}$" and "$\gamma_{\text{AF}}^{\text{e2e,R}_B}$" are the end-to-end SNRs of "R_b" when it uses *DF* and *AF* protocols, respectively and "γ'_{SD}" is the instantaneous SNR of the source "*S*" to destination "*D*" link [39].

$$\begin{aligned}
&\gamma_{\text{DF}}^{\text{e2e,R}_B} = min\left(\gamma'_{\text{SR}_B}, \gamma_{\text{R}_B\text{D}}\right) < \kappa, && \text{for DF relaying} \\
&\gamma_{\text{AF}}^{\text{e2e,R}_B} = \frac{\gamma'_{\text{SR}_b}\gamma_{\text{R}_b\text{D}}}{\gamma'_{\text{SR}_B} + \gamma_{\text{R}_B\text{D}} + 1} < \kappa, && \text{for AF relaying} \\
&\gamma'_{\text{SD}} < \kappa && \text{for direct "S" to "D" link}
\end{aligned} \quad (3.16)$$

This method has been suggested for the proposed system model since DSSC can enhance system performance. Additionally, it reduces the complexity at the receiver as no hardware is required for its implementation.

3.8 PERFORMANCE METRICES

In order to assess the performance of a wireless system, various metrics are used. In the proposed work, the following three parameters- *outage probability*, *throughput* and *spectral efficiency* which would be examined has been discussed below.

3.8.1 OUTAGE PROBABILITY

In Information theory, "*outage probability*" of a communication channel is defined as "the probability that a given information rate is not supported." This could be because of variable channel capacity. In other words, “Outage probability” is defined as the probability that information rate is less than the required threshold information rate” [15].

For the proposed work, the general expressions for outage probability for the Partial Relay Selection and 2 Round Relay Selection can be given as, by Equation (3.17) [24] and equation (3.18) respectively,[25], where "γ_{SR}", "γ_{RD}" and “γ_{th}" are the SNRs of the source to relay link, relay to destination link and threshold SNR respectively.

$$P_{OUT}^{PRS} = Pr(\gamma_{SR} < \gamma_{th}) + Pr(\gamma_{SR} \geqslant \gamma_{th}, \gamma_{RD} < \gamma_{th}) \quad (3.17)$$

$$P_{OUT}^{2RRS} = \sum_{i=1,M=0}^{N} \sum_{j=1}^{(N)} \prod_{j\in\Omega_j^M} \left[Pr\{\gamma_{SRj} \geqslant \gamma_{th}\} Pr\{\gamma_{RjD} < \gamma_{th}\}\right] \prod_{i\notin\Omega_j^M} Pr\{\gamma_{SRi} \leqslant \gamma_{th}\} \quad (3.18)$$

3.8.2 THROUGHPUT

The amount of data that may be sent over a network during a particular time period is referred to as *throughput*(“Th”) of the network. Generally, *throughput* capacity is measured in “bits per second”**.** The *delay-limited transmission mode* was taken into consideration in our suggested work [25], and the average throughput was calculated by calculating the system's *outage probability* ("P_{OUT}") when a *fixed transmission rate* ("R") was used. The *effective transmission rate* and the *information transmission time* (“1 – τ”) are the two factors that determine the system throughput. equation (3.19) is used to compute it and is provided below [25]:

$$Th = R * (1-P_{OUT}) * (1-\Gamma) \quad (3.19)$$

3.8.3 SPECTRAL EFFICIENCY

The spectral efficiency ($\eta_{spectral}$) of a communication system is the ratio of the transmitted data rate (“R”) and the channel bandwidth (“B”), as in equation (3.20) [25]. The bandwidth (“B”) of a communication system is defined by the highest data rate that the system can transfer which in the theory is equal to the Shannon’s channel capacity (“C”) given by Equation (3.21).

$$\eta\_spectral = \frac{R}{B} \text{ bits/Hz} \quad (3.20)$$

$$C = B \log_2(1 + SNR) \quad (3.21)$$

It is derived analytically by adding the data rate in each partition link, weighted according to the steady state selection probability (“$p_{\mathrm{S,D}}$". and “$p_{\mathrm{R}_{best}}$”). The analytical expressions for spectral efficiency for FD and HD case has been shown in equation (3.22) and equation (3.23) respectively [26]. In the proposed system model, the achievable spectral efficiency of S−Rb −D link using FD and HD relay are “R” and “R/2”, respectively, where R is the transmission data rate.

$$\eta^{FD}_{spectral} = p_{\mathrm{S,D}}*R + p_{\mathrm{R}_{best}}*R \quad (3.22)$$

$$\eta^{HD}_{spectral} = p_{\mathrm{S,D}}*R + p_{\mathrm{R}_{best}}*(\frac{R}{2}) \quad (3.23)$$

3.9 DISCUSSION

This chapter provided a description of the theories needed for the proposed work. The various cooperative relaying protocols that can be applied in an RF Energy Harvesting network are described, along with the accompanying mathematical equations. A brief overview of the relay selection strategies and combining techniques including the DSSC technique are also presented here. A thorough explanation of the proposed work is provided in the following chapter.

CHAPTER 4

PROPOSED WORK

4.1 OVERVIEW

Relay selection is essential for attaining diversity benefit and ensuring Quality of Service (*QoS*) in cooperative networks. Apart from network efficiency, "*energy efficiency*", is a crucial factor in choosing the best relay in an RF energy harvesting network. In order to address the issue of relay selection with the optimal "power-energy trade-off", new algorithms are therefore required. A novel optimization method known as *two-round relay selection (2 RRS)* chooses the ideal relay for cooperation based on the energy status of the available relays as well as information of the *CSI* of all the "source-relay" and "relay-destination" channels.

The network performances of the proposed Two Round Relay Selection (*2 RRS*) method and an existing Partial Relay Selection (*PRS*) scheme are simulated for a *DSSC* based *full-duplex* dual hop relay-aided *RF Energy Harvesting Network*. The proposed work compares the outage probability, throughput, and spectral efficiency of the above two relay selection schemes operating under the two primary cooperative relaying protocols — *Amplify and Forward (AF)* and *Decode and Forward (DF)*. Additionally, the simulations were repeated for *half-duplex* mode, to compare the performance of the *full-duplex* model to that of the conventional *half-duplex* mode. The results of this study are discussed in detail in the following chapter.

4.2 SYSTEM MODEL

A single source ("S") to destination ("D") communication is carried out with the help of best relay ("R_B") in a *full-duplex* dual hop network where information is transmitted from the source to the destination either directly ("S"-"D" link) or indirectly ("S"- "R_B"- "D" link). All the relays ("R_1" to "R_N") have *PSR* receiver construction for the purpose of RF energy harvesting and information processing. The best relay ("R_B") selected in accordance with the two relay selection schemes is used to forward data to the destination. At the destination, the received signal is selected according to the "DSSC" technique. The proposed system can be modelled as shown in Figure 4.1.

