COGNITIVE SPECTRUM SHARING PROTOCOLS FOR ENERGY HARVESTING WIRELESS SENSOR NODES

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Certificate

This is to certify that the thesis titled **" Cognitive Spectrum Sharing Protocols for Energy Harvesting Wireless Sensor Nodes"** submitted by **Mansi Peer** for the partial fulfillment of the requirements for the degree of *Master of Technology* in *Electronics & Communication Engineering* is a record of the bonafide work carried out by her under my guidance and supervision at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted anywhere else for the reward of any other degree.

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Abstract

Energy consumption is one of the primary concerns in the deployment of futuristic wireless sensor networks. On one hand due to advent of technologies such as Internet of Things (IoT), there has been tremendous growth in development of wireless sensor nodes, however, on the other hand these nodes are energy constrained, hence have limited lifetime. Energy harvesting from radio frequency (RF) signals has been proposed as a viable solution to alleviate this problem. Most of the recent work in the field of RF energy harvesting has involved cooperative relaying and cognitive radio networks. But now energy harvesting techniques have been employed to cooperative spectrum sharing framework as well.

In this work, a hybrid time switching and power splitting spectrum sharing protocol for energy harvesting wireless sensor nodes is proposed. In the developed framework, an energy constrained sensor node adopts a time switching and power splitting based relaying protocol to harvest energy and spectrum from primary user. In exchange, it helps the primary user to achieve its target rate of performance. We have analyzed the impact of time duration allocated for energy harvesting and information reception/transmission at sensor node on the Quality of Service (QoS) of primary user.

Further, we have proposed another energy harvesting and spectrum sharing protocol for multiple sensor nodes that not only optimizes the performance of primary system but also simultaneously maintains a satisfactory QoS of the secondary system. We have analyzed how increase in the number of energy harvesting sensor nodes improve the primary and secondary performance.

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Chapter 1

Introduction

1.1 Motivation

As predicted by industry analysts, by the year 2020, 50 billion devices will be connected to mobile network worldwide [1]. The large scale of devices being connected to the Internet, where the data is generated by the things without any human intervention, has brought in the notion of Internet of Things (IoT). With emerging 5G wireless networks researchers are anticipating to unlock the potential of IoT further. 5G networks are envisioned to bring in together different wireless technologies paving a way for heterogeneous networks that can accommodate diverse devices. These devices may be wireless sensors used for monitoring temperature, pressure or stress and may include actuators which can be used to remotely control devices or make adjustments in real time. Consequently, devices with sensing abilities that form a wireless sensor network (WSN) constitute a subset of IoT. There are two major concerns in the deployment of large scale WSN given as follows:

- **Energy inefficiency**: Energy consumption by the sensor nodes has been identified as one of the primary concerns. Further, most of the sensor nodes are deployed in hostile or inaccessible environment where replacing the batteries or providing stable energy source may not be feasible. The battery disposal also has a serious impact on the global carbon emission levels. It contributes significantly to global warming and causes concern for the environment.

- **Spectrum Under-Utilization**: In addition to above, recent frequency spectrum measurements have shown that although most of the spectrum band is allocated under license, the spectrum usage is very low. The unprecedented increase in the number of nodes has prompted researchers to come out with ways to better utilize this limited resource.

Energy harvesting from radio frequency (RF) signals has been proposed as a viable solution to alleviate the problem of human intervention in replacement of the batteries hence making the system more energy efficient. Not only does a RF signal carry information but energy too, so information transmission and power transfer can occur simultaneously [2]. As the wireless sensor nodes do not need to send the data all the time, therefore providing a dedicated spectrum to sensor networks is not an economically viable approach. In order to alleviate the above problem of spectrum inefficiency, techniques such as cooperative spectrum sharing (CSS) have been proposed which facilitate spectrum sharing between users, thus eliminating the need for dedicated spectrum band for sensor nodes.

In this thesis work our goal is to improve the spectrum usage and energy efficiency simultaneously. In the course of this work we came up with a hybrid time switching and power splitting spectrum sharing protocol to improve primary user's outage performance and provide spectrum access to secondary user. Later, we added the concept of optimal sensor node selection for forwarding primary user's information using the already proposed hybrid protocol.

1.2 Contributions

We have proposed a hybrid time switching and power splitting spectrum sharing protocol for energy harvesting wireless sensor nodes. The work involves the performance analysis in terms of outage probability of both primary and secondary system.

Secondly, we have proposed an energy harvesting and spectrum sharing protocol for multiple sensor nodes. We have developed a robust single node selection algorithm taking into account the energy harvesting ability of the nodes and the desired target rates. Further, we have done a outage probability analysis for primary and secondary systems and demonstrated the system performance enhancement through the results obtained.

1.3 Terminologies

1.3.1 Energy Harvesting

Energy harvesting is the process by which ambient energy is captured and converted directly into electricity for small and mid-sized devices, such as autonomous wireless sensor nodes, consumer electronics and vehicles. In this work we have focused on RF energy harvesting where the energy harvesting node scavenges energy from the surrounding node transmitting it's own information.

1.3.2 Cooperative Relaying

Cooperative relaying network consists of three nodes, namely source, destination, and a third node supporting the direct communication between source and destination denoted as relay. There are two main relaying strategies:

- **Amplify & Forward**: The relay node first amplifies the signal received from source and then retransmits it to the destination.

- **Decode & Forward**: The relay firstly decodes the signal received from the source and only upon successful decoding forwards the information to the destination.

1.3.3 Cooperative Spectrum Sharing

The conventional cooperative spectrum sharing scheme deals with primary users (PUs) having a licensed spectrum band and secondary users (SUs) that can have access to the licensed bands in exchange of their cooperation to the primary user to enhance it's performance.

1.4 Outline

The remaining thesis is organised as below:

Chapter 2 deals with the proposed protocol 1 where in we have considered a cooperative cognitive network. The secondary sensor node can harvest energy and spectrum from primary using a hybrid time switching and power splitting spectrum sharing protocol.

Chapter 3 deals with the proposed protocol 2 where in the we have multiple sensor nodes in the secondary network available for cooperation with the primary user. The optimal selection of the sensor node encompasses the knowledge of channel conditions and also the amount of energy harvested at each of the nodes.

Chapter 4 concludes the thesis work and also deals with the future work that can be done.

Chapter 2

A Hybrid Spectrum Sharing Protocol for Energy Harvesting Wireless Sensor Nodes

2.1 Introduction

As already mentioned, we have proposed a hybrid time switching and power splitting spectrum sharing protocol for energy harvesting wireless sensor nodes. Specifically, we use an approach of simultaneous energy harvesting and spectrum access to alleviate the major concerns of wireless sensor nodes such as limited power and spectrum. Over a last decade or so, RF energy harvesting has attracted great deal of attention from many researchers. Most of the recent work in the field of RF energy harvesting has also involved cooperative relaying [2–4]. In [2], authors have proposed two energy harvesting relaying protocols, namely the Time switching-based relaying (TSR) protocol, where the energy constrained amplify and forward (AF) relay node switches between the energy harvesting and information decoding modes, and Power splitting-based relaying (PSR) protocol, where a fraction of power received at relay is devoted to energy harvesting and rest of the power is utilized for information decoding. In both the protocols, the relays were assumed to be half-duplex. In [3] energy harvesting protocol was extended to full-duplex relays so that energy harvesting and information transmission from relay to primary destination occurs simultaneously that ensures uninterrupted information transmission. The energy stored in the battery can be used for further transmissions at relay.

Energy harvesting techniques have also been employed to complement cognitive radio networks. In a cognitive radio framework, two set of users namely primary and secondary users are allowed to co-exist in the same frequency band. Primary user, also termed as licensed user, has a license to operate on a particular frequency band. Secondary user, also termed as cognitive user or unlicensed user, accesses the licensed band of primary user without degrading the performance of primary user. Furthermore, by incorporating RF energy harvesting techniques, secondary/cognitive user can be made self-sustaining. For instance, in [5], a model has been proposed where low-power mobile nodes in the secondary networks called the secondary transmitters (STs) harvest energy from the RF transmissions of the primary transmitters (PTs). In this framework, STs can operate in any of the following three modes: harvesting mode, transmitting mode or idle mode. In the harvesting mode a ST lying in the harvesting zone of an active PT harvests energy from PT's transmissions, and in transmission mode a ST lying outside the guard zones of all the active PTs is able to transmit its information. When in idle mode neither harvesting nor transmission takes place.

Most of the above works on energy harvesting were based on underlay protocol wherein the performance of ST is limited by amount of interference acceptable at PR. Furthermore they did not consider cooperative spectrum sharing protocols. We believe that the cooperative and cognitive techniques are complementary to each other and thus by modeling ST as an energy constrained cooperative relay, performances of both primary and secondary systems can be enhanced simultaneously. In our previous work [6], we had proposed a two phase cognitive relaying protocol wherein secondary user, characterized as a self-sustaining energy constrained sensor node, harvests energy from the primary signal transmission based on PSR protocol. Further, it utilizes the harvested energy to assist the primary user to achieve the target rate of communication in exchange for access to primary's spectrum.

With respect to [6], in this chapter we have proposed a hybrid time switching and power splitting spectrum sharing protocol that not only improves the energy efficiency but also leads to better spectrum utilization. Unlike [6], in the proposed work we incorporate unequal division of time between the two phases and if ST fails in decoding primary signal in phase 1, it will transmit the secondary signal in phase 2.

