COGNITIVE ENERGY HARVESTING SYSTEM UNDER FINITE BATTERY CONSTRAINTS

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Submitted by:

ASHISH SURI

Roll No. 2K17/SPD/03

Under the supervision of

MR. ANURAG CHAUHAN

DEPARTMENT OF ELECTRONICS AND COMMUNICATION
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

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DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

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I, Ashish Suri, Roll No. 2K17/SPD/03 student of M.Tech. Signal Processing and Digital Design, hereby declare that the project Dissertation Titled "Cognitive Energy Harvesting System Under Finite Battery Constraints" which is submitted by me to the Department of Electronics and Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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Date:

DEPARTMENT OF ELECTRONICS AND COMMUNICATION
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the Project Dissertation titled "Cognitive Energy Harvesting System Under Finite Battery Constraints" which is submitted by Ashish Suri, Roll No. 2K17/SPD/03, Department of Electronics and Communication, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date:

ANURAG CHAUHAN

SUPERVISOR

Assistant Professor,

Department of Electronics and

Communication Engineering,

Delhi Technological University,

Bawana Road, Delhi-110042

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ABSTRACT

Wireless energy harvesting is regarded as a promising energy supply alternative for energy-constrained wireless networks. In this system, the secondary nodes can harvest energy from the primary network (PN) while sharing the licensed spectrum of the PN. A novel idea of implementing energy harvesting in non-relay assisted cognitive radio network under finite battery power is presented where supercapacitors are used as energy storage elements in the secondary network (SN).

The performance of the network can be described using following performance metrics:

i. Outage Probability

ii. Throughput

iii. Channel capacity

Variation of performance metrics upon variation in Interference power, total input transmit power, system parameters (e.g., EH interval, conversion efficiency) is studied. Variation in instantaneous power in the battery during the transmission is also studied. The simulation of the results is carried out using MATLAB.

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List of Abbreviations

AWGN	Additive White Gaussian Noise
CCRN	Cooperative Cognitive Radio Network
CDF	Cumulative Distribution Function
CSI	Channel State Information
DMC	Discrete Memoryless Channel
DPM	Dynamic Power Management
EH	Energy Harvesting
EH-CRN	Energy Harvesting Cognitive Radio Network
EM	Electromagnetic
ENO	Energy Neutral Operation
EMR	Electromagnetic Radiation
ESC	Energy Synchronization Communication
FCC	Federal Communications Commission
MAC	Multiple Access Channels
MH	Metal Hydride
MIMO	Multiple Input Multiple Output
PD	Primary Destination
PDF	Probability Density Function

PN	Secondary Network
PS	Power Splitting
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
RV	Random Variable
SD	Secondary Destination
SINR	Signal-to-Interference Noise Ratio
SN	Secondary Network
SNR	Signal-to-Noise Ratio
SS	Secondary Source
SSDF	Spectrum Sensing Data Falsification
SU	Secondary User
TS	Time Switching
WSN	Wireless Sensor Network
WRSN	Wireless Rechargeable Sensor Network
WRT	With Respect To

CHAPTER 1

INTRODUCTION

In this chapter, we discuss cognitive radio network and its properties which emphasize its advantages in wireless sensor networks (WSNs) following network protocols to share spectrum under guidelines such that more number of users can accommodate the spectrum efficiently. We first briefly explain what cognitive networks are, how they work, their fundamentals and outline their versatile characteristics.

1.1 COGNITIVE RADIO NETWORKS

In this era of continuous advancements in wireless technology, since last twenty years technology has given rise to a huge amount of new wireless applications in both licensed and unlicensed bands. The wireless spectrum of frequencies over which reliable communication can be achieved is divided into frequency bands. For instance, in [11] TV white spaces which are widely distributed over 50 MHz-700 MHz in which licensed band is 54-56 MHz out of a fixed range of 50-70 MHz (specified for channel 2) band as used in a practical system. Licensed frequency bands allow only licensed users whereas unlicensed band is crowded due to free spectrum. Furthermore, studies in [13] have shown that often the licensed bands are left unutilized which leads to inefficient use of spectrum. Bridging this void between large users in the unlicensed spectrum and under-utilizing of the licensed spectrum has been of great research interest. A dynamic spectrum access methodology was proposed in [21] and has paved the path for the cognitive radio technology.
Cognitive radio is defined as the smart spectrum sensing system which adapts its various parameters (e.g., battery power, frequency band, switching algorithms, etc) in real-time. Cognitive radio allows unlicensed users (also known as secondary users) to access the vacant frequency bands of licensed users (also known as primary users) through dynamic allocation of spectrum.

Cognitive radio is a type of methodology which allows optimization of the available RF spectrum while minimizing interference power disturbing the network. Possible functions of cognitive radio include:

- The ability of transreceiver to determine its geographic location.
- Identify and authorize its user.
- Encrypt and decrypt signals.
- Sense neighboring wireless devices in operation.
- Adjust output power and modulation characteristics.

There are two types of users in cognitive radio network namely:

- Primary users: These wireless devices are mainly the parent network which holds the major access to the spectrum i.e., they have top priority to access licensed spectrum. In general, priorities are decided upon considering certain Quality of Service (QoS) constraints which should be obeyed.
- Secondary users: These users are allowed to access the spectrum licensed to primary users but under certain conditions hence the name secondary users. These users are expected to make a connection only on behalf of one condition i.e., they should not disturb the primary network and ensure their communication to be reliable any cost.

Apart from these two main network attributes, there are other factors which decide the strength of a network and define its characteristics such as the channel definition, propagation loss, trunking efficiency, etc.

The study of cognitive radio networks is there in practice for over a decade and has various applications in the field of wireless communication thus it is important to analyze its properties and make the decision accordingly.

There are basically three modes by which SUs can share the spectrum with PUs [15]:

a) Overlay mode: In this mode, the secondary users will simultaneously transmit in the primary user’s spectrum if and only if the Quality of Service (QoS) for primary users can be maintained.
b) Underlay mode: In this mode of spectrum sharing, the secondary users keep their transmission power below a certain threshold such that it doesn’t disturb the primary user’s transmission.
c) Interweave mode: It is the simplest mode in which a secondary user can access the primary user`s spectrum only when there is a vacancy of frequency band i.e. when no primary user is accessing that band.

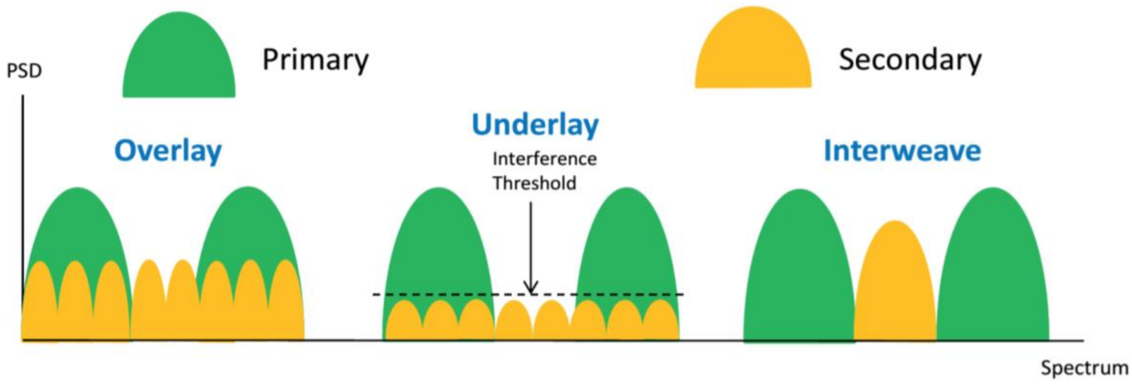

Figure 1.1 Various modes of spectrum sharing in cognitive radio

Fig. 1.1 illustrates the three modes of spectrum sharing in cognitive radio where *x*-axis the denotes spectrum and *y*-axis denote the power spectral density (PSD) of primary and secondary users. It is evident from the above figure that the overlay and underlay mode of spectrum sharing allows both primary and secondary users to communicate simultaneously. Whereas, in case of interweave mode, secondary users are only allowed to access the unutilized band of the primary user's frequency spectrum. In this thesis, we focus on cognitive radio working in underlay mode.