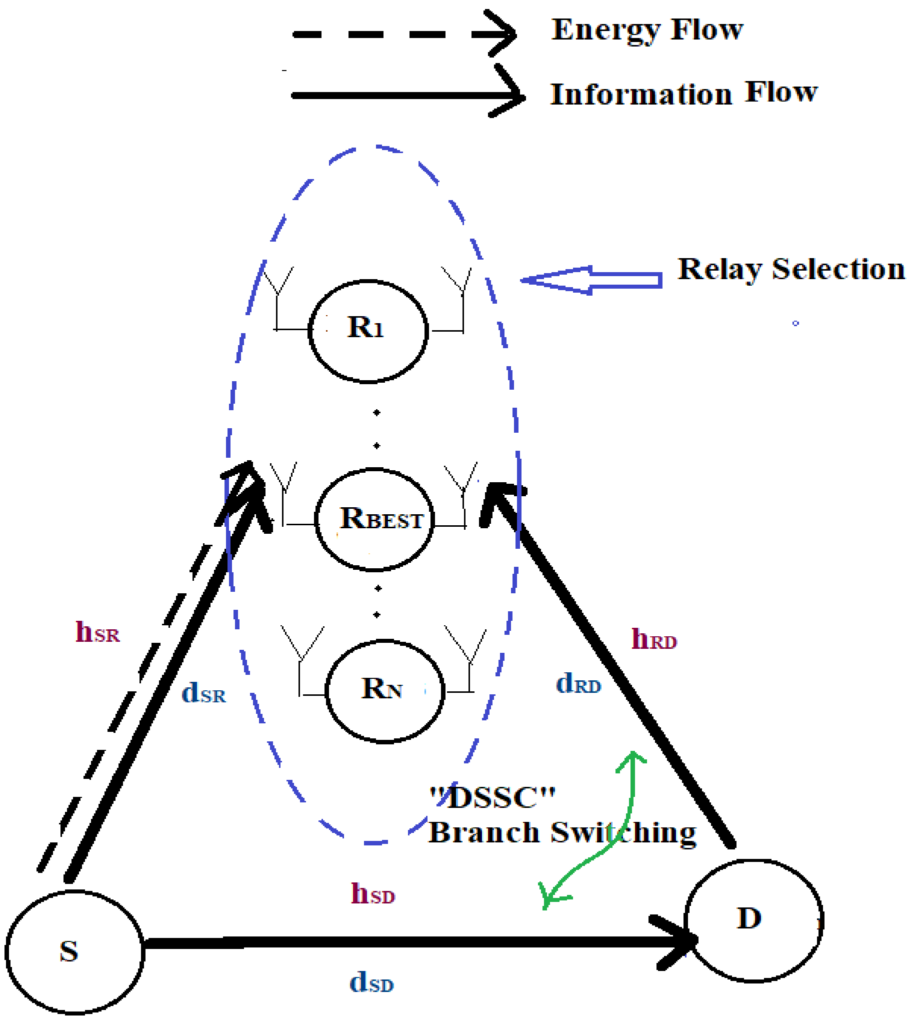


Figure 4.1: Proposed System Model

The following are some of the assumptions to the considered model [24]:

- All the nodes of the system are static and only the relays can harvest RF energy from the source. The source and the destination have a fixed power supply.
- The relays are assumed to be in a straight line between "S" and "D" assuming a practical model of distance and *path-loss*. The distance from "source to destination", "source to relay" and "relay to destination" are given by, "d_{SD}", "d_{SR}" and "d_{RD}" respectively.
- In this architecture, the source and destination have a *single antenna*, each, whereas the relays have *two antennas*, one for receiving information and the other for broadcasting data. "Self-interference" effect from the transmitting antenna of "R_B" to its receiving antenna is assumed to be negligible for *HD* mode of operation.

- All the wireless links of the network undergo frequency non-selective “Rayleigh block fading”. The channel fading co-efficient of the “source-destination”, “source-relay” and “relay -destination” links are respectively given by, “h_{SD}”, “h_{SR}” and “h_{RD}” respectively.

4.3 RELAYING PROTOCOL FOR THE SYSTEM MODEL

The entire communication from source to destination is carried out using a two-phase protocol, as shown in Figure 4.2 [24]. A transmission block-time "T" is split into two slots of equal duration (“T/2”). During the first slot of the transmission block time, the information is transmitted from the source to the relays (“S” -> “R”). In the second sub-slot, energy is harvested at the relay receiver according to “PSR” protocol. After processing the data in the second sub-slot, the relay ("R_B"), chosen in accordance with the relay selection algorithms, transmits the data to its destination using the harvested energy.

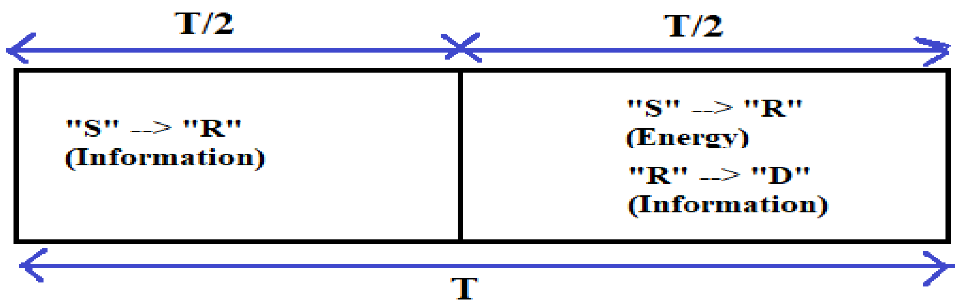


Figure 4.2: A relay transmission protocol used in the proposed model [24]

The processing of the received information at the relay depends on the relay's operating protocol.In the proposed work, the performance of the system model is examined ,considering both the protocols “Amplify-and-Forward”(***AF***) and “Decode-and-Forward”(***DF***) separately. The working of the protocols are as follows:

- **DF Relaying Protocol**: The relay receiving the information in the “Decode and Forward” (*DF*) protocol decodes it before processing it for subsequent transmission.

- **AF Relaying Protocol:** In contrast, the received data is amplified at the relay receiver before being transferred to the destination in an “Amplify-and-Forward” (*AF*) system.

4.4 DISTRIBUTED SWITCH AND STAY COMBINING (DSSC) TECHNIQUE

At the receiver of the destination, *Distributed Switch and Stay Combining* (DSSC) method is applied, which selects the best connection between the direct link ("S"- "D" link) and the relaying link ("S"- "R_B"- "D" link) for receiving the data in a certain transmission block. The end-to-end SNRs of the direct ("S"- "D") link and the relaying link ("S"- "R_B"- "D") link, are given by, "γ_{SD}" and "γ_{SRD}" respectively. The instantaneous SNR of ("S"- "R_B") and ("R_B"- "D") links are given by,"γ_{SR_B}" and "γ_{R_BD}" respectively.