2.2 Proposed System Model and System Performance Analysis

2.2.1 System Model

We have considered a cooperative spectrum sharing system [7] which consists of two source-destination pairs. One is primary transmitter-primary receiver (PT-PR) and other is secondary transmitter-secondary receiver (ST-SR) corresponding to the primary and secondary systems respectively as shown in Fig.2.1. We assume that direct communication between PT and PR is not possible due to limitation of transmission range, fading, obstacles etc., [2]. In this scenario PT needs the cooperation of a secondary node ST, which will act as a decode and forward (DF) relay [1], to transmit from PT to PR. Moreover, ST, which is a sensor node, has no power of its own and will be powered wirelessly by harvesting energy from the PT-ST transmission. The block transmission time T is divided into two phases of duration αT and $(1-\alpha)T$. In phase 1, during αT time, PT broadcasts its information signal x_p which will be received at ST and

[1]Interested readers may refer to [8] for details on control signaling involved between the primary and secondary system

SR. The total power, P, power received at ST during phase 1 will be divided between energy harvesting and information decoding using PSR protocol.

The channel between each pair of transmitter and receiver is assumed to be frequency non-selective rayleigh slow fading channel. The channel coefficients corresponding to PT-ST, ST-SR, ST-PR and PT-SR links are h_1, h_2, h_3 and h_4 respectively. We have $h_i \sim \mathcal{CN}(0, d_i^{-v})$, i = 1, 2, 3, 4, where v is the path loss exponent and d_i is the distance between the respective transmitter and receiver. The channel gain $\beta_i = |h_i|^2$ is exponentially distributed and is denoted as $\beta_i \sim \mathcal{E}(d_i^v)$, where d_i^{-v} is the mean of the distribution. The transmit power at PT is denoted as P_p. The signal received at j^{th} node in k^{th} phase is denoted as y_{jk}, where $j = 1, 2, 3$ for ST, SR, PR respectively and $k = 1, 2$ for phase 1 and phase 2 respectively. In phase 1, signal received at ST from PT is given by

$$y_{11} = \sqrt{P_p} h_1 x_p + n_a \tag{2.1}$$

where $n_a \sim \mathcal{CN}(0, \sigma_a^2)$ is the AWGN noise received at ST. As power splitting protocol is used at ST, γP and $(1-\gamma)P$ power is made available to the energy harvesting and information receiver branches of the ST node respectively, where $0 \leq \gamma \leq 1$. We have assumed that the power required for processing is negligible compared to transmission power at ST [2]. So, the signal received at energy harvester is given by

$$\sqrt{\gamma} y_{11} = \sqrt{\gamma P_p} h_1 x_p + \sqrt{\gamma} n_a. \tag{2.2}$$

Energy harvested in time αT is given by

$$E_h = \eta \gamma P_p |h_1|^2 \alpha T \tag{2.3}$$

where $\eta \ \epsilon$ (0,1] is the conversion efficiency of the RF to DC conversion circuitry used. Power extracted from the harvested energy is the transmit power available at ST node and will be given by

$$P_h = \frac{E_h}{(1-\alpha)T} = \frac{\eta \gamma P_p |h_1|^2 \alpha}{(1-\alpha)}. \tag{2.4}$$

The signal received at information receiver of ST is given by

$$\sqrt{(1-\gamma)} y_{11} = \sqrt{(1-\gamma) P_p} h_1 x_p + \sqrt{(1-\gamma)} n_a + n_c \tag{2.5}$$

where $n_c \sim \mathcal{CN}(0, \sigma_c^2)$ is the sampled AWGN due to RF to baseband signal conversion. From (5), the total AWGN variance at ST is given by $\sigma^2 = (1-\gamma)\sigma_a^2 + \sigma_c^2$.

Rate achievable at ST will be

$$R_1 = \alpha \log_2(1 + SNR_1) \tag{2.6}$$

where $SNR_1 = \frac{(1-\gamma)P_p|h_1|^2}{\sigma^2}$.

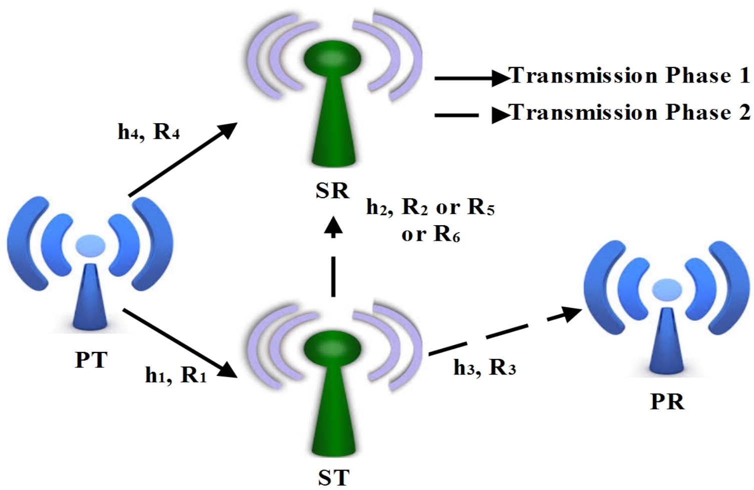

Figure 2.1: System Model

Signal received at SR is given by

$$y_{21} = \sqrt{P_p} h_4 x_p + n_{sr} \tag{2.7}$$

where $n_{sr} \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN noise added at SR.

Rate achievable at SR in phase 1 is given by

$$R_4 = \alpha \log_2 \left(1 + \frac{P_p |h_4|^2}{\sigma^2}\right). \tag{2.8}$$

In transmission phase 2, three scenarios are possible depending on whether ST and/or SR are able to successfully decode PT's information in phase 1. The three cases are as follows:

- **Case 1** In this case both ST and SR decode PT's information. ST transmits signals x_p and x_s with ρP_h and $(1-\rho)P_h$ power respectively, where $\rho \; \epsilon \; (0,1)$. Signal received at PR is given by

$$y_{32} = \sqrt{\rho P_h} h_3 x_p + \sqrt{(1-\rho)P_h} h_3 x_s + n_{pr} \tag{2.9}$$

where $n_{pr} \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN noise added at PR. Signal received at SR is given by

$$y_{22} = \sqrt{(1-\rho)P_h} h_2 x_s + \sqrt{\rho P_h} h_2 x_p + n_{sr}. \tag{2.10}$$

Rate achievable at PR is given by

$$R_3 = (1-\alpha) \log_2 \left(1 + \frac{\rho P_h |h_3|^2}{(1-\rho) P_h |h_3|^2 + \sigma^2}\right). \tag{2.11}$$

Rate achievable at SR, conditioned on successful decoding of x_p at ST and SR is given by

$$R_2 = (1-\alpha) \log_2 \left(1 + \frac{(1-\rho) P_h |h_2|^2}{\sigma^2}\right). \tag{2.12}$$

- **Case 2** In case 2, ST is unable to decode x_p with target rate in phase 1. So, complete harvested power at secondary node is used for secondary transmission and the signal received at SR in phase 2 is given by

$$y_{22} = \sqrt{P_h} h_2 x_s + n_{sr}. \tag{2.13}$$

Hence, rate achievable at SR is given by

$$R_5 = (1-\alpha)\log_2\left(1 + \frac{P_h|h_2|^2}{\sigma^2}\right). \tag{2.14}$$

- **Case 3** In case 3, ST successfully decodes x_p however SR fails to decode it. Hence, the primary signal present in the combined signal transmitted by ST will create interference at SR. So, the rate achievable at SR in phase 2 will be given by :

$$R_6 = (1-\alpha)\log_2\left(1 + \frac{(1-\rho)P_h|h_2|^2}{\rho P_h|h_2|^2 + \sigma^2}\right). \tag{2.15}$$

2.2.2 Outage Probability Analysis of Primary System

The outage at primary system will occur if any of the PT-ST and ST-PR links fail in achieving the target rate of communication i.e. R_{pt}. Therefore, outage at PR is given by

$$P_{oP} = P[\min(R_1, R_3) < R_{pt}]$$

$$= 1 - P[R_1 > R_{pt}]P[R_3 > R_{pt}]. \tag{2.16}$$

If any of the two links fail (this explains the use of minimum operator) then the overall primary transmission will be in outage. Using (2.6),

$$P[R_1 > R_{pt}] = 1 - P\left[|h_1|^2 < \frac{t}{m(1-\gamma)}\right]$$

$$= e^{\frac{-d_1^v t}{m(1-\gamma)}} \tag{2.17}$$

where $t = 2^{R_{pt}/\alpha} - 1$ and $m = \frac{P_p}{\sigma^2}$. Similarly,

$$P[R_3 > R_{pt}] = P\left[\frac{\rho\ P_h|h_3|^2}{(1-\rho)P_h|h_3|^2 + \sigma^2} > (2^{\frac{R_{pt}}{1-\alpha}} - 1)\right]. \tag{2.18}$$

Using (2.4)

$$P[R_3 > R_{pt}] = P[b|h_3|^2|h_1|^2 > a] \tag{2.19}$$

where $a = \frac{\sigma^2(1-\alpha)(2^{R_{pt}/(1-\alpha)}-1)}{\eta\gamma P_p\alpha}$, $b = \rho - (2^{R_{pt}/(1-\alpha)} - 1)(1-\rho)$. This b can be either positive or negative. Hence,

$$P[R_3 > R_{pt}] = \begin{cases} P[|h_3|^2|h_1|^2 > \frac{a}{b}], & \alpha < 1-\delta \\ P[|h_3|^2|h_1|^2 < \frac{a}{b}] = 0, & \text{otherwise} \end{cases} \tag{2.20}$$

where $\delta = \frac{R_{pt}}{\log_2(1+\frac{\rho}{1-\rho})}$.