1.2 UNDERLAY MODE

In this mode, the main priority is to decide a threshold power below which the secondary user is allowed to communicate within the secondary network while utilizing the unused band of the primary network. To avoid interference to PN, SU's transmission power is usually much lower in comparison to that of PU. SUs have a large spread of bandwidth as compared to PU, which is why it is usually referred to as ultrawideband communication systems. This defines a new constraint on SN transmissions in which they need to have low power and short distance communication.

As discussed in [7] many digital signal processing and interference avoidance techniques have been published, some of which are beamforming and spread spectrum. Beamforming is defined as the superposition of multiple waves through the use of multiple antennas to guide them towards the receiver. Spread spectrum is defined as the technique in which original signal has a small bandwidth and high power and it is multiplied by the spreading code which results in a wideband signal with low power causing lower interference to the existing network. For the receiver to decode the signal without any distortion the spreading code is shared with the receiver node (in this case it is secondary destination). Now the signal at the receiver has been multiplied with same spreading code to obtain the desired signal hence it is suitable for underlay network. The challenging part in case of spread spectrum is that a spreading code has to be defined such that it results in overall signal's input power to be lesser than the threshold interference power.

1.3 ENERGY HARVESTING

Energy harvesting is highly useful in order to operate multiple devices at the cost of a few devices. As described in [22], energy harvesting techniques have been classified as follows:

a) Power Splitting

As discussed in Section 1.1, SN harvests energy from PN by various means and the harvested energy can be utilized in various tasks of the secondary network. In a power splitting methodology, SU extracts a fraction of power from PU in each cycle. The fraction is chosen such that it doesn't disturb the PN transmission. The power thereafter is stored in an electronic storage device (usually supercapacitor) and utilized for further transmission. A part of the power of the received signal is used to harvest energy and the remainder is used to fetch information. It is most popular and modified way of energy harvesting in the current scenario which thereby comes out to be reliable for long-distance communication. Power splitting causes disturbances in PN where transmission power is less which degrades the performance of both PN and SN.

b) Time Switching

Usually, under PS, there is a chance in a drop of QoS in low power PN due to the constant extraction of power. This scenario can be overcome by the use of time switching (TS). In the case of TS, SN harvests energy from the received message signal for a fraction of time and fetches the information from the message signal for the rest of the interval. Therefore the PN transmits the signal for the majority of the duration while the SN just utilizes a fraction of time interval to harvest signal power and stores it for the rest of the interval. Time switching is an efficient technology where time parameter is used to decide the energy harvesting period.

To support continuous environmental monitoring, energy harvesting wireless sensor networks (WSNs) are very critical, in which nodes transmitting under the governance of base station are capable of storing energy for their sustenance. Since the nodes are highly active for a long period of time and work continuously, thereby the power in them gets drained and thus they require more energy to operate in the network. The limited power storage in the nodes is the main problem due to which EH phenomenon has to be utilized and communication has to be performed or completed in multiple hops between SS and SD. The energy harvesting mechanism provides ample possibility for a node to incorporate sustainability over a period of time while conserving the QoS. The powered system under the energy harvesting technique gives rise to independency in the network as it shall be less reliable on harvesting energy each cycle and rather utilizing stored energy, which also reduces the cost of infrastructure.

There are numerous sources of natural and synthetic energy that are available to us thus they can be harvested by the sensor node and rehabilitated to electrical energy, and each power source delivers a different power density, shown in Table 1.1.

Table 1.1 Energy-Harvesting Sources and their Corresponding Power Densities

ENERGY SOURCE	**TYPES**	**ENERGY HARVESTING METHOD**	**POWER DENSITY**
Radiant	Solar	Solar cells (indoors)	$< 10\mu W/cm^2$
		Solar cells (outdoors, sunny days)	$15mW/cm^2$
	RF	Electromagnetic conversion	$0.1\mu W/cm^2$ (GSM)
		Electromagnetic conversion	$0.1\mu W/cm^2$ (WiFi)
Mechanical	Wind Flow and Hydro	Electromechanical conversion	$16.2\mu W/cm^2$
	Acoustic Noise	Piezoelectric	$960\mu W/cm^2$
	Motion	Piezoelectric	$330\mu W/cm^2$
Thermal	Body heat	Thermoelectric	$40\mu W/cm^2$

Over the past few years, the efficiency of energy harvesting technologies has been identified as the essential parameter to determine the desirability of the system. Hence, the efficiency has to be greatly improved in order to achieve continuous power without any rectification network, which eventually enhances the productivity of the power supply, such as in the case of a photovoltaic cell. Furthermore, WSN devices are very energy efficient, due to which they can function using harvested energy for a long period of time without shutting down and do not cause energy exhaustion.

Energy harvesting is the phenomenon of extraction of energy from external sources and it is also commonly known as energy scavenging or power harvesting. The external sources are useful to extract the energy, some of which are popularly in use as mentioned below:

- Solar power
- Thermal power
- Wind energy
- Salinity gradients
- Kinetic energy (also known as ambient energy).

The harvested power is stored in the storage devices which is briefly explained in the following section on the basic energy conservation and storage. Commonly known energy storage devices are wireless autonomous wearable electronics (WAWE) and wireless sensor networks (WSNs). These devices store a very small amount of power generally with the help of low-energy electronic equipments. Since the demand for extracted energy is utilized through the exploitation of oil, coal, etc. there are plenty of energy harvesters in the field which employ the same function and convert it as kinetic energy. For example, a considerably large amount of EM energy is present in the environment because of the modern gadgets like radio and TV broadcasting and a considerable amount of temperature gradient is also present due to combustion engines in urban areas. A crystal radio is one of the oldest and popular applications of ambient power collected from ambient Electromagnetic Radiation (EMR).

To understand the versatile nature of energy harvesting, we should first explain the storage node structure which gives an idea on the device characteristics and their properties which manage and provide harvested energy to communicate to the required network nodes. Sensor nodes are very helpful in decreasing the size of the system to a very small level by employing technology. It consists of:

- An embedded device having one or more than one sensing units (their operation is to sense the input variation and make a specific record in their database).
- A radio receiver which receives the transmitted signal such that its fidelity should be highly accurate.
- A processing unit which helps in analyzing the data received the system and to make out something productive from the overall system,
- One power unit.
- One energy predictor.