The operation of DSSC can be summarized as follows [25]:

1. Initially, for any transmission block time, the SNR of the current branch is compared to a predefined threshold ("γ_q"), commonly referred to as the "switching threshold ". Here the value of switching threshold is 7.
2. If the link's SNR exceeds the threshold, it is chosen to be the active branch in the ensuing transmission block period.
3. Else if the SNR of the current link is below the threshold value, the current branch is "switched" to the other alternate link.
4. Finally, the destination ("D") performs the switching operation after sending the necessary feedback to the source ("S") and the best relay ("R_B"). The switching function for the system model in AF and DF relaying, can be expressed by equations 4.1 and 4.2 respectively [24].

For DF relaying, the branch switching occurs when:

$$\gamma_{e2e,R_B} = min(\gamma_{SR_B}, \gamma_{R_BD}) < \gamma_q \quad (4.1)$$

For AF relaying, the branch switching occurs when:

$$\gamma_{e2e,R_B} = \left(\frac{\gamma_{SR_B} * \gamma_{R_BD}}{\gamma_{SR_B} + \gamma_{R_BD} + 1}\right) < \gamma_q \quad (4.2)$$

4.5RELAY SELECTION SCHEME FOR THE SYSTEM MODEL

In the proposed work, the proposed Two Round Relay Selection (2 RRS) scheme has been used for performance evaluation of the DSSC system model with respect to the existing Partial Relay Selection (PRS)scheme. Both the schemes are discussed below:

4.5.1 PARTIAL RELAY SELECTION (PRS) SCHEME

A well-known existing relay selection approach is partial relay selection (PRS), in which the best relay is selected based on the knowledge of the channel state information (CSI) of the relay links. The *CSI* for any one hop is used for this scheme. [21–26]. Depending on which hop's *CSI* is available, it can be further split into two types:

- **PRS I**-The partial relay selection scheme is given by (*PRS I*) if CSI is accessible for the first hop (“S”- “R”) only.

- **PRS II**. On the other hand, if *CSI* of only the second hop can be accessed, it is indicated by (*PRS II)*.

For “N” number of relays, the best relay (“R_B") according to PRS I and PRS II can be expressed by Equations 4.3 and 4.4 respectively. [24]

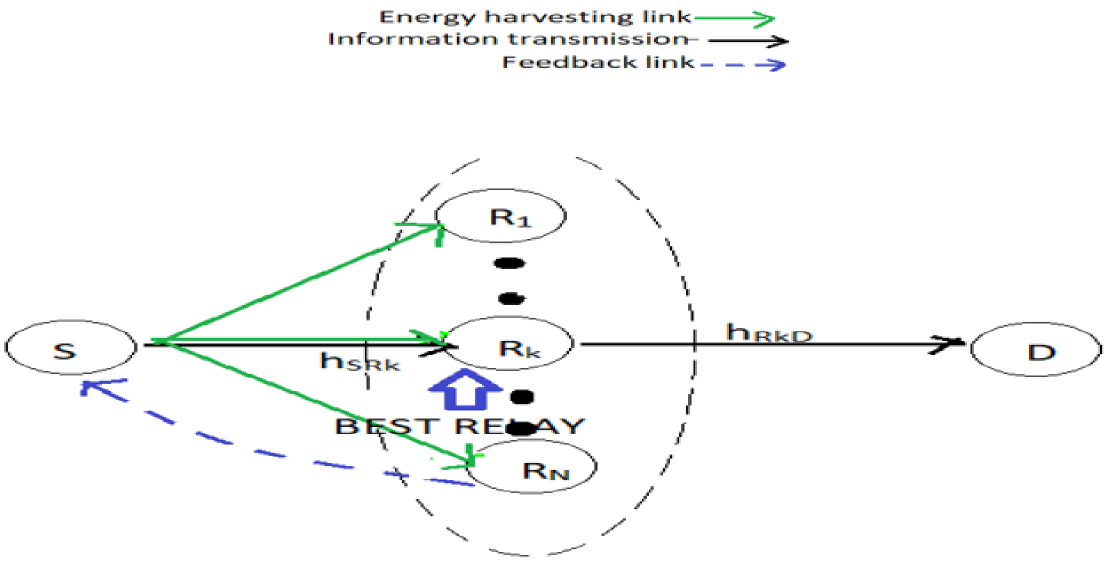
For PRSI,

$$R_B = \text{argmax}\left\{\left(\gamma_{SR_i}\right)\right\} \; ; \quad \forall\, i \leq N \tag{4.3}$$

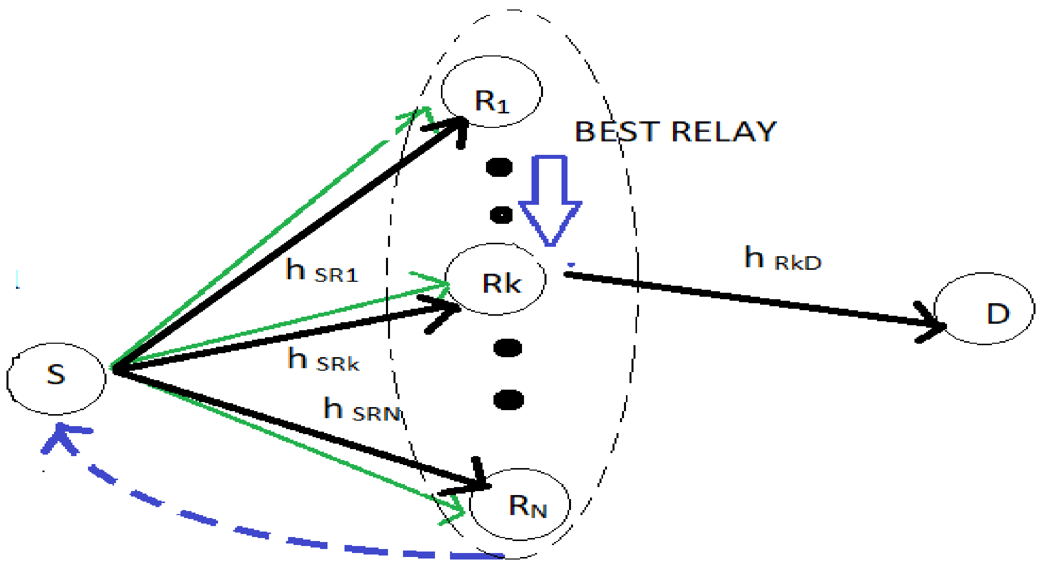
For PRS II,

$$R_B = \text{argmax}\left\{\left(\gamma_{R_i\text{D}}\right)\right\} \; ; \quad \forall\, i \leq N \tag{4.4}$$

A schematic representation of PRS I and PRS I scheme has been shown in Figure 4.3 (a)and Figure 4.3(b) respectively. The algorithms for the two schemes are elaborated in Table 4.1 and Table 4.2 respectively [25].