The second equality in (2.20) can be explained by the fact that the probability of $|h_3|^2|h_1|^2$ being less than a negative number is 0. The first term in (2.20) involves product of two independent exponentially distributed random variables. This can be determined as

$$P[R_3 > R_{pt}] = \begin{cases} \int_0^\infty f_{|h_1|^2}(x) P[|h_3|^2 > \frac{a}{bx}]dx, & \alpha < 1-\delta \\ 0, & \text{otherwise.} \end{cases} \quad (2.21)$$

Further for $\alpha < 1-\delta$, using the form $\int_0^\infty e^{-\frac{\beta}{4x}-\theta x}dx = \sqrt{\frac{\beta}{\theta}}K_1(\sqrt{\beta\theta})$ [9], where $K_1(.)$ is the modified first order bessel function of second kind, we obtain

$$P[R_3 > R_{pt}] = \frac{1}{d_1^{-v}} \int_0^\infty e^{-\frac{x}{d_1^{-v}}}.e^{-\frac{a}{bxd_3^{-v}}}dx$$

$$= \sqrt{\frac{4a}{bd_1^{-v}d_3^{-v}}}K_1\left(\sqrt{\frac{4a}{bd_1^{-v}d_3^{-v}}}\right). \quad (2.22)$$

The closed form expression for the outage probability of the primary system is given by

$$P_{oP} = \begin{cases} 1-\phi u K_1(u), & \alpha < 1-\delta \\ 1, & \text{otherwise} \end{cases} \quad (2.23)$$

where $\phi = e^{\frac{-d_1^v t}{m(1-\gamma)}}$, $u = \sqrt{\frac{4a}{bd_1^{-v}d_3^{-v}}}$.

2.2.3 Outage Probability Analysis of Secondary System

The secondary system will be able to achieve the target rate i.e. R_{st} for the three cases considered earlier with certain probability associated with each one of them as determined below:

1. PT-ST, PT-SR and ST-SR links successfully achieve the target rates R_{pt}, R_{pt} and R_{st} respectively.

$$P_{s1} = P[R_1 > R_{pt}]P[R_4 > R_{pt}]P[R_2 > R_{st}] \quad (2.24)$$

2. PT-ST link fails to achieve the target rate but ST-SR link achieves the rate R_{st}.

$$P_{s2} = P[R_1 < R_{pt}]P[R_5 > R_{st}] \quad (2.25)$$

3. PT-SR link fails to obtain the target rate. However, PT-ST and ST-SR links achieve the rate R_{pt} and R_{st} respectively.

$$P_{s3} = P[R_1 > R_{pt}]P[R_4 < R_{pt}]P[R_6 > R_{st}] \quad (2.26)$$

Hence by combining all the above cases, the secondary system outage probability can be given as

$$P_{oS} = 1 - (P[R_1 > R_{pt}]P[R_4 > R_{pt}]P[R_2 > R_{st}] + P[R_1 < R_{pt}]P[R_5 > R_{st}] + P[R_1 > R_{pt}]P[R_4 < R_{pt}]P[R_6 > R_{st}]) \quad (2.27)$$

where

$$P[R_4 > R_{pt}] = P\left[|h_4|^2 > \left(\frac{(2^{\frac{R_{pt}}{\alpha}}-1)\sigma^2}{P_p}\right)\right] = e^{\frac{-d_4^v t}{m}}. \quad (2.28)$$

$$P[R_2 > R_{st}] = P\left[\frac{(1-\rho)\ P_h|h_2|^2}{\sigma^2} > (2^{\frac{R_{st}}{1-\alpha}} - 1)\right]. \quad (2.29)$$

Using (2.4)

$$P[R_2 > R_{st}] = P[|h_2|^2|h_1|^2 > c] \quad (2.30)$$

where $c = \frac{\sigma^2(1-\alpha)(2^{R_{st}/(1-\alpha)}-1)}{\eta\gamma P_p\alpha(1-\rho)}$.

$$Pr[R_5 > R_{st}] = P\left[|h_2|^2|h_1|^2 > d\right] \quad (2.31)$$

where $d = \frac{\sigma^2(1-\alpha)(2^{R_{st}/(1-\alpha)}-1)}{\eta\gamma P_p\alpha}$.

$$P[R_6 > R_{st}] = P\left[|h_2|^2|h_1|^2 > \frac{d}{e}\right] \quad (2.32)$$

where $e = (1-\rho) - \rho(2^{\frac{R_{st}}{1-\alpha}} - 1)$.

The terms in (2.30), (2.31), (2.32) can be found similar to (2.21). So,

$$P[R_2 > R_{st}] = \sqrt{\frac{4c}{d_1^{-v}d_2^{-v}}}K_1\left(\sqrt{\frac{4c}{d_1^{-v}d_2^{-v}}}\right), \quad (2.33)$$

$$P[R_5 > R_{st}] = \sqrt{\frac{4d}{d_1^{-v}d_2^{-v}}}K_1\left(\sqrt{\frac{4d}{d_1^{-v}d_2^{-v}}}\right), \quad (2.34)$$

$$P[R_6 > R_{st}] = \begin{cases} \sqrt{\frac{4d}{ed_1^{-v}d_2^{-v}}}K_1\left(\sqrt{\frac{4d}{ed_1^{-v}d_2^{-v}}}\right), & \alpha < 1-\mu \\ 0, & \text{otherwise} \end{cases} \quad (2.35)$$

where $\mu = \frac{R_{st}}{\log_2(\frac{1}{\rho})}$.

The closed form expression for the outage probability of the secondary system obtained by

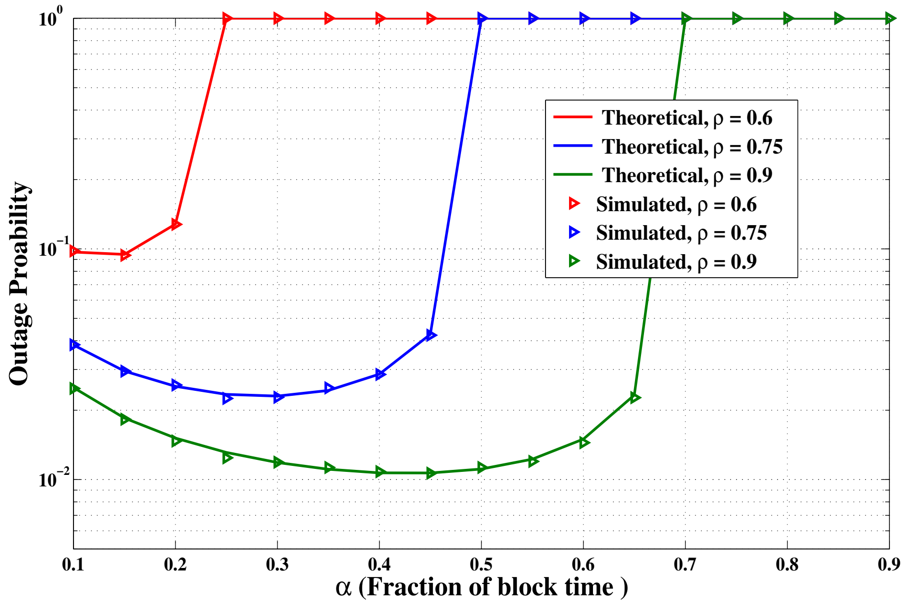

Figure 2.2: Plot of Primary outage probability against α for ρ = 0.6, 0.75, 0.9, ν = 30m, η = 0.8 and γ = 0.75.

substituting (2.17), (2.28), (2.33), (2.34) and (2.35) in (2.27), is given by

$$P_{oS} = \begin{cases} 1-(\phi e^{\frac{-d_4^v t}{m}} wK_1(w) + (1-\phi)yK_1(y) + (1-e^{\frac{-d_4^v t}{m}})\phi z K_1(z)), & \alpha < 1-\mu \\ 1-(\phi e^{\frac{-d_4^v t}{m}} wK_1(w) + (1-\phi)yK_1(y)), & \text{otherwise} \end{cases} \tag{2.36}$$

where $w = \sqrt{\frac{4c}{d_1^{-v} d_2^{-v}}}$, $y = \sqrt{\frac{4d}{d_1^{-v} d_2^{-v}}}$ and $z = \sqrt{\frac{4d}{e d_1^{-v} d_2^{-v}}}$.

2.3 Simulation And Results

In this section, we present the plots of primary and secondary system outages. The following parameters have been selected for the simulations :

- The distances between PT-ST, ST-PR, PT-SR and ST-SR are νm, (50-ν)m, 10m, 10m respectively where 50m is the distance between the PT-PR link and ST is assumed to be placed between PT and PR.
- P_p = 30 dBm.
- Noise variance, σ^2 = -90 dBm.
- The value of target rates for both primary and secondary systems is chosen to be 1 i.e. $R_{pt} = R_{st} = 1$.