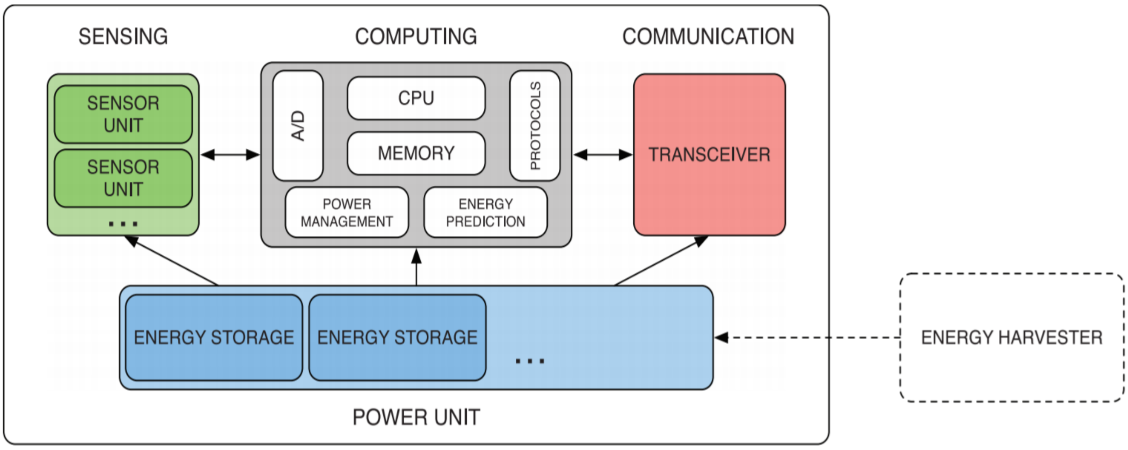

Figure 1.2 Energy Harvesting Node Architecture

A simplified energy harvesting system that employs various aforementioned attributes is neatly described in Fig. 1.2. The circuit used by energy harvester extracts the energy from the network and converts into the electrical equivalent either direct conversion or by use of some sort of converter. In the discussion, the latter one is described as the energy storage unit which provides the power harvested from the source to the required node whenever necessary. Furthermore, energy predictor is there to examine the amount of power that is available at each node and the contribution that it makes on the node. This concludes the performance index of the overall system using energy harvesting.

Power management is an essential tool to keep the devices channelized and transmission safe from any disruption in the network. While the work has been done on the energy harvesting devices, it is equally important to understand the basic nature of batteries. The energy-efficient conventions have prolonged the span of a general WSNs for environmental applications. Recent advancements in the wireless communication literature have shown that the RF signal sources donate energy to energy harvesting devices have opened a new path for exploring the Energy Harvesting in Wireless Sensor Networks (EH-WSNs). The task of an EH-WSN is to power the network node by the energy harvested during the span of charging such that it should preserve the connection over the transmission, thus call dropping is no longer an issue. In addition to this, EH-WSN is incorporated to obey the network laws so that each node can be timely serviced inside a network while keeping their privacy intact.

For over a decade we have seen sensor nodes being powered by batteries typically alkaline such as Nickel-Metal Hydride (Ni-MH), Lithium-ion (Li-ion), or Lithium Iron Disulphide (Li-FeS_2). These batteries have been studied to provide a constant output of nearly 2.1 volts which is a generic property of a primary cell. Compared to latter i.e., Li-FeS_2 are more popular to use because usually, we have studied the adverse properties of alkaline batteries that they are cheap, lower capacity and comparatively short lifetime. In the early 2000s, the concept of rechargeable Li-ion batteries have transformed the energy storage efficiency as battery capacity and its lifetime both are increased to nearly 150Wh/kg as earlier we would get off about 60Wh/kg. Thus Ni-MH batteries are more popular in the discussion due to such properties of regenerating power and rechargeability. Energy harvesting architecture of such technologies is typically interesting to study, as in this thesis we explored few architectures from which most suitable ones are as follows:

- Harvest-Use Architecture
- Harvest-Store-Use Architecture

The fundamental system which can justify the flow of energy distribution and conservation in the wireless energy network can be neatly illustrated by the diagram in Figure 1.3 and 1.4.

a) Harvest-Use Architecture

The energy harvesting system is based on an architecture where the sensing node is fed the energy from the energy source. Figure 3.4 shows that the energy source performs its usual operation in which it transmits the source power to the energy harvesting system where an energy harvesting system or element is directly in touch with the energy source. The source is transmitting the heavy powered signal which is subject to a fraction cut for energy harvesting in order to operate for the sensor node.

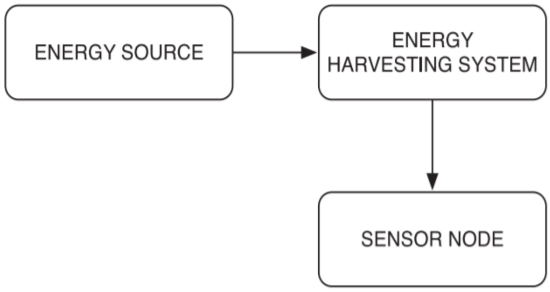

Figure 1.3 A sensor node architecture where the harvested energy is used directly to power the node

The sensor node is connected to energy harvesting system where it is recharged. The energy harvested from the energy source is completely used in transmission. This is the major drawback of this system that is the system is unable to account the energy which is required and which is not. It directly transmit the data accordingly the requirement without any negotiations with the energy source. The wastage of resources is done in this case as the practical scenario states that sensor nodes require very small amount of energy to operate and transmit information. The fraction of power which is extracted from the energy source is not fixed. This implies that there can be extra energy left after each transmission which can be stored and used for next transmission. Thus to overcome this drawback a new architecture known as harvest-store-use architecture is defined.

b) Harvest-Store-Use Architecture

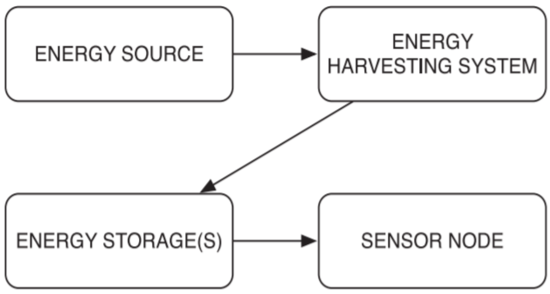

Figure 1.4 A sensor node architecture where the harvested energy is stored for later use in the sensor node

This mode of architecture has an additional component of storage device which stores the extra energy and thus it is more energy-efficient. The energy is strategically used and optimized for the use. The previous architecture resulted in few altercations so we require more reliable, sensible and optimal methodology of storage of energy. The harvest-store-use architecture is close to any possible ideal architecture where the main issue i.e., the wastage of energy is perfectly handled.

In this architecture, the data is released for transmission from the energy source. For typical operation we consider that the operations are being executed on the primary network successfully, now the energy harvesting system with a feedback path is connected to the system and does its work by taking a fraction of the energy transmitted by the energy source. The fraction of energy thus received is now taken care like a scarcity parameter. The energy is stored in a supercapacitor or any rechargeable device for that reason. This system is capable of accounting the energy required by the network and thus respond as per the requirement.

1.4 DEVICES & THEIR SIGNIFICANCE

Supercapacitors are widely used as energy storage devices as their operation same as that of the regular capacitor. The supercapacitor is different in physical properties i.e., consists of a larger surface area. As capacitance of a capacitor is directly proportional to the area of cross-section. This enhances the power density and energy capacity of a supercapacitor as compared to a regular capacitor. It is also found that the charging time of supercapacitor is better than an ordinary one.

We know that by the property of capacitance, any capacitor which is charging quickly shall also be discharged at the same rate thus a supercapacitor also discharges quickly. To compensate the effects of rapid discharging the device is modified to heavy charging cycle which will prevent quick discharging of the same. The modelling for the design of supercapacitor is one of major issue for EH-WSNs, which has encouraged the modern research to work more on the modelling of the properties as according to predefined assumptions.

Rechargeable batteries, on the other hand, are a different class of energy storage devices in which the lucrative property of such devices is high power densities, energy capacity, etc. Nickel-Metal Hydride (Ni-MH), Lithium-Ion (Li-Ion), and Lithium-Ion Polymer (LiPo, a Li-Ion rechargeable battery in a pouch format) are the usual type of batteries that are in use for the energy harvesting. Since sensor nodes are of versatile nature the nodes are designed in order to operate on various limitations. The nodes are subject to various conditions which define the better operability of rechargeable batteries over supercapacitors.

The optimal operation can be derived by the use of both rechargeable and supercapacitor due to properties like long lifespan, low-temperature sensitivity and working, large range of storage index. Supercapacitors and rechargeable batteries are also more classified on the basis of the reference index. This way of addressing is now in research for modification and give a better glance on the operability thus Table 1.2 gives a brief description of each device and their corresponding limitations.