(a) PRS I



(b) PRS II

Figure 4.3: A schematic representation of PRS strategy

Table 4.1. Algorithm for Partial Relay Selection (PRS I) Scheme

```
Begin
Input number of relays, N
Initialize R_B = 1; max=-9999
    for i =1 to N
    Update channel co-efficient of all the source to relay links, hSR[i]
        if
         hSR[i] > max;
         max = hSR[i];
         R_B =arg (max);
        end if
    end for
End
```

Table 4.2. Algorithm for Partial Relay Selection (PRS II) Scheme

```
Begin
Input number of relays N
Initialize R_B = 1; max=-9999
    for i =1 to N
    Update channel co-efficient of all the relay to destination links, hRD[i]
        if
         hRD[i]> max;
         max = hRD[i]
        R_B =arg (max);
        end if
    end for
End
```

4.5.2 TWO ROUND RELAY SELECTION (2RRS)

The proposed 2 RRS relay selection considers both the harvested energy and the channel conditions of both the hops for the purpose of relay selection. Figure 4.4 provides a schematic illustration for the 2RRS relay selection and the corresponding algorithm for the 2RRS relay selection system is elaborated in Table 4.3.

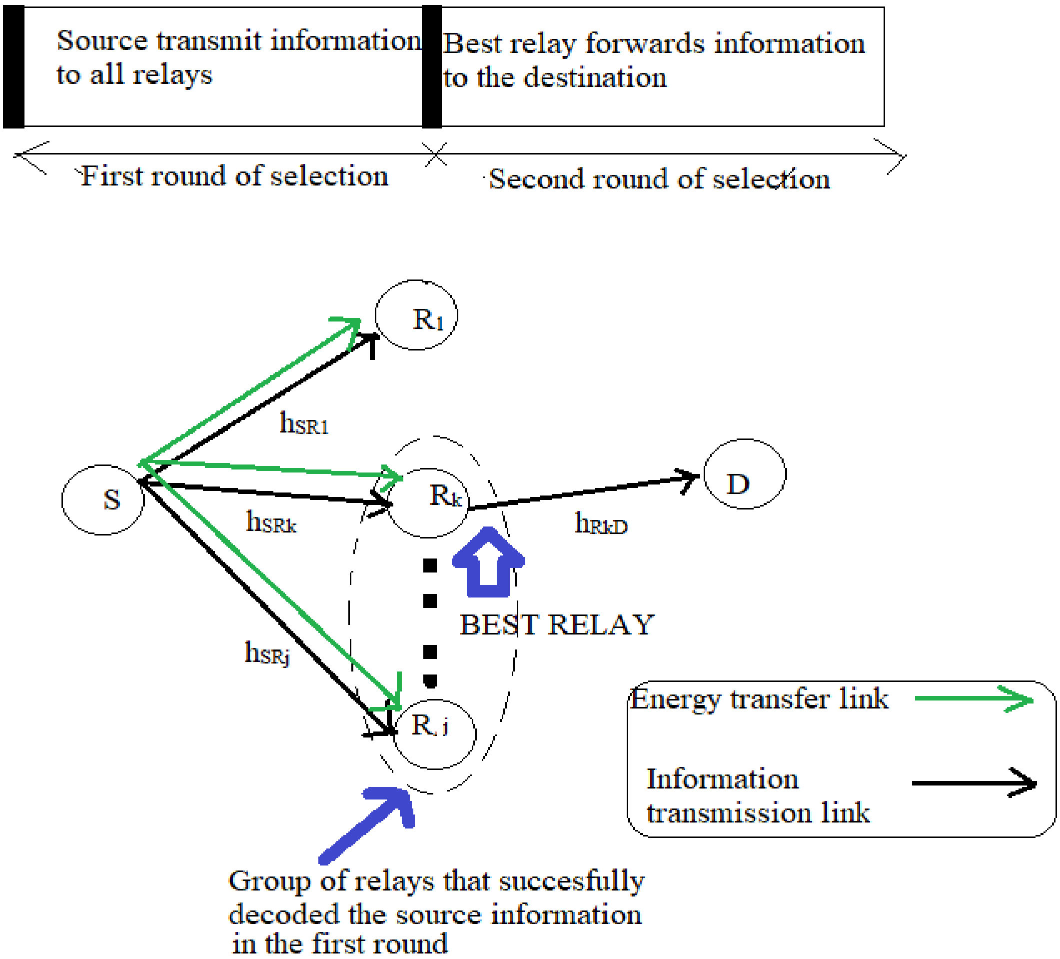


Figure 4.4: A schematic representation of 2RRS strategy

The algorithm operates in two rounds; where the relays selected in the first round undergoes another selection evaluation in the second round to be deemed as the best relay(“R_B”). The two rounds of relay selection can be described as below:

#Round 1: The source sends information to all of the relays in the first round. The relays convey their channel status information (CSI), which includes the received SNR and the amount of energy gathered, to the destination after receiving the transmitted data. All relays' SNRs (γ_{RjD}) are compared to a predetermined threshold (γ_q). Relays whose SNR is higher than the threshold

SNR value can now correctly decodes the information of the source “S”. They are chosen as the top relays and go through a second round of selection.

#**Round 2**: In the second round, the SNR of all the relays is evaluated using the top relays from the first round. The best relay is the one with the highest “R”-“D” channel strength (SNR). The SNR of the “j-th” relay in the group of relays is given in equation (4.5),

$$\gamma_{R_jD} = \frac{P_{R_j} h_{RjD}^2}{\sigma_0} \tag{4.5}$$

The most effective relay out of N number of relays is selected based on the following algorithm in Table 4.3. The destination notifies each relay of the best relay it has chosen. The most effective relay then transmits the information from the source to the target.

Table 4.3. Algorithm: Two Round Relay Selection (2-RRS) Scheme

Begin
Input number of relays, ***N***, threshold SNR, γ_q
  while S transmits to N relays
  Update γ_{SRi};
    for i =1 to N
    Initialize round_1_success=0;
      while ($\gamma_{SRi} >= \gamma\_q$)
      round_1_success=round_1_success +1;
      end while
    end for
(First Round Relay Selection)
      if round_1_success>0
        for j=1 to round_1_success
        Update γ_{RjD};
        R_B=arg {max (γ_{RjD})}
        end for
      end if
(Second Round Relay Selection)
  end while
End

4.6 DISCUSSION

An overview of the proposed work was provided in this chapter A full-duplex dual hop relay-aided RF energy harvesting network has been taken into consideration in order to evaluate the performance of the current DSSC based PRS relay selection scheme to the proposed 2 RRS scheme. In two-round relay selection (RRS), the best relay for data transmission is selected by independently weighing the energy gathered at each relay and the CSI of both connections. Only the CSI of the first hop is necessary in partial relay selection, commonly referred to as PRS I. Therefore, a more accurate evaluation of the energy-information trade-off is possible if the 2 RRS method is used. Two algorithms have been discussed. Along with the implementation of the transmission protocol, two well-known relaying protocols—AF and DF—have also been implemented for the relay operation. The next chapter provides an explanation of the outcome of this work.