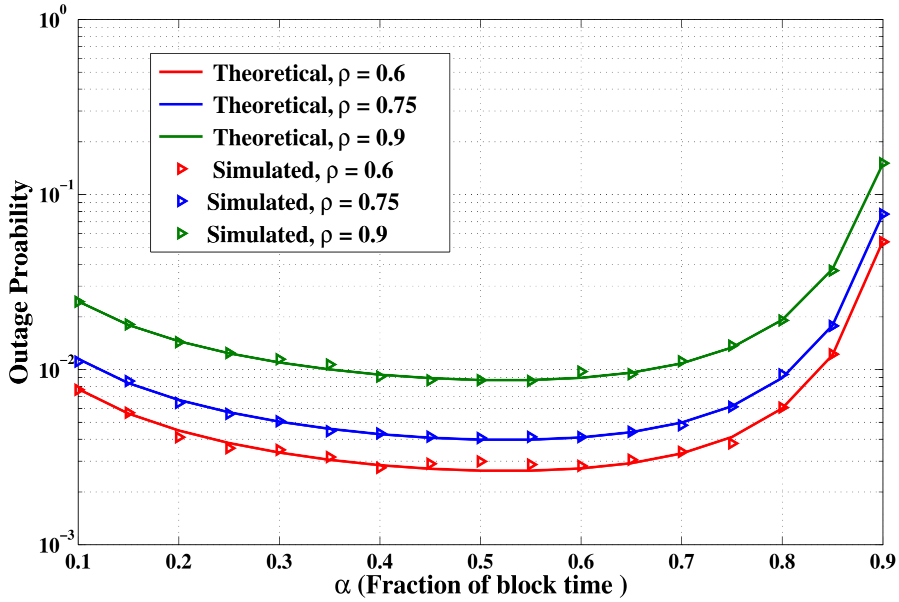

Figure 2.3: Plot of Secondary outage probability against α for $\rho = 0.6$, 0.75, 0.9, $\nu = 30$m, $\eta = 0.8$ and $\gamma = 0.75$.

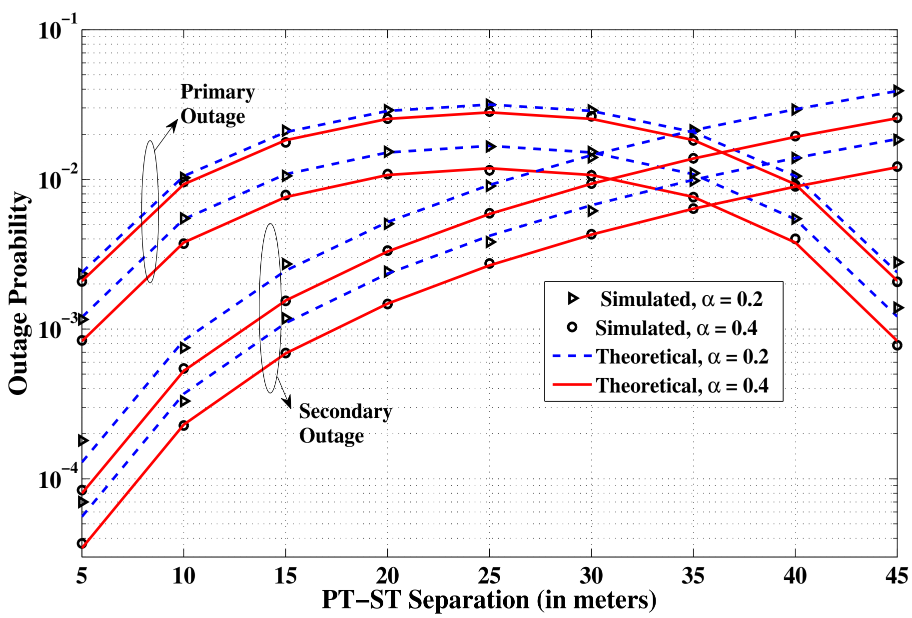

Figure 2.4: Plot of Primary and Secondary outage probabilities against the PT-ST separation for $\alpha = 0.2, 0.4$ and $\rho = 0.75, 0.9$, $\eta = 0.8$ and $\gamma = 0.75$.

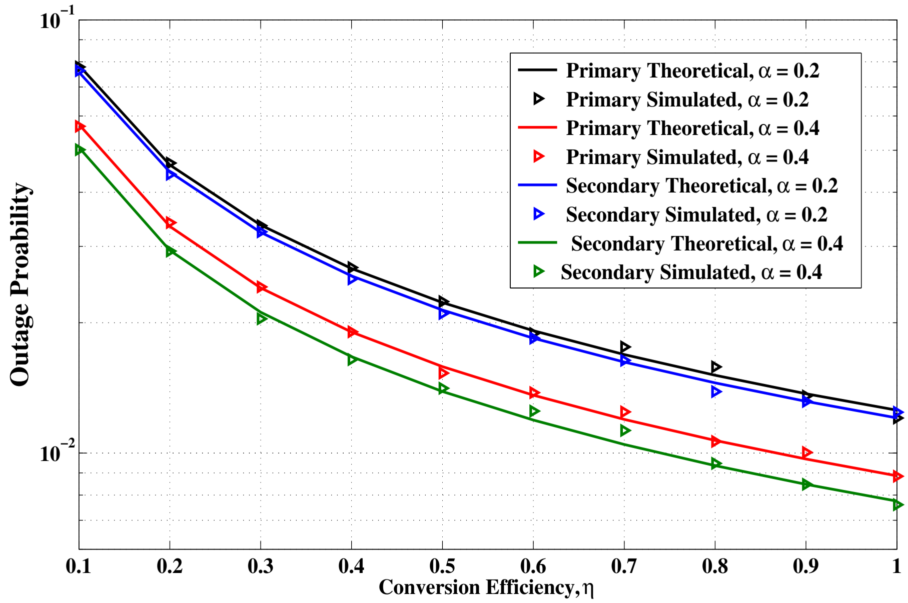

Figure 2.5: Plot of Primary and Secondary outage probabilities against Conversion Efficiency for $\rho = 0.9$, $\alpha = 0.2, 0.4$, $\nu = 30$m and $\gamma = 0.75$.

Fig.2.2 and Fig.2.3 shows the plots of primary and secondary system outages with respect to α for $\rho = 0.6$, 0.75, 0.9. From the figures it is quite apparent that the primary outage decreases with increase in α. This can be explained as follows. As α increases, more energy is harvested at ST which results in better performance of ST-PR link. However, after a certain value of α, corresponding to each ρ, there is an abrupt increase in primary outage. Since there is no direct link between PT and PR so when the ST-PR link becomes a failure, primary outage increases to 1. This can be also be verified from (2.23). Further, secondary system outage at first decreases and later on increases with increase in α. The initial drop is due to the reason as stated for the primary case. The increase in the secondary outage occurs at higher values of α because as α increases further, the fraction of time available for transmission in phase 2 reduces.

Now, consider Fig.2.4 which plots the primary and secondary outages with respect to PT-ST distance i.e. ν. As can be seen from Fig.2.4, primary outage at first increases and later on decreases. As ν increases ST moves away from PT that leads to the PT-ST link outage. Hence, the overall primary outage sees an increase. However, as ST moves away further, it gets closer to PR. So, ST-PR link outage decreases and overall primary outage becomes low. In the secondary system case, as the ST moves away from PT less amount of energy is harvested and hence outage performance degrades. Fig.2.5 shows the dependence of primary and secondary outages on the conversion efficiency, η, of the RF circuitry at ST. As η increases the primary and secondary outage decreases because greater amount of energy is harvested.

Chapter 3

A Unified Spectrum Sharing and Energy Harvesting Protocol for Multiple Wireless Sensor Nodes

3.1 Introduction

We previously mentioned that this chapter deals with a cooperative cognitive radio network where in we are dealing with multiple energy harvesting sensor nodes in the secondary system. In recent years work is being done in bringing together the complementary techniques of CSS and energy harvesting (EH) as it is beneficial for creating a standalone secondary system which is capable of meeting its energy and spectrum requirements using primary's resources [6], [10]. In our previous work [6] we combined both CSS and EH to enhance the performance of primary and secondary systems. Meanwhile in [10] they have also incorporated the two techniques together where the secondary transmitter has to harvest a predefined amount of energy and alamouti coding has been used for simultaneous primary and secondary transmissions. But the performance of the system can be further enhanced by further integrating the concept of optimal selection which we are doing in our present work. The limitation of the framework in [6], [7], is that SU remains silent if it is not decoding PU's information and in [11] the use of two different SU puts a constraint on the level of transmission power to avoid interference.

In the proposed scheme we alleviate the above drawbacks by utilizing a hybrid energy harvesting and spectrum sharing protocol wherein the best node among multiple sensor nodes is selected to forward the information of primary system. As a consequence, since the orthogonal channel (channel corresponding to the best node) [1] is required for PU's information transmission same diversity order as the cooperative diversity using multiple orthogonal channels [12]. In addition to the above we have employed a hybrid power splitting and time switching protocol where an optimal time duration is obtained during which if energy is harvested we will achieve the best

[1] We have considered that direct link fails.

QoS for the primary system.

The main contributions of the chapter are summarized as follows:

- The selection process is robust in the sense that it makes joint use of both the channel conditions as well as the amount of energy harvested in a CSS scenario thus giving a better performance compared to [13].
- The node selection procedure is such that the node with maximum achievable rate is selected that is also capable of supporting secondary's transmission.
- The results obtained show that the value of fraction of power allocated for energy harvesting and information decoding at the nodes play a significant role in primary and secondary outage performance.
- Unlike [10] we have used optimal sensor node selection and have shown that the outage performance of the primary system is improved by increasing the number of sensor nodes in the secondary network. Further, the outage performance is also limited by the value of fraction of power allocated for primary and secondary transmissions.

We have also extended this work in part II of the chapter. The part II aims at giving an insight into the fact that how there is a trade off between the power consumption at the BS and the number of sensor nodes present in the WSN to achieve a desired primary system performance.

Part I

3.2 Proposed System Model and Performance Analysis

3.2.1 System Model

The proposed system model consists of base station BS, one primary cellular user CU, N number of sensor nodes (secondary transmitters or STs), and one central monitoring station or SR as shown in Fig.1. The link between BS and CU is assumed to fail due to deep fade or presence of obstacles [2], hence BS requires the assistance of the secondary user for transmission of the primary information x_p to CU. Here, it is to be noted that BS constantly monitors the channel conditions and gathers all the necessary CSI [2] for deciding the best sensor node. After this BS broadcasts the message which includes the information of selected node and also the mode in which the selected node has to operate [3].