Table 1.2 Comparison between Super-capacitors and Rechargeable Batteries

ENERGY STORAGE DEVICE	**ADVANTAGES**	**LIMITATIONS**
Supercapacitor	1. Much higher recharge cycle life. 2. High cycle efficiency (>95%). 3. Much longer lifetime compared to batteries. 4. Environment-friendly. 5. Broader range of voltage and current. 6. High performance in low temperatures.	1. Expensive 2. Low energy per unit weight. 3. Low per cell voltage. 4. High self-discharge rate. 5. High dielectric absorption.
Rechargeable Battery	1. Inexpensive 2. Low self-discharge rate. 3. High energy per unit weight.	1. Lower recharge cycle life. 2. Much lower lifetime.

1.5 THESIS OUTLINE

Chapter 1: INTRODUCTION: Presents fundamental laws of cognitive radio and their characteristics. It discusses an underlay model, basics of energy harvesting, architecture and storage devices.

Chapter 2: LITERATURE REVIEW: It discusses the energy harvesting cognitive radio models, throughput variations due to design parameters and battery-assisted wireless sensor networks. It presents existing work gives the motivation to study battery enabled underlay energy harvesting (EH) cognitive radio network (CRN).

Chapter 3: SYSTEM MODEL: Presents a well-labeled network layout of our proposed system. It defines basic notations used, specific definitions (e.g., PDF and CDF) and working of proposed model.

Chapter 4: NETWORK ANALYSIS: It defines critical attributes that examine the network performance to justify the network model structure, working, and reliability.

Chapter 5: RESULTS AND SIMULATION: It defines the coordinates of the system model, its parameters and determines the effect of interference power, total input transmitted power on the performance metrics.

Chapter 6: CONCLUSIONS: It concludes the proposed work, describes its significance in a practical scenario and discusses the future scope.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we look into the research papers which were crucial for obtaining a standard base for the project. This section summarizes prominent aspects from the existing literature relevant to the study to get a closer look into the modeling of the network model and define its characteristics suitably.

The idea of cognitive radio was first presented by Joseph Mitola III and Gerald Q. Maguire Jr. in 1999 [2], in the article "Cognitive Radio: Making Software Radios More Personal". They emphasized the lack of spectrum utilization and discussed theories to design a system which can meet requirements such as effective utilization of spectrum, computational resources, and energy management. Furthermore, the paper suggests that a cognitive radio is a tool by which a network technology can adaptively and dynamically lookout for the spectrum vacancy in wireless transmissions. It can enable more communication networks to perform communication simultaneously by improving their radio behavior. It uses approaches like adaptive radio (where the communication system itself monitors and improvises the performance) and SDR where analog components of the network are utilized in order to make intelligent software to access the spectrum.

In [3], the authors have discussed the various cognitive radio systems which employ relay node and found that the relay nodes are helpful in attaining a long-distance communication as compared to the non-relayed system. These relay nodes are defined between input and output of the network model in which a relay node is powered by the energy harvested at the input node. Each relay node is independent and carries a signal forward towards destination. There are three general relaying protocols which were studied in [3,5.6], are as mentioned below:

a) Amplify-and-Forward (AF): In this protocol, a signal is first collected from the transmitter and then it is stored at the relay which performs the amplification of the signal that enhances the power and maintains the signal strength required to travel a certain distance. This methodology is found to be more flexible and has a lower cost of infrastructure.

b) Decode-and-Forward (DF): In this protocol, the relay node decodes the signal received from the input, encodes it in way that the encoded signal is now different from what sender had originally sent. It then retransmits to the receiver so that the overall security aspect of the network is improved. The main drawback of this protocol is that it takes a lot of time to decode which requires more computational power.
c) Compress-and-Forward (CF): In this protocol, the signal received is first compressed by the relay node which then encoded and transmitted to the receiver. The signal redundancy received from the input signal is increased using this protocol.

In paper [7,13], the two most common channel fading models used were are namely, Rayleigh fading and Nakagami-M fading. The research was based upon the MIMO system which employed a Rayleigh faded channel configuration and determines the network parameters by varying the channel coefficients. Rayleigh fading is very similar to chi-square distribution which is helpful in the analysis of multipath fading system, Also, a radio link contains reflected and the refracted paths which are best explained using Rayleigh fading model. On the other hand, the authors mentioned that Nakagami-M Fading is widely used in cognitive radio where relay networks are designed for indoor and land-mobile multipath radio link propagation. To study the various channel fading model it is necessary to address some commonly used channels which are as described in [9]. Initiating with the Discrete Memoryless Channel (DMC) which is a set of n simple transmitter-receiver systems, the communication takes place using codewords between each transmitter and receiver pair with n channel uses (each input symbol per channel use). The receiver is then subject to a decoding algorithm which is applied on the received signal which is a combination of the original transmitted signal and noise.

According to [11], another commonly used channel is AWGN channel in which the received signals at the primary receiver node are considered as Y_1 and Y_2 which are related to the transmitted signal of the primary transmitter X_1, X_2 as shown below:

$$Y_1 = X_1 + h_{21} \cdot X_2 + N_1 \tag{2.1}$$

$$Y_2 = h_{12} \cdot X_1 + X_2 + N_2 \tag{2.2}$$

where, h_{12}, h_{21} are the fading coefficients (quasi-static) and are available prior to the communication between transmitter and receiver just to make sure the security of channel remains intact. For simplicity, we can assume that $h_{11} = h_{22} = 1$ and the corresponding rate of transmission are calculated in bits/channel use.

According to [7][11], in case of for a large cognitive radio network, it assumes that the Gaussian noise and fading paths are independent of each other. In [24], the author referred sum-rate as throughput-sum which is defined as the sum of all the transmission rates in the network which may or may not is simultaneously be achieved. The diversity of throughput-sum laws is also discussed which emphasizes on the fact that there is a scarcity of channel bandwidth. In a practical cellular network, the interference increases considerably due to the increase in the number of nodes which may lead to huge loss of information during communication. To overcome such huge loss, sum throughput scaling laws have been implemented which concluded that, when one simply wants to communicate, assuming multi-trans receiver network with highly packed density, then each one of the nodes asks other nodes to share the sum-rate scales as the function of the number of nodes n. The number of nodes n is allowed to increase which means that the density of a cell shall be increasing as $n \to \infty$. Moreover, the area of congestion shall also expand linearly with n. Since we are aware of node limitations such as power management, node density, and hopping algorithm, multiple mid-way transreceivers shall be required to perform complete transmission.

As proposed in [24], the fundamental of throughput-scaling is dependent upon the arrangement of nodes, node structure, and physical-layer processing capability. Thus in case of an ad-hoc network, it is assumed that the scaling is affected due to a number of reasons as mentioned below:

- When it is assumed that the signal at the input node is Poisson distributed, the scaling laws result in the scaling of per-node rate by a factor of $\frac{1}{\sqrt{n}}$.
- In the case of a MIMO system, linear growth in sum-rate is observed while the throughput of the system is at a constant value.
- For uniform distribution input signal, by applying schemes like nearest-neighbour forwarding a per-node throughput of $\frac{1}{n \cdot \log(n)}$ $Bits/s/Hz$ is practically achieved.

- In the last case, where the network is interference based where the cooperation is restricted in the communication. Therefore, per-node throughput is scaled by a factor of $\frac{1}{\sqrt{n}}$.

The advancements in the above stated scaling laws conclude that the nodes are highly sensitive to throughput variations in case of input signal distributions [22]. We shall conclude a unique scaling parameter in the following sections to determine the exact throughput variation in the network by the help of some predefined experiments. The cognitive radio is designed such that it utilizes all the constraints, influencing factors and scaling laws to obtain an optimized employable wireless communication network.