CHAPTER 5

RESULTS AND ANALYSIS

5.1 OVERVIEW

This chapter presents the results of the simulations of the proposed work, which also emphasizes the advantages that various cooperative relaying protocols may have when combined with different relay selection procedures. The performance of the proposed *2RRS* based relay selection strategy in a *DSSC* based system has been studied and compared with existing *PRS* based *DSSC* system [24] under both *full duplex* and *half duplex* modes in a *dual hop relay-aided RF energy harvesting network*. Both the Decode and Forward (*DF*) and Amplify and Forward (*AF*) schemes are examined separately in order to assess the performance of the suggested model. The proposed model has been simulated using MATLAB R2015a.The results are obtained using Monte-Carlo simulation. The detailed analysis and comparison of the performance of the proposed *2RRS* based relay selection system model and the existing *PRS* based system, in terms of the variation of outage probability (OP), throughput and spectral efficiency with respect to transmit SNR, has been presented below.

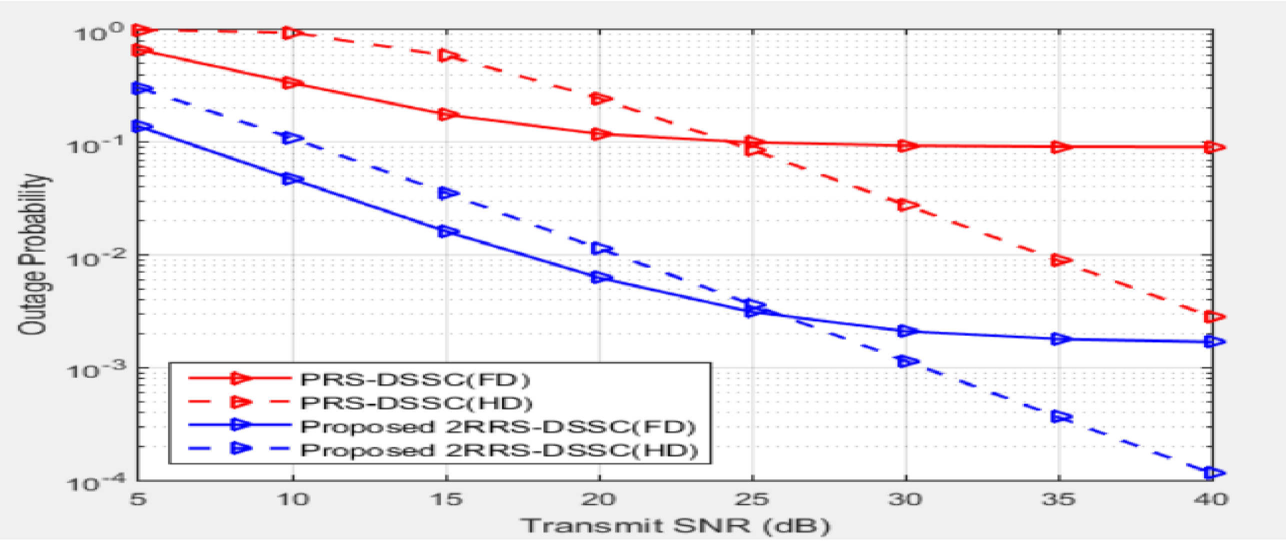
5.2 PARAMETER SETTING

Table 5. 1. System parameters used in the performance evaluation

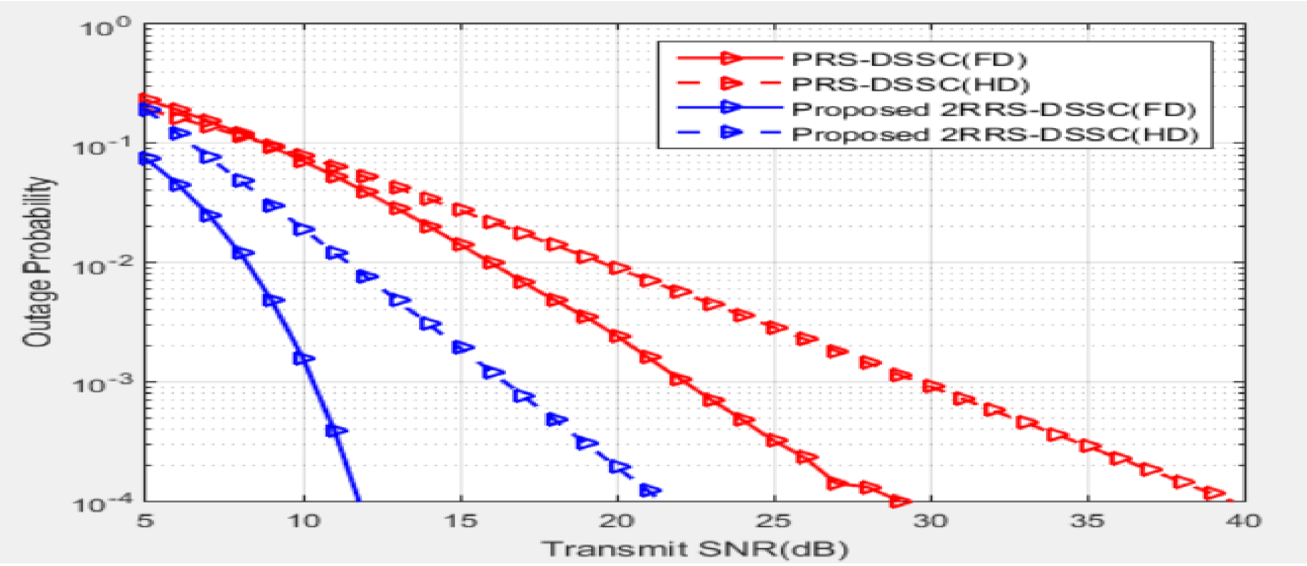
Number of relays (N)	3
Transmission rate of source(R)	3 bps/Hz
Energy efficiency(η)	0.4
Harvesting time (Γ)	0.4s
Distance from source to relay	0.5m
Distance from source to destination	1m
Noise power(watt/Hz)	1[24]
Path loss exponent(m)	3[24]
Switching threshold(k)	7[24]
Outage threshold (FD/HD)	7 (2^r -1) / 63 (2^{2r} -1)
Power splitting ratio (β)	0.4

5.3 PERFORMANCE ANALYSIS OF OUTAGE PROBABILITY VERSUS TRANSMIT SNR FOR THE PROPOSED 2 RRS SCHEME AND THE EXISTING PRS SCHEME IN A DSSC-BASED SYSTEM

The performance comparison of outage probability of the proposed DSSC based 2-RRS system with the existing PRS method versus transmit SNR has been shown in the Fig 5.1(a) and Fig 5.1(b) for AF and DF protocols respectively.



(a) AF protocol



(b) DF protocol

Figure 5.1: Outage probability performance of the proposed 2-RRS scheme and existing PRS scheme for full-duplex and half-duplex DSSC system

It is observed that the proposed 2-RRS method performs better than the current PRS in terms of outage probability for both scenarios of HD and FD relaying. Following is an explanation for this: In PRS, only the channel information of the first hop, (“S”- “R”) is required for relay selection. However, in 2 RRS, the quantity of RF energy harvested at the relays is also taken into account for relay selection in addition to the channel hop information. As a result, the relay with greater energy performs at its best. Thus, the performance is optimized because the probability of an outage is decreased because the relay with more energy would transmit data with a stronger signal. Additionally, there is an inverse relation between transmitted SNR and outage probability i.e., as transmit SNR rises, the outage probability of an overall system decreases. For instance, in Figure 5.1(a), the outage probability of the proposed 2 RRS DSSC based system decreases by 10% when transmit SNR is increased from 15dB to 20dB.