The total transmission time T is divided into two phases of time duration αT and $(1-\alpha)T$ respectively, where α is the time switching factor. We have considered that energy harvesting

[2] The underlying MAC protocol assures that the CSI for the channels between BS and sensor nodes and also sensor nodes and CU is known at BS.

[3] Interested readers may refer to [8] for details on control signaling involved between the primary and secondary system

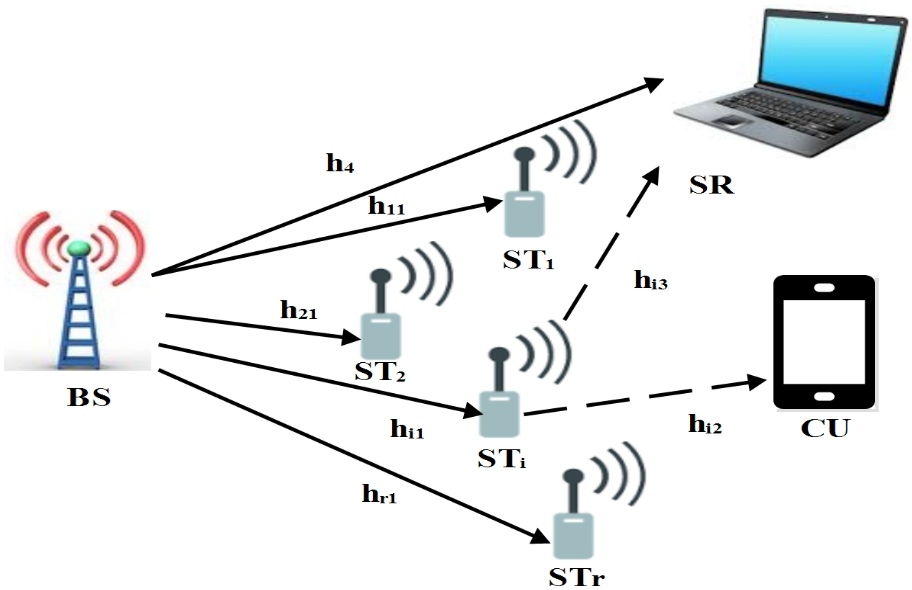

Figure 3.1: System model where ST_i is the best relay.

based on hybrid power splitting and time switching spectrum sharing protocol takes place at the selected sensor node in phase 1 of transmission. Energy harvesting and information decoding is carried out with γP_i and (1-γ)P_i power, where P_i is the power received at ST_i and $0 \leq \gamma \leq 1$ is the power splitting factor. The selection process is carried out as given in Algorithm 1.

The channels between each pair of transmitter and receiver are assumed to be Rayleigh flat fading and are denoted as h_{i1} for BS-ST_i link, h_{i2} for ST_i-CU link, h_{i3} for ST_i-SR link, h_4 for BS-SR link, where i = 1, 2, 3....N. We have $h_{ij} \sim \mathcal{CN}(0, d_{ij}^{-v})$ and $h_4 \sim \mathcal{CN}(0, d_4^{-v})$ where v is the path loss exponent, d_{ij} and d_4 is the distance between the respective transmitter and receiver and $j = 1, 2, 3$ for BS, CU and SR respectively. The channel gains $\beta_{ij} = |h_{ij}|^2$ and $\beta_4 = |h_4|^2$ are exponentially distributed and are denoted as $\beta_{ij} \sim \mathcal{E}(d_{ij}^v)$ and $\beta_4 \sim \mathcal{E}(d_4^v)$ respectively , where d_{ij}^{-v}, d_4^{-v} are the mean of the distribution. Also, we are assuming that h_{ij} are independent and identically distributed (i.i.d.) ∀ i, j. Hence, $d_1 = d_{i1}$, $d_2 = d_{i2}$ and $d_3 = d_{i3}$ $\forall i$. The AWGN noise added at each receiver is denoted as $n \sim \mathcal{CN}(0, \sigma^2)$

The signal received at i^{th} sensor node and at CU, SR in k^{th} phase is denoted as $y_{st_i}^k$, y_2^k and y_3^k respectively. In phase 1 BS broadcasts its signal x_p with a transmit power P_p. The signal received at ST_i from BS is given by

$$y_{st_i}^1 = \sqrt{P_p} h_{i1} x_p + n \tag{3.1}$$

The ST then splits the signal between the energy harvester and information decoder. The signal received at the energy harvester branch of ST_i is given by

$$\sqrt{\gamma} y_{st_i}^1 = \sqrt{\gamma P_p} h_{i1} x_p + \sqrt{\gamma} n. \tag{3.2}$$

Algorithm 1 Selection Procedure

Let R_i be the rate achievable at ST_i in phase 1, R_{pt} is the primary target rate and $R_i^{'}$ be the rate achievable at CU when ST_i is transmitting x_p and x_s with ρP_h and (1-ρ)P_h power respectively, where P_h is the harvested power. Also, R_{sr} is the rate achievable at SR in phase 1.

for $i = 1 : 1 : N$ **do**
  if $R_i > R_{pt}$ **then**
    Select ST_i.
  end if
  $i \leftarrow i + 1$
end for
Create a set D of the selected nodes.
if set D is empty **then**
  S = 1
else if $\max_i[\mathrm{R}_i^{'}] > R_{pt}$ **then**
  Select the node from D for transmission of combination of x_p and x_s signal in phase 2.
  if $R_{sr} > R_{pt}$ **then**
    S = 2
  else
    S= 3
  end if
else
  S = 4
end if
  switch S
  case 1
No node is able to decode x_p.
Select the node that achieves the maximum rate for transmission of x_s in phase 2.
  end case
  case 2
Broadcast a composite signal consisting of x_p and x_s in phase 2 from the node that can achieve the maximum rate for primary system.
Interference due to x_p at SR can be cancelled out.
  end case
  case 3
Broadcast only x_s in phase 2 from the node that can achieve the maximum rate for secondary system.
Interference due to x_p at SR can not be cancelled out.
  end case
  case 4
Broadcast only x_s in phase 2 from the node that can achieve the maximum rate for secondary system
  end case
  end switch

Table 3.1: Table containing the details of the four possible cases in phase 2.

Case	Condition	Signal received at SR	Rate achievable corresponding to ST_b-SR link
Case 1	a) Decoding set D is empty. b) Sensor node achieving maximum rate at SR corresponding to x_s transmission is selected.	$y_3^2 = \sqrt{P_h} h_{b3} x_s + n$	$R_{b3} = (1-\alpha)\log_2\left(1 + \frac{P_h\|h_{b3}\|^2}{\sigma^2}\right)$
Case 2	a) Decoding set D is non empty. b) Node in D meets the criterion $max_i[R_i^{'}] > R_{pt}$. c) SR decodes x_p successfully in phase 1.	$y_3^{2'} = \sqrt{(1-\rho)P_h} h_{b3} x_s + \sqrt{\rho P_h} h_{b3} x_p + n$	$R_{b3}^{'} = (1-\alpha)\log_2\left(1 + \frac{(1-\rho)P_h\|h_{b3}\|^2}{\sigma^2}\right)$
Case 3	a) Decoding set D is non empty. b) Node in D meets the criterion $max_i[R_i^{'}] > R_{pt}$. c) SR unsuccessful in decoding x_p in phase 1.	$y_3^{2''} = \sqrt{(1-\rho)P_h} h_{b3} x_s + \sqrt{\rho P_h} h_{b3} x_p + n$	$R_{b3}^{''} = (1-\alpha)\log_2\left(1 + \frac{(1-\rho)P_h\|h_{b3}\|^2}{\rho P_h\|h_{b3}\|^2 + \sigma^2}\right)$
Case 4	a) Decoding set D is non empty. b) No node in D meets the criterion $max_i[R_i^{'}] > R_{pt}$. c) Node in D achieving maximum rate at SR corresponding to x_s transmission is selected.	$y_3^{2'''} = \sqrt{P_h} h_{b3} x_s + n$	$R_{b3}^{'''} = (1-\alpha)\log_2\left(1 + \frac{P_h\|h_{b3}\|^2}{\sigma^2}\right)$

Energy harvested at each ST_i in time αT is given by

$$E_{hi} = \eta\gamma P_p |h_{i1}|^2 \alpha T \tag{3.3}$$

where $\eta \, \epsilon$ (0,1] is the conversion efficiency of the RF to DC conversion circuitry used. The transmission power available at the energy harvesting sensor node is given by

$$P_{hi} = \frac{E_{hi}}{(1-\alpha)T} = \frac{\eta\gamma P_p |h_{i1}|^2 \alpha}{(1-\alpha)}. \tag{3.4}$$

The signal received at information receiver of each ST_i, assuming the impact of power splitting on the noise component is not significant, is given by

$$\sqrt{(1-\gamma)} y_{st_i}^1 = \sqrt{(1-\gamma) P_p} h_{i1} x_p + n \tag{3.5}$$

The rate achievable at ST_i is given by

$$R_i = \alpha \log_2(1 + SNR_i) \tag{3.6}$$

where $SNR_i = \frac{(1-\gamma)P_p|h_{i1}|^2}{\sigma^2}$.

Signal received at SR is given by

$$y_{31} = \sqrt{P_p} h_4 x_p + n \tag{3.7}$$

Rate achievable at SR in phase 1 is given by

$$R_{sr} = \alpha \log_2 \left(1 + \frac{P_p |h_4|^2}{\sigma^2}\right). \tag{3.8}$$

Thus depending on the selection algorithm four cases are possible and they are as mentioned in Table 3.1. ST_b denotes the best sensor node. h_{b3} denotes the channel coefficient of the link between best node and SR. Also, P_h is the power harvested at the best node. The four cases illustrate the possible achievable rates for ST_b-SR link in phase 2 depending on the channel conditions and amount of harvested energy.