Energy harvesting has been discussed in [17][18][20] which suggests that, in general, it is the highly profitable implementation of nodes in wireless networks. In [19], the authors discussed that there is the number of energy harvesting techniques out of which time switching and power splitting technique has been mostly adopted in the practical scenario. In [20], energy harvesting from ubiquitous RF signal was demonstrated, which according to the authors is useful in charging devices in places like the jungle, remote areas or where there is lack of electricity utility. Moreover, their study suggests that the RF signals have lesser power which poses big challenges to energy harvesting and its use. The experiment could harvest a RF signal from 1-mile distant transmitter that generates a field-strength of 103.724 dBu (decibels or dB referenced to 0.775 volts) at the location of the receiver. The maximum charge on storage capacitor achieved was recorded 2.8V. In [8], a multiple-input-multiple-output(MIMO) underlay system utilizing spectrum sensing is studied, that is a secondary node can harvest energy from the primary user and then utilize the energy in transmission and for its own working. The study provided optimum signal-to-interference-noise ratio as a variation of interference power of the network. Some trade-offs have also been proposed in [10] which are vital to understanding the perfect balance between optimal-time switching factor and the energy-rate. The analysis reveals that the secondary system can be operated by harvesting a sufficient amount of energy in each cycle without hindering primary transmission. In order to maximize the efficiency, there are several methods which are discussed in [12], where a transmitter node is modified such that it reduces internal power consumption and gives better throughput for the overall system.

Energy harvesting in a cognitive relay network has been performed [18], in which underlay mode of transmission is used. The transmission is occurring such that the secondary network is reliably harvesting sufficient amount of energy needed for secondary network (SN) transmission. A similar model has been discussed in [14], where transmission in the secondary network maintains a table of required energy data at each node which is manipulated so that the throughput of the system becomes optimal. In this particular research, each node consists of a separate sensor which although requires energy, smaller in comparison to the energy required to operate. A particular model in which there is low-power communication in secondary network is studied in [17], which shows that primary transmitters (PTs) reside in a guard zone and energy harvesting zone due to node mobility, due to which an ST can harvest energy if the primary transmitter is near, and transmits fixed amount of power when it lies outside the guard zone. The work was performed for a Wi-Fi network which has multiple hotspots at different locations and has its own area under which it can support any secondary node (SN). Thus, the research concludes ST transmission probability is increased by installing a number of Wi-Fi hot spots. On the other hand, there are studies which are exclusively done for non-RF signal and ambient sources which discuss sensing decisions and collision probability. The work provides a model in which CR harvests energy from various energy-rich ambient sources and primary user signals by using sensing decisions. The sensing decisions are obtained as per the sensing matrix which defines the probability of a node to be chosen in the next cycle. The quality of Service (QoS) of PU is protected in this process whereas to guarantee the performance, various sensing parameters are defined such as collision probability, sensing channel SNR, sensing time, etc. There are studies which emphasize on the different transmission modes namely delay-sensitive mode and delay-tolerant mode [1]. The former one states that the channel is transmitting at a fixed rate of information and requires predefined energy in each cycle whereas the latter one states that for each cycle, the information rate is highly sensitive to the input signal at the transmitting node. For example, in [1] the network is evaluated over the performance of outage probability and its variation over the dependent variable namely interference power and total input transmitted power at the primary transmitter. The discussion is highly interesting when talking about the throughput of the system. Throughput is a measure of reliability in wireless communication networks. It determines whether a network is suitable to be implemented in the practical scenario because if it is not so, then designing such a network is a waste of effort for any system. The throughput of the system was observed for the delay-sensitive and delay-tolerant mode.

In [21], a basic implementation of a battery-based cooperative network has been performed in which there are four main classifications for the study of battery status as mentioned below:

- When the battery is empty (which may be either occur when battery consumes all power left for transmission or at the start of transmission).
- When the battery has finite energy but couldn't transmit due to a threshold limit.
- When the battery is full due to charging in the harvesting cycle.
- When the battery has finite energy but greater than the threshold limit so that it can allow transmission.

Furthermore, battery supported architecture hold greater reliability than ordinary system [19] because it adds more constraints during communication which gives precise, better and more pragmatic results. In [20], it is observed that the amount of harvested energy is variable and it also discusses the various limitations of energy sources (for example, the solar energy source is unable to generate energy in the night). This reason has given rise to designing of a whole new individual network on energy harvesting architecture, also known as energy-neutral operation (ENO). In energy-neutral operation, it is assumed that the energy harvested by the sensor node is typically larger by few units than that required by it, as the sensor node shall never be deficient of the power supply and shall always be able to operate in any condition [22][26]. Hence the implementation of network in the practical scenario is a challenging task and is very difficult to achieve. To satisfy the great task by the ENO, various techniques have been proposed [25]. As an example, design of an adaptive system, which utilizes the information related to the energy required by the sensor nodes was proposed. This will make ENO able enough to predict the main flow of energy distribution for the sensor node.

To monitor the sensor node, operations are designed on the basis of reactive approaches which adjust the aspects of node response in the harvesting architecture. Existing models are designed with the help of a few machine-learning algorithms to analyze the system and make a proper decision on the question of energy monitoring convention.

To rightly understand the significance of the energy storage, the power management schemes [23] are scheduled to be matched with the ENO. Some of the popular schemes which are in work in the current space are as follows:

- Dynamic Power Management (DPM)
- On-Demand Medium Access Control
- Joint Energy-Harvesting and Operation Scheduling
- Energy Synchronized Communication
- Harvesting-Aware Utility-Based Sensing Rate Allocation Algorithm

Additionally, methods such as duty cycling and adaptive sensing, adaptive control topology regulator, obliging transmission, frame length optimization, adaptive throughput, and mean suspension optimal energy-neutral policies have been proposed [26] for EH-WSNs to exploit the performance of the network. Adaptive duty cycling or control are mechanisms that allow the energy-harvesting sensor nodes to unconventionally regulate their duty cycle (that is, stirring the sensors) according to the energy requirement in the working environment. In this case, the nodes are presumed to have prior information on the energy profile. Since energy storage devices have the inadequate capacity and are inclined to energy seepage, it is not always advantageous to maximize well-preserved energy, especially when excessive energy could be obtained. It trusts on this fact to recommend an energy synchronization communication (ESC) practice that aims to minimalize the communication delay in the EH-WSNs through dynamically synchronizing the node's commotion patterns or working schedule with the achievable energy budget and simultaneously achieving energy-neutral operation (ENO). To signify the amount of harvested energy accumulated from the environment and the disturbance in the magnitude of power supply, can be useful for aforementioned power management techniques to estimate the required energy used for signal processing, sensing and employing power managing tools in WSNs. Also, an energy clustering protocol which maintains equal clustering of the network is also helpful.

The literature survey helped us gain a better insight with reference to the energy harvesting in cognitive radio with a relay-assisted network, various techniques to avoid congestion and maintaining good throughput for the wireless communication network. It illustrated the channel parameters and their behaviour on the performance of the network, where each channel corresponds to its own protocol. The design of the channel is studied in detail in the next section. Observing the work so far, it is found that cognitive radio has played an important part in this domain of research. The fact still remains; the performance metrics and accuracy achieved so far needs more improvement and modifications. It is also seen that relay is unnecessarily causing few disadvantages such as trying to breach the information, might result in loss of signal due to its working and/or result in damaging the hierarchy of the network. The new work can be done by focusing on this critical point. The striking and most important finding from the survey is that much of the cognitive radio energy harvesting has been done with relay network without any practical significance given to battery storage. The battery implementation would highly enhance the throughput and with that, the outage probability will get a fine precision line in its characteristic curve. In case of infinite battery model, SS transmits data in each cycle without monitoring a node is sufficiently charged or not. Whereas, in case of finite battery SS transmits data only when SS has sufficient energy for transmission. Thereby a sophisticated model which can adhere to the properties required by the sensor nodes is very difficult to obtain. In general, while wireless sensor networks are obeying basic network properties to follow the ENO, the major challenge is to make sure the protocols are being followed. The cause of this problem is dependent on various nodes i.e., an energy harvesting storage device should consider the network as a whole rather than an individual node as a whole. It means that an individual node shall not be able to provide sufficient energy distribution in comparison to a network consisting of a large number of nodes. As the environmental extraction of energy is huge and variable, a suitable model which can detect the necessary changes and predict the supervisory effects on the network can be useful for the work. Such a model will require a lesser amount of time and complexity of the operation. The discussion doesn’t end here itself as the technology is being revamped on its own each day. To account a few, wireless networks with recharging capability are also being introduced also commonly known as Wireless Rechargeable Sensor Networks (WRSNs). We take this opportunity to exploit this window of modification in the base model and hence obtain a working network model which refines the existing literature to ensure a practically reliable wireless communication network.