Moreover, FD relaying has a better performance on all relay selection strategies compared to HD. This is because, with FD, "Rb" can concurrently harvest energy from "S" and transmit information from "S" to "D," whereas with HD approach, "R_B" must use the PS ratio " β" to divide energy harvesting and information processing. However, as demonstrated in Figure 5.1(a), the FD system performs worse than the HD system in the AF protocol at high SNRs [above 15 dB]. The cause of this is that the signal quality at the relay receiver degrades at high SNRs as a result of increased self-interference of the FD relay antennas. Additionally, as AF protocol is utilized, the transmitted signal's noise is enhanced, which results in poor performance. However, this is not the case if a DF system is considered. In DF relaying, the relays first decode the signal before sending it to the target. Thus, signal noise is diminished. The signal quality received at the destination is higher, which lowers the chances of an outage as can be seen from Figure 5.1(b). Table 5.1 compares the proposed 2-RRS scheme with the existing PRS [24,25] in terms of outage probability performance gain.

Table 5.2. Performance gain in Outage probability of the proposed 2-RRS scheme over the existing PRS scheme in a full-duplex DSSC based system under AF relaying protocol

TRANSMIT SNR	**10dB**	**15dB**	**20 dB**
PROPOSED 2RRS over PRS(FD) [% Improvement]	14.771%	15.253%	17.852%
PROPOSED 2RRS over PRS(HD) [% Improvement]	12.267%	13.225%	14.642%

The results are based on Figures 5.1(a) when the relay operates in AF mode. According to Table 5.2, the proposed 2-RRS method outperforms the PRS scheme by about 15% when the transmit SNR is 15 dB while operating in FD. This can be explained by the fact that when the transmit SNR increases, the quality of the signal received at the relay increases as well, which results in fewer outages. The performance boost for HD, however, is 13% at the same transmit SNR. This can be explained by noting that HD requires less signal power for processing because of the receiver's power-splitting architecture, hence the relay is not able to provide the signal with a higher quality at the destination. This leads to more outage and hence the system performance gets degraded.

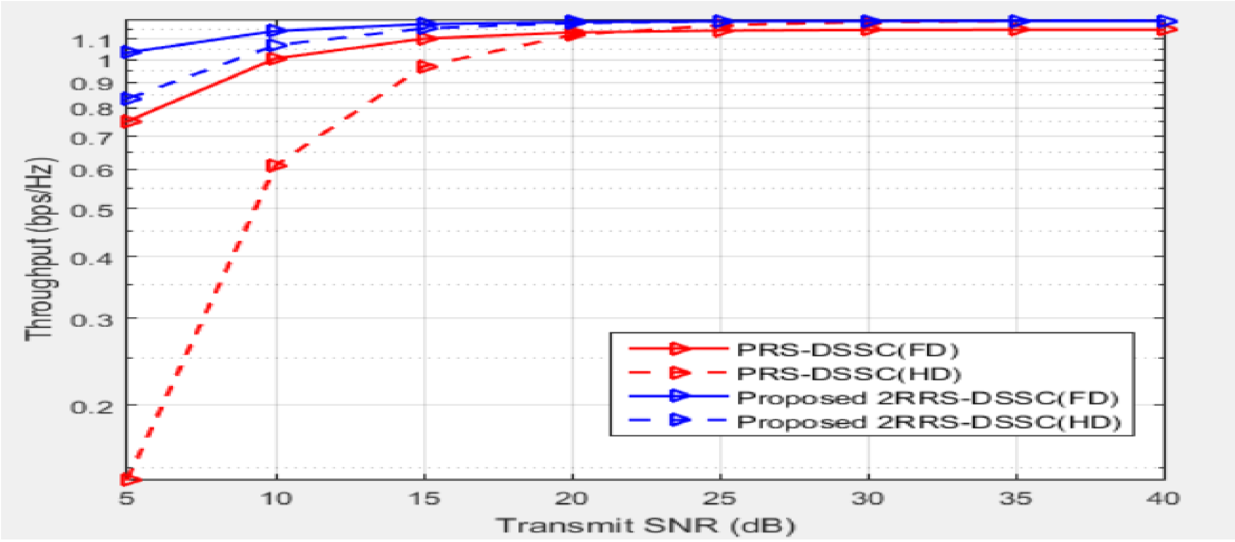
Table 5.3. Performance gain in Outage probability of the proposed 2-RRS scheme over the existing PRS scheme in a full-duplex DSSC based system under DF relaying protocol

TRANSMIT SNR	**10dB**	**15dB**	**20dB**
PROPOSED 2RRS over PRS(FD) [% Improvement]	16.927%	18.526%	18.995%
PROPOSED 2RRS over PRS(HD) [% Improvement]	15.718%	15.996%	16.138%

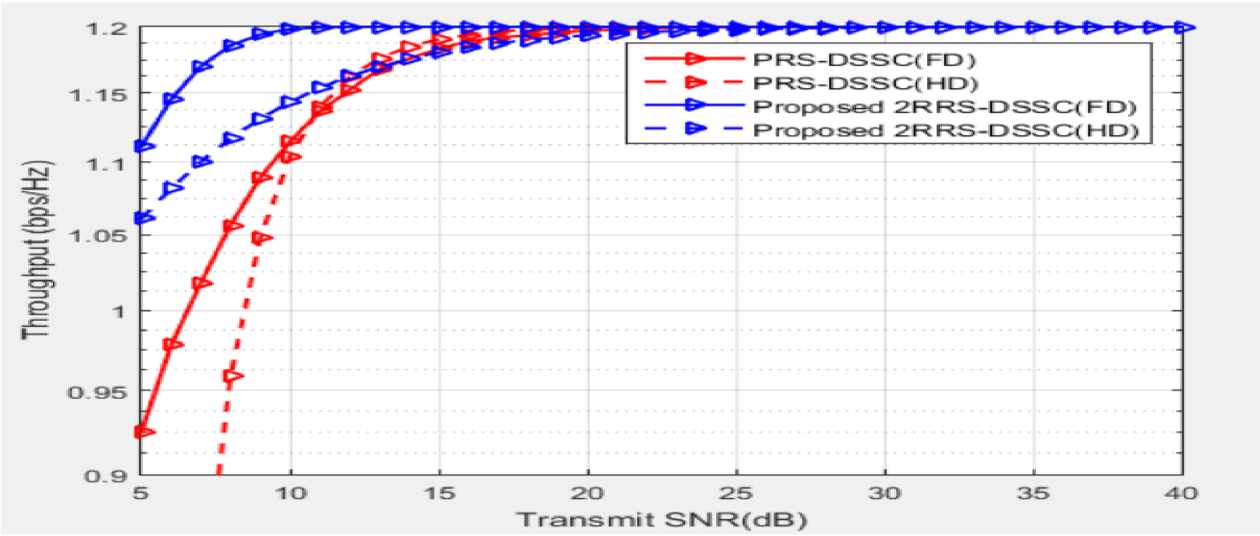
Table 5.3 compares the outage probability performance gain of the proposed 2-RRS DSSC-based system to that of the existing PRS-scheme when the DF scheme is taken into account. The following observations can be analyzed using the same methodology as AF. The sole distinction is that in the case of DF, the outage performance gain of the 2 RRS scheme is comparatively greater than in the case of AF. This is understandable since, unlike AF, where signal processing only amplifies the signal, in DF, the signal is decoded block by block to prevent errors and further error-correcting methods are added to the signal to enhance its quality. Better signal quality results in fewer outages and, therefore, a lesser probability of outage. In general, as transmit SNR increases, the outage probability of a DF system reduces. For instance, at 20 dB, the suggested 2 RRS-FD system outperforms the PRS counterpart by around 19 percent. This is also evident from Figure 5.1(b).