3.2.2 Outage Analysis of Primary System

Probability that no ST_i is able is decode is given by

$$P_1 = P[R_1 < R_{pt}] P[R_2 < R_{pt}] ...... P[R_N < R_{pt}] \tag{3.9}$$

It is assumed that each ST_i is equidistant from BS and CU. Hence, the channel gains corresponding to each of the sensor nodes will be i.i.ds. So,

$$P_1 = (P[R_1 < R_{pt}])^N \tag{3.10}$$

$$P_1 = \left(1 - e^{\frac{-d_1^v t}{m(1-\gamma)}}\right)^N \tag{3.11}$$

where $t = (2^{\frac{R_{pt}}{\alpha}} - 1)$ and $m = \frac{P_p}{\sigma^2}$.

Probability that atleast one of the relays decode $BS's$ information is given by

$$P_1^{'} = 1 - P_1 \tag{3.12}$$

The sensor nodes that are able to decode are placed in a decoding set D. This set can contain sensor nodes ranging from 1 to N. Primary outage can be given by

$$P_{oP} = P_1 + P_1^{'} P_2 \tag{3.13}$$

where $P_2 = \left[\sum_{k=1}^{N} \binom{N}{k} p^{N-k}(1-p)^k P[\max(R_1^{'}...R_k^{'}) < R_{pt}]\right]$ and $R_i^{'}$ is given as

$$R_i^{'} = (1-\alpha)\log_2\left(1 + \frac{\rho P_h |h_{i2}|^2}{(1-\rho)P_h|h_{i2}|^2 + \sigma^2}\right). \tag{3.14}$$

$$P[\max(R_1^{'}...R_k^{'}) < R_{pt}] = \left(P[R_1^{'} < R_{pt}]\right)^k$$

$$= \begin{cases} [1 - uK_1(u)]^k, & \alpha < 1-\delta \\ 1, & \text{otherwise.} \end{cases} \tag{3.15}$$

where $u = \sqrt{\frac{4a}{bd_1^{-v}d_2^{-v}}}$, $a = \frac{\sigma^2(1-\alpha)(2^{R_{pt}/(1-\alpha)}-1)}{\eta\gamma P_p \alpha}$, $b = \rho - (2^{R_{pt}/(1-\alpha)} - 1)(1-\rho)$, $\delta = \frac{R_{pt}}{\log_2(1+\frac{\rho}{1-\rho})}$ and $K_1(.)$ is the modified first order bessel function of second kind.

The closed form expression for primary outage will be given by

$$P_{oP} = \begin{cases} P_1 + P_1^{'}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^k w^k\right], & \alpha < 1-\delta \\ P_1 + P_1^{'}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^k\right] = 1, & \text{otherwise.} \end{cases} \tag{3.16}$$

where $w = [1 - uK_1(u)]$ and $p = \left(1 - e^{\frac{-d_1^v t}{m(1-\gamma)}}\right)$.

3.2.3 Outage Analysis of Secondary System

The total outage of the secondary system calculated by taking into account all the four cases can be given as

$$P_{oS} = P_1 P[\max(R_{13}....R_{N3}) < R_{st}] + [1-P_1][1-P_2]P[R_{b3}^{'} < R_{st}]P[R_{sr} > R_{pt}]+$$
$$[1-P_1][1-P_2]P[R_{b3}^{''} < R_{st}]P[R_{sr} < R_{pt}]+[1-P_1]P_2\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^k P[\max(R_{13}...R_{k3}) < R_{st}]\right] \tag{3.17}$$

where R_{i3} is the rate corresponding to ST_i-SR link when only secondary signal is transmitted at ST_i. Further,

$$P[R_{b3}^{'} < R_{st}] = [1 - vK_1(v)] \tag{3.18}$$

where v $= \sqrt{\frac{4c}{d_1^{-v}d_3^{-v}}}$ and c $= \frac{\sigma^2(1-\alpha)(2^{R_{st}/(1-\alpha)}-1)}{\eta\gamma P_p \alpha(1-\rho)}$.

$$P\left[\max(R_{13}R_{23}....R_{i3}) < R_{st}\right] = [1 - yK_1(y)]^i. \tag{3.19}$$

$$P[R_{b3}^{''} < R_{st}] = \begin{cases} 1 - zK_1(z), & \alpha < 1-\mu \\ 1, & \text{otherwise} \end{cases} \tag{3.20}$$

where $\mu = \frac{R_{st}}{log_2\left(\frac{1}{\rho}\right)}$, $y = \sqrt{\frac{4d}{d_1^{-v}d_3^{-v}}}$ $z = \sqrt{\frac{4d}{ed_1^{-v}d_3^{-v}}}$,
$d = \frac{\sigma^2(1-\alpha)(2^{R_{st}/(1-\alpha)}-1)}{\eta\gamma P_p\alpha}$ and $e = (1-\rho) - \rho\left(2^{\frac{R_{st}}{1-\alpha}} - 1\right)$.

$$P[R_{sr} > Rpt] = e^{\frac{-d_4^v t}{m}} \tag{3.21}$$

The closed form expression for the outage probability of the secondary system obtained by substituting (3.11), (3.15), (3.18), (3.19), (3.20) and (3.21) in (3.17), is given in (3.22) where $Q = [1 - yK_1(y)]$, $R = [1 - vK_1(v)]$,
$T = \left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^k w^k\right]$, $P_{21} = P_1 + P_1^{'}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^k w^k\right]$, $P_{22} = P_1 + P_1^{'}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^k\right]$ and $\phi = e^{\frac{-d_4^v t}{m}}$.

$$P_{oS} = \begin{cases} P_1Q^N + P_1^{'}(1-P_{21})R\phi + P_1^{'}(1-P_{21})T(1-\phi) + P_1^{'}P_{21}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^kQ^k\right], & \alpha < 1-\delta \text{ and } \alpha < 1-\mu \\ P_1Q^N + P_1^{'})(1-P_{21})R\phi + P_1^{'}(1-P_{21})(1-\phi) + P_1^{'}P_{21}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^kQ^k\right], & \alpha < 1-\delta \text{ and } \alpha \geq 1-\mu \\ P_1Q^N + P_1^{'}(1-P_{22})R\phi + P_1^{'}(1-P_{22})T(1-\phi) + P_1^{'}P_{22}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^kQ^k\right], & \alpha \geq 1-\delta \text{ and } \alpha < 1-\mu \\ P_1Q^N + P_1^{'}(1-P_{22})R\phi + P_1^{'}(1-P_{22})(1-\phi) + P_1^{'}P_{22}\left[\sum_{k=1}^{N}\binom{N}{k}p^{N-k}(1-p)^kQ^k\right], & \alpha \geq 1-\delta \text{ and } \alpha \geq 1-\mu \end{cases} \tag{3.22}$$

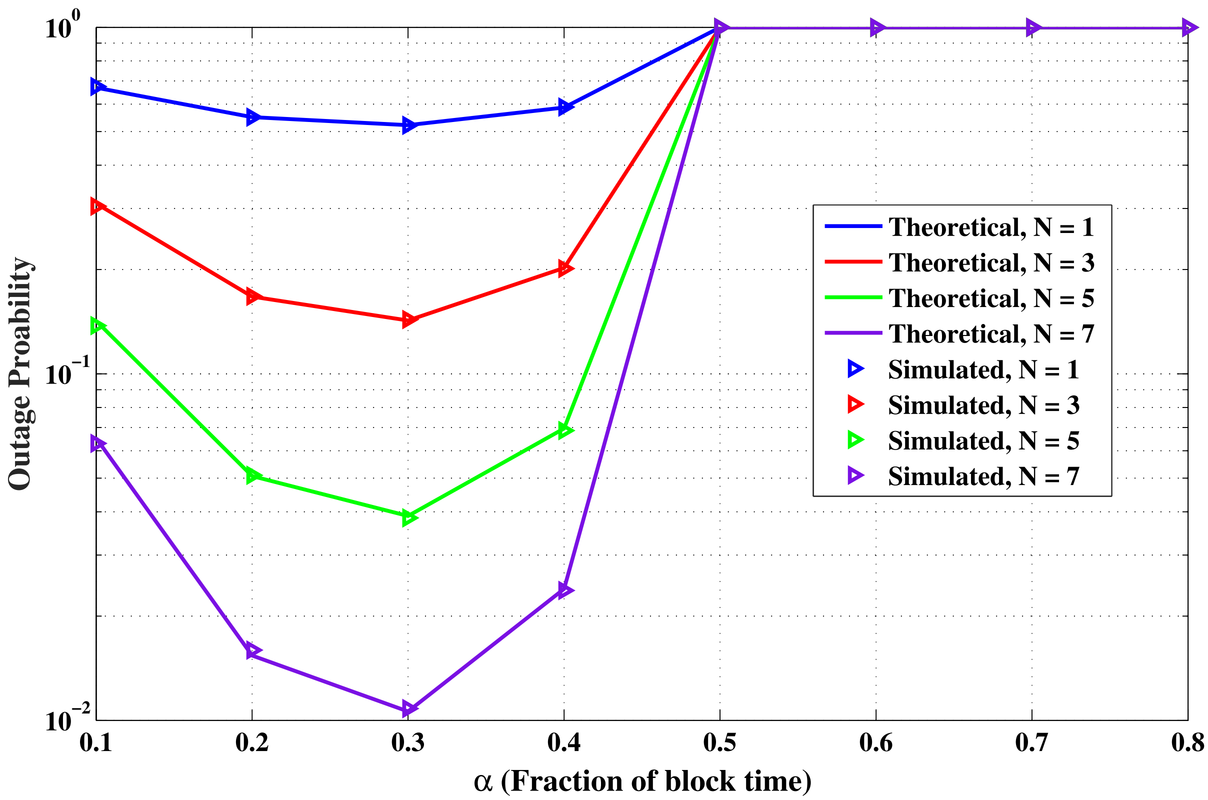

Figure 3.2: Plot showing the outage probability of primary system with respect to α for N = 1, 3, 5, 7.