CHAPTER 3

SYSTEM MODEL

In this chapter, we discuss the various design characteristics of cognitive radio energy harvesting model which are capable of storing the energy in energy storage devices. The modelling involves the physical coordinates of system attributes, their channel properties, distribution, etc. Later we also comment on the productivity of the system as well as the basic outline of the final network.

3.1 NETWORK LAYOUT

On the basis of available research and literature, in order to design the network the architecture of the system is based on the proximity with the secondary network [1]. In network model, we shall consider a MIMO system in which there are several number of transmitters and number of receivers in both the networks namely PN and SN. The MIMO system communicates independently i.e., the user from the primary network transmits the data encrypted for the user at the receiver end of the PN. Similarly, a user at the SN transmits towards the user at the receiving end of the SN. The main property by which both of them are connected is that the PN and SN shall share common frequency band which signifies the sharing spectrum phenomenon. The PN and SN communicate for various purposes like energy harvesting, spectrum access, and power control. The nodes are designed such that they can transmit and receiver via same structure built-in themselves and wouldn't require any additional node for the same. The receiver end is assumed to be highly sensitive, tuned to the predefined frequency with an assumption that no losses are made in the transmission of the data throughout the process. The transmitter is also allowed to transmit data to the receiver present in the same network without incurring any loss at transmission end. In case of SN, we have assumed that it is a single node structure which consists of a single node present at both the transmitter end and the receiver end. These nodes are equipped with energy storage devices as already discussed in Chapter 2. SN is dependent upon the energy harvested from the RF spectrum of the PN for transmission of data. It is necessary to study the network parameters of both the networks to further define their characteristics. The channel is characterized by Rayleigh fading model while the link gain parameters are also studied [1]. Now, assume that there is a number of transmitters grouped together in the form of cluster and which behaves as the point to a dense network, similarly, assume that there is a number of receivers grouped together which also as a cluster behaves as the point to a dense network. The receiver and transmitter designed in the mentioned paper are also subject to the same conditions and thereby the basic outline of the considered network is derived from the [1]. Though, there is a vast scope in modelling of battery, thus as of now, we have assumed that the battery is also residing inside the node architecture i.e., now a node shall be incorporating the node design, transmitter design, variable losses, battery storage device and other miscellaneous elements of the system. The overall network can be illustrated in Figure 3.1. The network is highly similar to as that of [3], where we have made few modifications to make sure that the system is designed to produce a good response to the network transmissions and provide a better insight to the critical aspects of the wireless communication system.

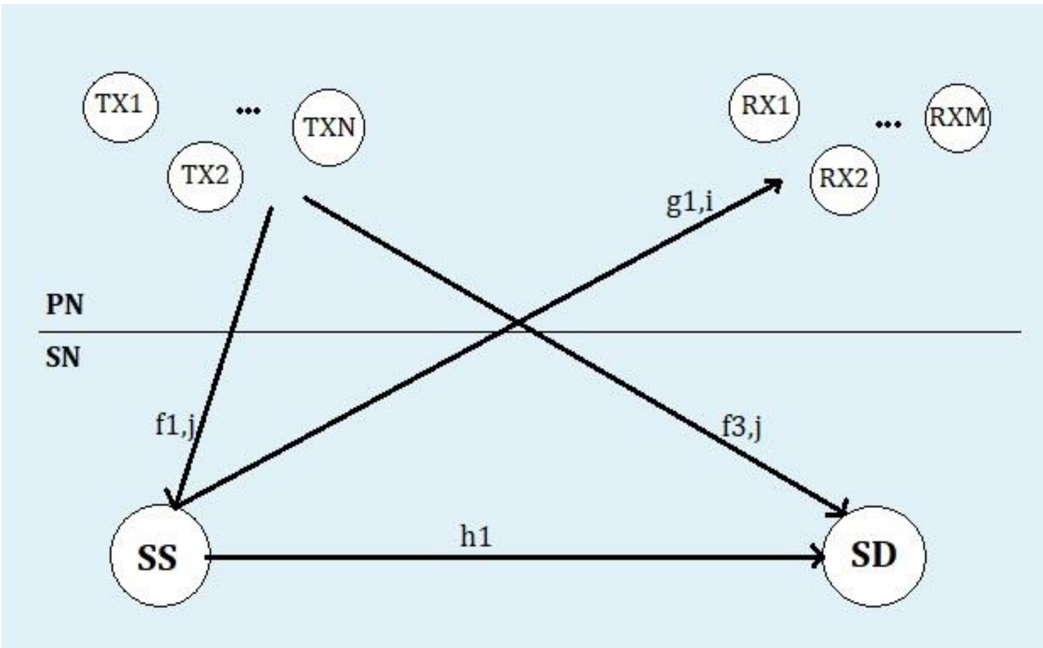

Figure 3.1 System model of the energy harvesting cognitive radio system

In Figure 3.1, we can see that there are two different networks namely primary and secondary, which further consist of their respective transmitters and receivers. These transmitters and receivers are also classified as the centre point to the number of transmitters and receiver inside it. A dense network is considered for better utilization of the space and faster communication within the cell. We know that the clustered network will be more capable to utilize bandwidth efficiently in comparison to a distributed network. In this scenario, less component like the directional antenna, omnidirectional antenna, beam analyzer, channel adapter, etc is required which only increases the cost of the network. The proposed network model here is economically efficient and manage trade-offs if any.

3.2 NOTATIONS AND ORGANIZATION

Consider a PN in which there are N number of transmitters at the input node, say $TX_1, TX_2, TX_3 \dots \dots \dots . TX_N$. Similarly, consider a SN in which there are M number of receivers at the output node say $RX_1, RX_2, RX_3 \dots \dots \dots . RX_M$. Now, as we mentioned that the receivers and transmitters are distributed densely around a centre point thus we can assume that their individual properties and characteristics are also identically distributed as the network is very small in size. We now consider that the N number of transmitter residing densely at a fixed coordinate shall be referred by PU_{tx}, whereas the M number of receivers residing densely at another different fixed coordinate shall be denoted by PU_{rx}. For further discussion of the network, we consider the PN transmitters to be PU_{tx} and PN receivers to be PU_{rx}.

In order to observe the channel characteristics, we must define the channel gain coefficients of the network i.e., parameters which signify characteristics of each path mentioned in the above layout. The channel gain coefficient from a secondary source (SS) to the i^{th} PU_{rx} is defined by $g_{1,i}$ for $i = 1, 2 \dots \dots \dots M$. Let us say that the channel gain coefficients from a secondary source (SS) to the secondary destination (SD) can be denoted by h_1. Similarly, channel gain coefficients from the $j^{th} PU_{tx}$ to SS and SD, are represented by $f_{1,j}$ and $f_{3,j}$ for $j = 1, 2 \dots \dots . N$, respectively. The distances between each node is an essential parameter because distance of separation defines channel distribution. We denote the distance between the $j^{th} PU_{tx}$ and SS and SD as $d_{1,j}$ and $d_{3,j}$ respectively. The representation of the distance between SS and the i^{th} PU_{rx} is denoted as $d_{4,i}$.