5.4 PERFORMANCE ANALYSIS OF THROUGHPUT VERSUS TRANSMIT SNR FOR THE PROPOSED 2 RRS SCHEME AND THE EXISTING PRS SCHEME IN A DSSC-BASED SYSTEM

For the proposed system's communication, a *delay-limited* transmission mode is considered, where the average throughput may be calculated by calculating the outage probability of the system under a fixed transmission rate. The suggested *2-RRS-DSSC*-based scheme's system throughput performance is shown in Figures 5.2 (a) and 5.2 (b) as a function of transmit SNR (dB) for the *AF* and *DF* protocols, respectively. In both situations, the suggested model's system performance is compared to the existing *PRS-DSSC* system model. Full-duplex and half-duplex modes of communication are individually taken into consideration for performance evaluation for both relaying techniques.



(a) AF protocol



(b) DF protocol

Figure 5.2: Throughput performance of the proposed 2-RRS scheme and existing PRS scheme for full-duplex and half-duplex DSSC system

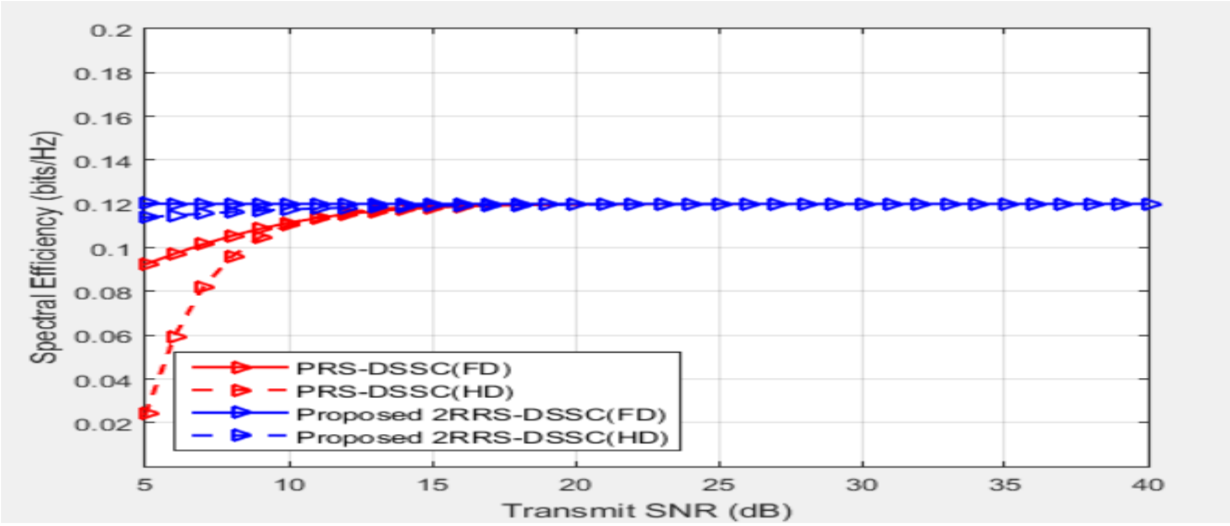
The above figure shows that the proposed 2-RRS scheme's throughput is comparatively higher than the PRS scheme in use. This can be justified as follows: The throughput of any communication channel can be described mathematically by equation (3.19) where, “R” is the transmission rate of the source, “p_{OUT}” is the outage probability and “Γ” is the effective transmission time. For fixed transmission rate and transmission time, the throughput of a system depends on the outage probability. The throughput decreases as the outage probability increases. As the outage probability of the 2 RRS scheme is found to be less than PRS scheme from previous results (Fig 5.1(a) and Fig 5.1 (b)), the 2 RRS system has a higher throughput than the PRS system.

Figures 5.2 (a) and 5.2 (b) also show that as the transmit SNR rises, the throughput of the two relay selection techniques increases for both *AF* and *DF* relaying. However, the throughput of all the systems tends to saturate when the transmit SNR is above 20dB.This can be explained as the transmit SNR increases, the outage probability of the system decreases. Hence for low values of outage probability the throughput tends to achieve effective transmission rate as can be explained from equation (3.19). Moreover, for a particular transmit SNR, the throughput of any relay selection strategy considered above, is more in *DF* than *AF* scheme. This is owing to the fact that in the case of AF, the outage probability is higher than in the case of *DF* due to the amplified signal noise at the relay receiver.

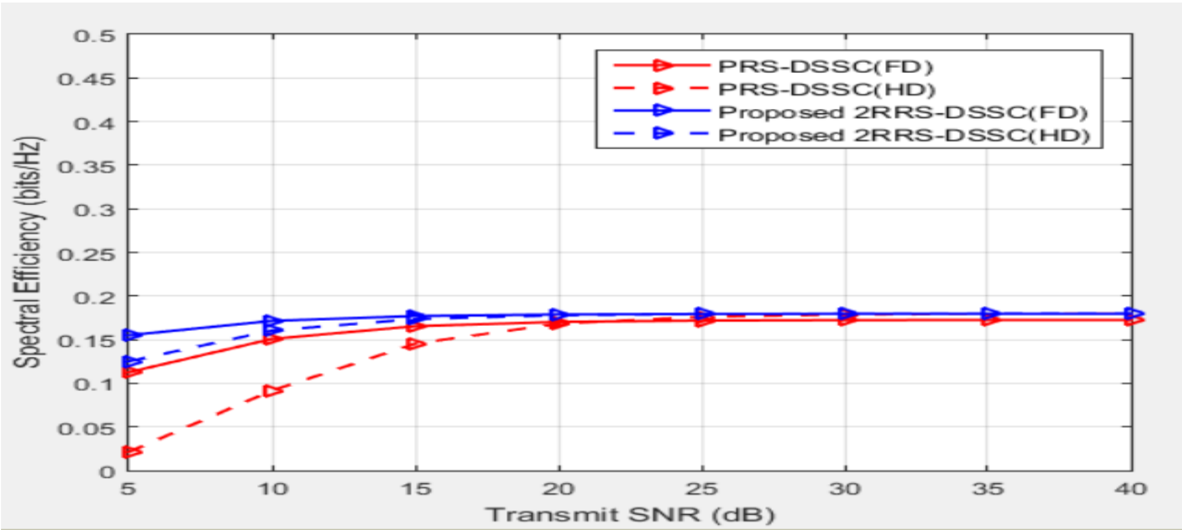
The benefit of *FD* relaying for a specific relay selection is the increased throughput over *HD*. However, because of self-interference at the relay, the FD system works poorly here as well as at high SNR [above 20 dB].