3.3 Simulation and Results

This section presents the study of the effect of various system parameters such as α, ρ and N on the outage performance of the primary and secondary system. Each ST_i is assumed to be equidistant from BS and CU. BS, CU and SR are assumed to be collinear. The remaining simulation parameters are given below:

- The distances between BS-ST_i, ST_i-SR, BS-SR and ST_i-CU are 30m, 20m, 10m, 20m respectively where distance between the BS-CU link is 50m.
- Noise variance at all the receivers, σ^2 = -90 dBm.
- The RF to DC conversion efficiency, η is taken as 0.8.
- $\gamma = 0.75$.
- $P_p = 10$ dBm.
- $v = 3$.

Fig.3.2. shows the variation in the outage probability for a primary system with respect to α for ρ = 0.75. It is quite obvious that with the increase in the number of sensor nodes there

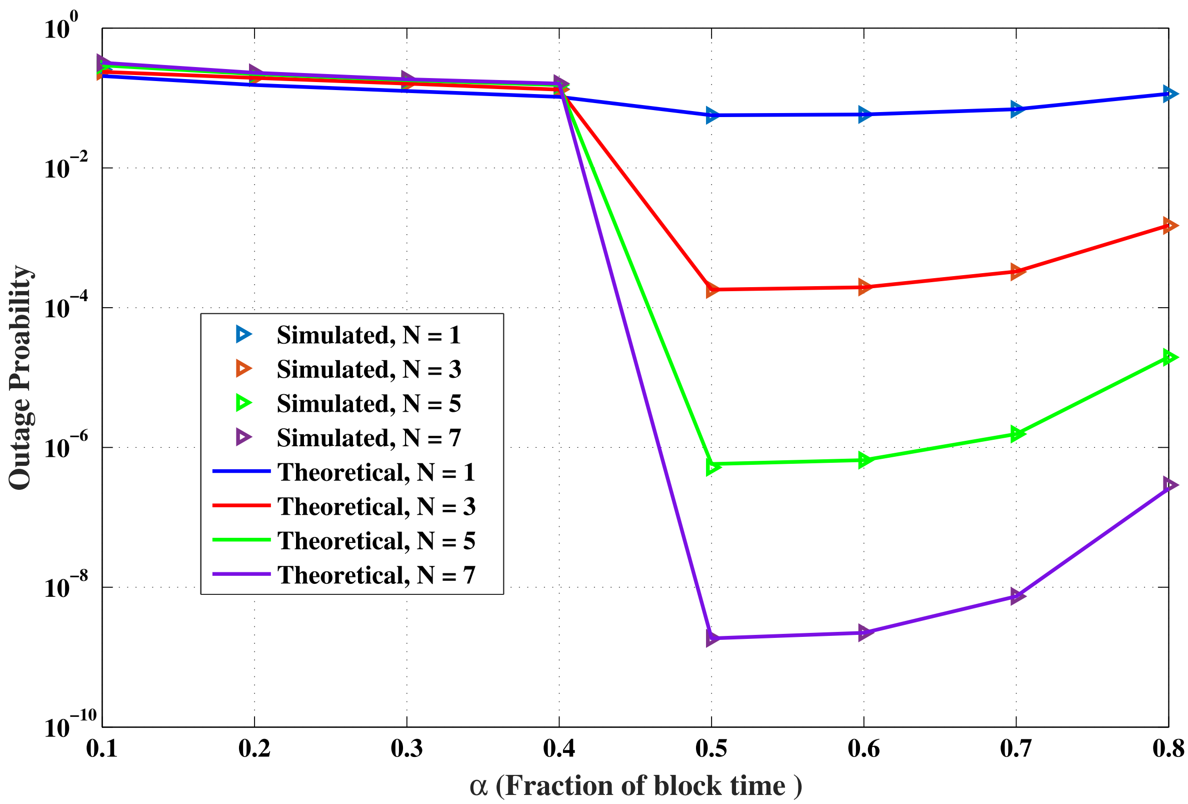

Figure 3.3: Plot showing the outage probability of secondary system with respect to α for N = 1, 3, 5, 7.

is a performance improvement because the decoding probability of x_p in phase 1 increases (9). Further, corresponding to each value of ρ there is a value of α beyond which the increase in N has no impact on the outage performance of primary system. This can be explained as follows. Since there is no direct link between BS and CU so when ST_i-CU link becomes a failure $\forall$ ST_i ϵ D, primary outage increases to 1. This can be also be verified from (3.16).

Fig.3.3. depicts the variation in the outage probability for a secondary system with respect to α for $\rho = 0.75$. Similar to primary system, with the increase in the number of sensor nodes the outage probability for secondary system decreases. This is due to the fact the proposed scheme selects the node which has the maximum harvested energy. Hence with an increase in number of nodes there is more probability that the selected node will have sufficient harvested energy to relay the information of secondary system, x_s, with less outage.

Part II

3.4 Power Reduction Using Multiple Sensor Nodes

In this section we have done an extended study on the multiple sensor node system model considered previously in part I. The prime difference is the inclusion of the direct link between BS and CU, unlike part I. In a network setup where the direct link is in operational mode the number of the sensor nodes assisting the forwarding of BS's data and power level at the BS will be the deciding factors for selection of the direct link or the WSN for the primary information transmission, which is the focus of this section. We observed that given the provision to expand the WSN by incorporating more number of sensor nodes the WSN assisted primary transmission will outperform the direct link system configuration at much lower power levels, hence saving big on energy. There can be a case where the WSN expansion is not feasible then the direct link configuration will do a better job.

3.4.1 Performance Analysis

The system model is the same as shown in Fig 3.1. An additional link between BS and CU is considered and the channel is denoted by h_d. We have $h_d \sim \mathcal{CN}(0, d_d^{-v})$ and $\beta_d = |h_d|^2$ where d_d is the distance between BS and CU. For making an unbiased comparison between the direct and relayed transmission we have taken the time of direct transmission equal to the time αT meant for EH and information decoding at the best sensor node. So the rate achievable corresponding to the direct link is given by

$$R_d = \alpha \log_2 \left(1 + \frac{P_p|h_d|^2}{\sigma^2}\right) \quad (3.23)$$

Hence, the outage probability of the BS-CU link can be calculated as

$$P[R_d > R_{pt}] = e^{\frac{-d_d^v t}{m}} \quad (3.24)$$

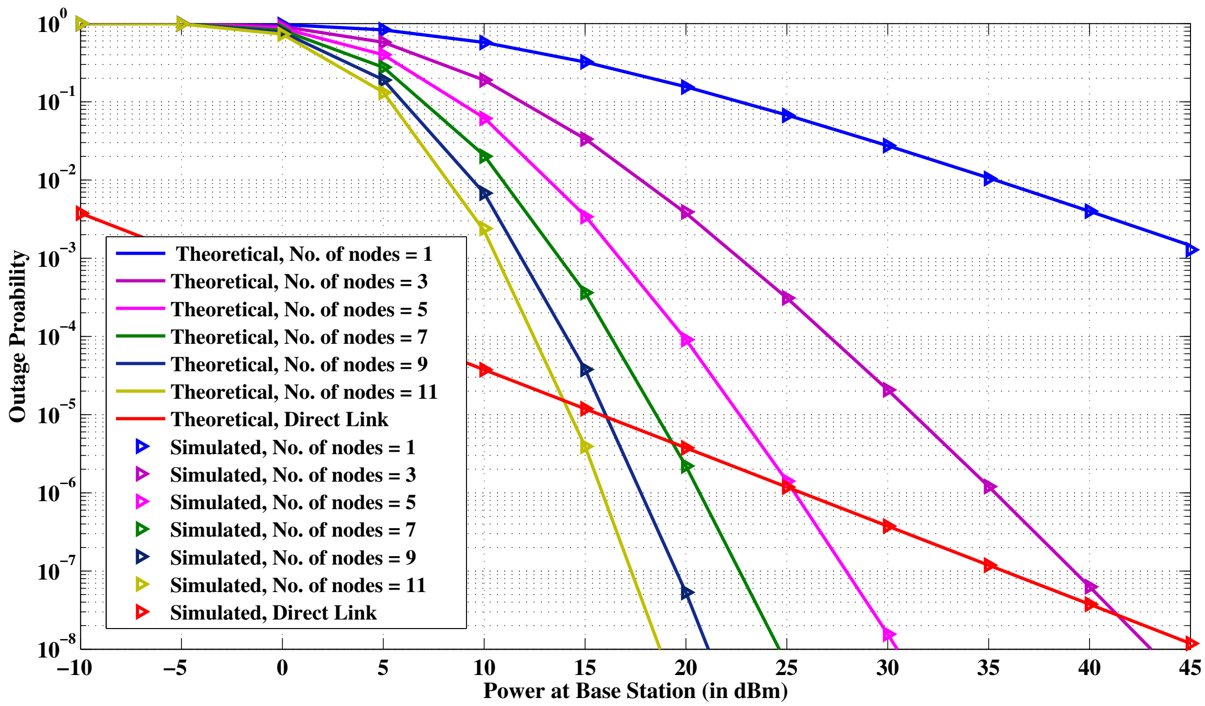

Figure 3.4: Plot showing the primary outage probability against the power at base station (BS) for N = 1, 3, 5, 7, 9 and 11.