Furthermore, the distance between SS to SD is denoted as d_6. The link gain realizations $|h_1|^2, |g_{1,i}|^2, |f_{1,j}|^2$ and $|f_{3,j}|^2$ are exponentially distributed with parameters $\lambda_1, \omega_{1,j}, \nu_{1,j}, \nu_{3,j}$ respectively. For example, $\lambda_1 = {d_6}^{-m}$, where m is the path loss factor. The link gains from the PU transmitters to the SS and SD are assumed to be identically distributed, i.e., $\nu_{1,j} = \nu_1$, $\nu_{3,j} = \nu_3$ for $j = 1, 2 \dots \dots \dots . N$. Similarly, the link gain realizations from SS to the PU receivers are assumed to be identically distributed, i.e., $w_{1,j} = w_1$ for $i = 1, 2, \dots \dots. M$. All channels are assumed to be quasi-static Rayleigh fading channels where the channel coefficients are constant for each transmission block but vary independently between different blocks.

Although we have described the main nodes and their architecture, there are several parameters which are essential to understand Firstly, the total time period one cycle in communication is taking place is given by T. The time period T includes the transmission from SS to SD including the information exchange, battery charging, and energy harvesting cycle. Let time slot allotted to EH is represented by variable α. It defines the amount of time period being used for harvesting the total energy from the PN. Also, it is necessary to know that the value of α should not exceed 1 since it is a fraction thus $0 < \alpha < 1$. In this network, an energy-constrained SS is transmitting the message to an energy-constrained SD through direct communication with the help of spectrum sharing with PN. Both the SS and SD are powered by the PU transmitters and thus they don't have any other medium of energy generation in them. The rechargeable batteries or supercapacitors used in the network are allowed to store the extra energy harvested during the EH interval. We have stated that the SN share the network with PN following the underlay mode of cognitive radio as mentioned in Chapter 1. The underlay network model of cognitive radio briefly states that the system must perform communication in such a way that it should be able to keep the power below the threshold defined by P_I. It is also assumed that all the power is utilized for transmission without any internal losses. The primary network is described as the cluster of input nodes where the total input transmitted power in PN is denoted by P_{PUtx}. Each node is unique in its respective distribution while the network is heavily dependent on the number of attributes. Let us denote parameters related to power distribution thus, the transmit power at SS can be denoted as $P_{s.}$ Energy harvested at the SS is a random variable defined by E_{hs}. The interference threshold power below which SN can perform transmission is defined by P_I.

To comment on the noise performance, we consider SN in which SNR is observed at the SD, denoted by τ_{SD}. The SN harvests energy from PN with a conversion rate known as conversion efficiency η. The system is prone to any external effects or disturbances, typically due to noise thus, to overcome such scenarios, there are few assumptions have been made to analyze the exact noise structure whose variance is defined by σ_n^2. The threshold required to define a successful communication can take one or more values as per the experimental requirements therefore, denoted by γ_{th}. The mathematical modeling of the network is briefly described in the forthcoming chapter while few random variables and arbitrary variables, which are required for the derivation purpose, are defined, e.g., $\rho = \frac{2\eta\alpha}{(1-\alpha)}$.

The distances and channel gain coefficients result in a random variable, which has its own distribution and characteristics. For properly defining all the aspects of network few random variables are assigned with predefined Probability Density Function (P.D.F) and Cumulative Density Function (C.D.F) which helps in deriving the closed integral equation. To discuss theses, let us consider the channel between SS and SD, this channel relies on the channel gain coefficient h_1 which, if we consider for distribution corresponds to the random variable X.

$$\mathrm{X} = |h_1|^2 \tag{3.1}$$

Its PDF is given by:

$$f_X(x) = \frac{1}{\Omega_1} e^{-\frac{x}{\Omega_1}}$$

…(3.2)

and its CDF is given by:

$$F_X(x) = 1 - e^{-\frac{x}{\Omega_1}}$$

…(3.3)

To classify further, the distance between SS and PU_{rx} is defined to have a channel gain coefficient $|g_{1,\mathrm{k}}|$ for $k = 1,2 \ldots\ldots\ldots..M$. We define some random variables which are used in the derivation in the next chapter.

$$\mathrm{Y} = \max|g_{1,\mathrm{k}}|^2$$

(3.4)

Its PDF is given by:

$$f_Y(y) = \frac{M}{\Omega_4} \sum_{k}^{M-1} \binom{M-1}{k} (-1)^k \cdot e^{-\left(\frac{k+1}{\Omega_4}\right)y}$$

…(3.5)

and its CDF is given by:

$$F_Y(y) = \left[1 - e^{-\frac{y}{\Omega_4}}\right]^M$$

…(3.6)

The primary transmitter is the main source of energy for SS and SD, which requires the threshold power limit value to be highly precise in order to give accurate results. The outage probability majorly depends on these oefficients and thus to symbolize the random variable corresponding to these coefficients, we denote them by Z_1 and Z_2 as mentioned below:

$$\mathrm{Z}_1 = \sum_{j=1}^{N} P_{PUtx} \left|f_{1,\mathrm{j}}\right|^2$$

…(3.7)

$$\mathrm{Z}_2 = \sum_{j=1}^{N} P_{PUtx} \left|f_{3,\mathrm{j}}\right|^2$$

…(3.8)

Their PDF is given by:

$$f_{Z_p}(z) = \frac{z_p^{N-1}}{\Gamma(N) \cdot \left(P_{PUtx}\, \Omega_p\right)^N}$$

…(3.9)

and their CDF is given by:

$$F_{Z_p}(z) = \frac{\Gamma\left(N\,,\ \frac{z_p}{P_{PUtx}\, \Omega_p}\right)}{\Gamma(N)}$$

…(3.10)

Where $p = 1, 2$ for Z_1 and Z_2 respectively.

The fundamental description and notation of parameters used in the system have been shown, whereas if any other distribution or any other random variable is required, then the classification is done in Chapter 4.

3.3 WORKING

The fundamental working of the given network is based on the fact that the cognitive radio network is employed with energy harvesting and the nodes performing the energy harvesting are the ones which are equipped with the supercapacitor or rechargeable devices which can store and use the energy later.

SS Harvest Energy / **Battery Charging**	**SS transmits the information to SD**
αT	(1- α)T

Figure 3.2 Protocols at SS in one EH-IT time slot

It is observed that at the start of the process PN is energy-rich and transmits data from the transmitter to receiver. The transmitter of the primary network is generally an energy source for the SN, therefore the SN is dependent on the energy harvesting from PN. The SS is allowed to perform spectrum sensing through which it will be allotted a specific channel in the primary user`s licensed frequency band. The band is allotted such that it doesn't disturb the communication of PN since the cognitive radio technology has been used in which the band allocation is mostly dynamic in nature. Therefore, it results in faster switching and transmission of the data. The SN which is equipped with the battery at its respective nodes undergoes charging which energizes the battery of individual nodes. The nodes which acquire sufficient amount of energy during the process of energy harvesting transmits the data to the SD and if it is not the case then it stays in the same spot to harvest more energy from the PN in the next cycle. The overall flow chart of the work is illustrated in Figure 3.3. It describes the essential steps and the key points taking place. In the EH cycle, the SS and SD charge their batteries for αT amount of time period whereas SS transmits the information to the SD for the remaining duration of $(1 - \alpha)T$. The SN is not allowed to transmit data at a power greater than interference threshold power P_I. The battery is used to store the necessary power which is used in the transmission of consequent data packets. The secondary network keeps the record of the battery level and updates changes if any.