5.5 PERFORMANCE ANALYSIS OF SPECTRAL EFFICIENCY VERSUS TRANSMIT SNR FOR THE PROPOSED 2 RRS SCHEME AND THE EXISTING PRS SCHEME IN A DSSC-BASED SYSTEM

The achievable spectral efficiency of the FDSSCR and HDSSCR for PRS and 2RRS systems when transmit SNR is varied from 5 to 40 dB is shown in Figures 5.3 (a) and 5.3 (b) for both AF and DF relaying respectively.



(a) AF protocol



(b) DF protocol

Figure5.3: Spectral Efficiency of the proposed 2-RRS scheme and existing PRS scheme for full-duplex and half-duplex DSSC system

The spectral efficiency of a system is a measure of how the bandwidth is effectively utilized for data transmission. It is the maximum number of bits supported per channel, or, to put it another way, it is the ratio of the system's bandwidth to the transmitted data rate (throughput).

The suggested 2 RRS system has the maximum spectrum efficiency in full-duplex mode, followed by the half-duplex 2 RRS system. For DF a 60% increase in spectral efficiency of full-duplex 2RRS scheme over full-duplex PRS scheme is noted at a transmit SNR of 30 db. The FD system outperforms the HD technique in terms of spectrum efficiency for both PRS and 2 RRS systems. This can be explained by the fact that in FD, since a relay can harvest energy from source and send data to destination concurrently, the throughput of FD relaying is higher than that of HD relaying where a power- splitting ratio is required for separate operation of RF harvesting and information transmission. It is observed from the figures 5.3(a) and 5.3(b)that as transmit SNR rises above 15 dB, all systems' spectral efficiency reaches a saturation point (the max transmission rate considered in this proposed work is 2 bps/Hz). Moreover, as can be seen in Fig 5.3 (b), for a particular transmit SNR, DF systems have a higher spectrum efficiency, because their throughput is higher than that of AF as was already found from the results of Figure 5.2 (a) and Figure 5.2(b).

Additionally, Figures 5.3(a) and 5.3(b) show that the spectral efficiency of all relay selection techniques tends to zero in the case of HD and low SNR (less than 13 dB). This can be explained by the fact that, at low values of SNRs, all the HD schemes are experiencing outages (outage probability around 1), as shown in Figure 5.1(a) and 5.1(b) respectively.

5.6 DISCUSSION

In this chapter, the suggested system model is simulated using MATLAB R2015a and the overall performance is examined and compared for the two relay selection strategies. The effectiveness of the proposed 2-RRS DSSC-based system is investigated and compared to the current PRS scheme. Study and comparison of the 2RRS DSSC-based system's performance with the current PRS scheme reveals that in terms of all three parameters—outage probability, throughput, and spectrum efficiency—the 2 RRS DSSC strategy outperforms the PRS relay selection method. Performance assessments of the various systems further highlight the advantages of using full-duplex over half-duplex approach. The proposed 2-RRS technique is superior for both AF and DF, as shown by a comparison of the outage performance of the two relay selection systems in Table 5.1 and Table 5.2 respectively. From Table 5.1, it can be observed that, at 20 dB of transmit power, the 2 RRS outperforms the conventional PRS method in terms of outage probability by about 17%.

CHAPTER 6

CONCLUSION

6.1 CONCLUDING REMARKS

In this thesis, the benefits of cooperative diversity in a wireless communication network that uses RF energy harvesting have been investigated. Additionally, the performance of the existing PRS-based DSSC-system model with the new 2 RRS relay selection scheme based DSSC system has been assessed and compared. The thesis provides a comprehensive examination of the relay selection strategies along with relaying protocols and combining methods that could be used in a relay-aided RF energy harvesting network to increase signal transmission efficiency. At the relays, the AF and DF protocols are implemented to assess how well the aforementioned selection strategies can perform. The benefit of the Amplify and Forward (AF) protocol is that it uses very little CPU power and bandwidth. Its disadvantage is that everything, including noise, is amplified and transmitted, unlike the DF protocol. The protocol's drawback is the substantial computational power needed for its operation. For performance evaluation, the relays have been operated under both full duplex selection relaying and half-duplex relaying mode. Relay positioning is another consideration. In the proposed system model, the relays are placed precisely halfway between the source and destination.

Our inference from the simulation results are as follows:

- The 2 RRS scheme outperforms the PRS scheme for the DSSC based system model under consideration, when outage probability, throughput, and spectral efficiency of a network are taken into account. The outage probability of 2 RRS scheme is contrasted with the PRS scheme under varying transmit SNR and the corresponding performance gain of 2RSS over the existing PRS scheme has been given in Table 5.1 and 5.2 respectively. As is evident from Table 5.1, the performance of 2 RRS full duplex relaying is comparatively better.

- For both the relay section schemes in the DSSC based system, full duplex relaying performs better than half-duplex relaying.

- Moreover, due to the lack of an error-correcting code at the relay terminal, the performance of the 2 RRS DSSC based system under Amplify and Forward protocol is inferior to the Decode and Forward protocol when DSSC is employed.

Additional research in this area might be the use a multi-user scenario to explore the potential for the relay to operate with many signal sources, Besides, the relays and the source could be mobile and hence observing the effect of a moving signal source or/and relay on the network performances could also be highly intriguing.

6.2 FUTURE DIRECTIONS

The system model that has been studied in this work is just one of many ways and procedures that may be used to improve the performance of a relay-aided RF energy harvesting network. It can be extended and modified further in order to improve the network performance at the receiver as discussed below:

- This work can be further extended to study the effect of distributed energy beamforming on the performance of the network. Energy beamforming can provide better diversity gains by transmitting RF energy in the same direction continually to the intended energy harvester.

- Mobility is yet another crucial element for RF-EHN. RF sources, or user nodes, can move around. Because of this, the efficiency of energy collection and data transmission can change over time. This necessitates the distribution of resources in a dynamic and adaptable manner which can impact the system performance.

- By using a variety of scheduling approaches, interference in RF energy harvesting can be turned into useable energy. To avoid interference management problems, spectrum scheduling might be implemented.

- Network coding can result in information transfer that uses less energy. The amount of RF energy captured in large networks is increased via network coding. As the nodes may harvest RF energy when relays or senders are not delivering any data, it results in efficient usage of time slots.

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