The rest of the outage analysis for the primary and secondary systems will remain the same as determined in part I.

3.5 Simulation and Results

This section highlights how the power at the BS and the values of ρ, N affects the outage probability of the primary and secondary system. All the simulation parameters have been kept same as before and we have kept $\alpha = 0.5$.

Fig 3.4 demonstrates that by varying the power level at BS different QoS can be obtained for primary system which is also impacted by the number of the sensor nodes in WSN. The plot also compares the performance with the direct transmission and the various cross-over points corresponding to each value of senor nodes can be seen. The crossover points are reached earlier ie. at a lower power value for higher number of sensor nodes. The increase in the number of sensor nodes renders to greater probability of selection of a more energy efficient node for data forwarding that results in power reduction.

In Fig.3.5 we have plotted the outage probability against the number of sensor nodes at $P_p = 5$ dBm, 10 dBm and 15 dBm. As expected with the increase in number of sensor nodes the outage performance is enhanced. In Fig.3.6 we observe that the secondary system outage probability decreases, then transits to a higher outage value as power level at BS goes up and then again decreases. This is because of the fact that at lower power the sensor nodes will not harvest

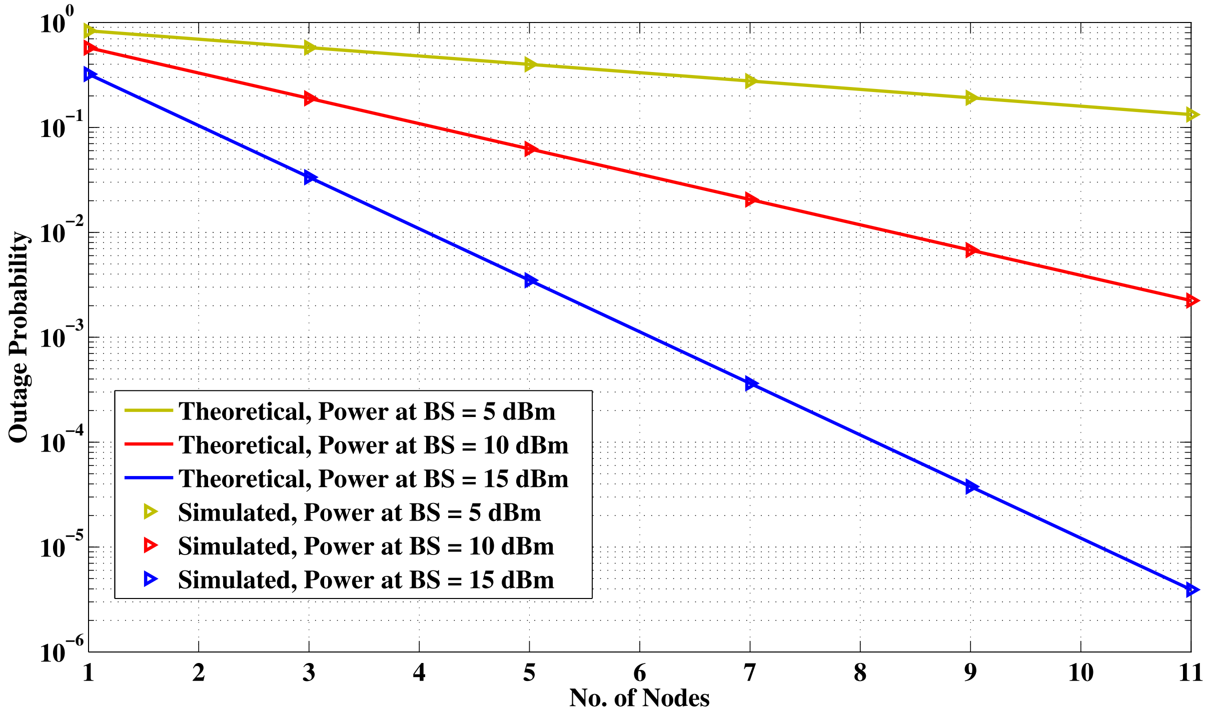

Figure 3.5: Plot showing the primary outage probability against the number of sensor nodes in WSN.

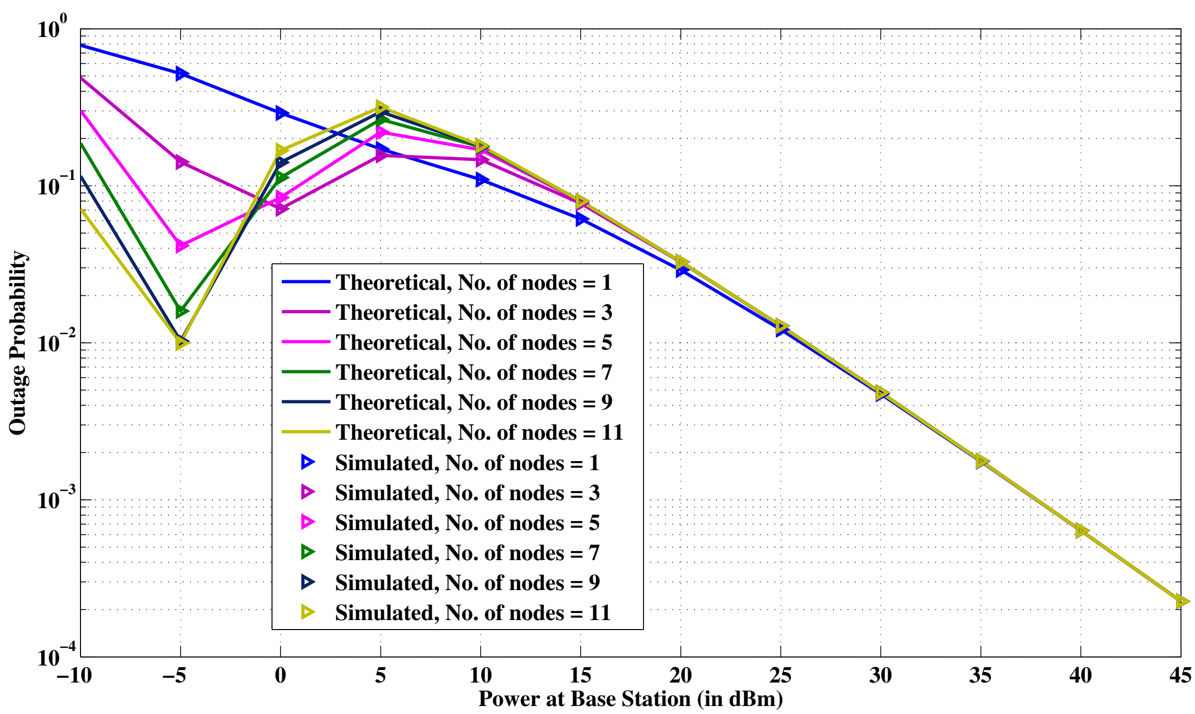

Figure 3.6: Plot showing the secondary outage probability against the power at base station (BS) for N = 1, 3, 5, 7, 9 and 11.

enough energy so the probability of only secondary signal transmission increases. Hence, the secondary outage probability shows an improvement. But as the power level reaches a certain level the probability of composite signal transmission sees a rise which results in relatively higher secondary outage. Finally, as explained in the case of primary plot with further increase in power the secondary performance gets better. Further, it is to be noted as the power level gets higher the increase in sensor nodes has no impact on secondary outage. The explanation being that the increase will further improve primary performance hence providing no significant improvement for secondary transmission.

Chapter 4

Conclusion and Future Work

4.1 Conclusion

Energy harvesting and cooperative spectrum sharing techniques when employed together can solve the energy and spectrum scarcity problems simultaneously. In this thesis we have worked on systems jointly using these schemes to further improve the performance parameters, which in our case is outage probability. In chapter 2, a hybrid time switching and power splitting spectrum sharing protocol was proposed, where the energy constrained ST node harvests energy from incumbent primary system and utilizes this energy for primary and secondary transmissions. It was shown that the proposed protocol not only improves the energy efficiency but also leads to better spectrum utilization. The analytical expressions for the primary and secondary outages were obtained, and verified through the simulation results. It was also observed that beyond a specific value of fraction of block duration, αT, the ST-PR link ceases to exist and only the secondary system has access to the spectrum.

In chapter 3, we have derived closed form analytical expressions for the primary and secondary outage probabilities in a CSS scenario and have validated it using the simulation results. Our results show that increasing the number of sensor nodes in the system the outage performance of the primary system can be significantly improved. In a scenario of multiple sensor nodes we adopted the method of first select and then harvest.

4.2 Future Work

This work can be extended to a scheme where in the block duration of T is divided into αT for information decoding and energy harvesting at ST. $\beta(1-\alpha)T$ duration is used for primary transmission. The factor β is decided upon the EH capability of ST. If transmission power available at ST is high, less time will be taken to achieve preset value of primary's rate (or to meet the preset requirement of QoS). Hence, remaining time can be allocated for secondary transmission.

4.3 Publications

- Mansi Peer, Neha Jain, Vivek Ashok Bohara, "A Hybrid Spectrum Sharing Protocol for Energy Harvesting Wireless Sensor Nodes" accepted in *The 17th IEEE International workshop on Signal Processing advances in Wireless Communications.*
- Mansi Peer and Vivek Ashok Bohara, "Spectrum and Energy Harvesting Protocols for Wireless Sensor Nodes" accepted as book chapter in *Wireless Energy Harvesting for Future Wireless Communications*, to be published by Springer-Verlag New York, USA.

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