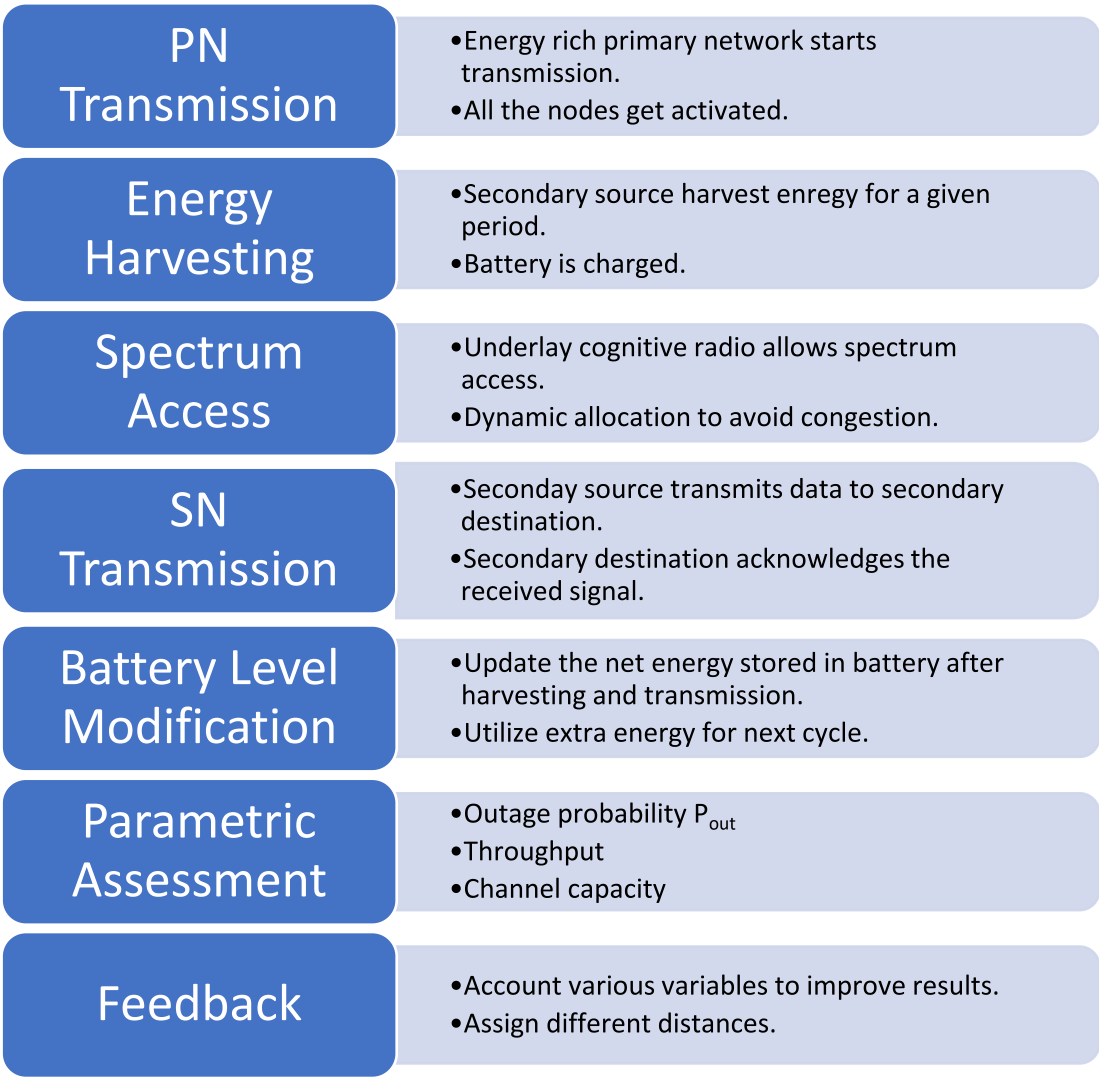

Figure 3.3 Flowchart representing critical stages of operation.

The communication depends on various parameters which classify the two cases, either outage or successful trasmission. The former one states that the transmission of data from the transmitter to receiver is not successfully performed due to various factors like low battery, threshold negligence, etc. The latter one states that the communication between SS and SD is secured and obeys all the protocols which guarantee the successful transmission of the data. The PN is independent and doesn't have any constraint on transmitting power. The SN, on the other hand, is restricted to few constraints and thus require guidance during transmission. The SD evaluates time for which system is not able to transmit i.e., outage. The parameter which are used to classify the outcomes are outage probability, throughput, and channel capacity. These three parameters shall be able to explain the system design and if any modifications are required then we can substitute them accordingly.

CHAPTER 4

NETWORK ANALYSIS

In this chapter, we define the attributes upon which the reliability of the network is judged. The network is subject to a number of conditions as per Chapter 3, thus to evaluate the performance and sustainability, we must observe the suitable performance metric's variations in accordance with system parameters. The proposed mathematical model and the respective derivations are presented in this chapter.

4.1 PERFORMANCE METRICS

In the previous chapter, we have defined the system model which is subjected to a few network constraints following which the system shall be called reliable enough to operate in a practical scenario. To comment on the stability, sustainability, and reliability, we study few performance parameters which give support to the corresponding work. Parameters are to be decided such that they classify the network critically on the basis of the fact that the SS is successfully transmitting the information to SD without any problem in the transmission. In wireless communication literature, the hunt for the suitable metric is challenging and thus by studying few, we have come up with elementary performance metrics given as follows:

- Outage Probability
- Throughput (delay-sensitive mode)
- Channel Capacity

In further discussion, we shall elaborate the terms and their significance which provide a better insight into the performance assessment of the system.

4.1.1 OUTAGE PROBABILITY

The outage probability P_{out}, is defined as the probability that the equivalent SIR at each hop is below a threshold value, γ_{th}. In this experiment, the cognitive radio non-relay assisted spectrum sharing network is considered to be in an outage, if one of the links is suffering from an outage. In this proposed scheme, we tend to determine the lower limit of P_{out} and assume that both processes i.e., battery state and energy harvesting are independent of each other. i.e.,

$$P_{out} = P(\Gamma_{SD} < \gamma_{th}) \quad (4.1)$$

Where, τ_{SD} denote the SIR random variables from SS to SD which can be defined as:

$$\Gamma_{SD} = \frac{P_s \cdot |h|^2}{P_{PUtx} \cdot |f_{3,j}|^2 + \sigma_n^2}$$

…(4.2)

Consider $\sigma_n^2 = 1$ therefore,

$$\Gamma_{SD} = \frac{P_s \cdot |h|^2}{P_{PUtx} \cdot |f_{3,j}|^2 + 1}$$

…(4.3)

Recalling Chapter 3, where we defined few random variables and from Equation (3.1, 3.7), we have

$$\Gamma_{SD} = \frac{P_s \cdot X_1}{Z_2 + 1}$$

…(4.4)

$$\Rightarrow \qquad P_{out} = P\left(\frac{P_s \cdot X_1}{Z_2 + 1} < \gamma_{th}\right)$$

…(4.5)

Where P_s is defined as the transmit power at SS and is given by expression as:

$$P_s = \min\left(\frac{E_{hs}}{(1-\alpha) \cdot T}, \frac{P_I}{\max |g_{1,j}|^2}\right)$$

…(4.6)

$$\Rightarrow \qquad P_s = \min\left(\frac{E_{hs}}{(1-\alpha) \cdot T}, \frac{P_I}{Y_1}\right)$$

…(4.7)

Now, we know that the energy harvested E_{hs} is a critical function of stored energy and the transmitted power of PU, therefore the expression for E_{hs} is a function of maximum battery storage capacity i.e., B_{max} and the instantaneous energy E_i. Suppose, the instantaneous energy harvested in the battery is derived with some conversion efficiency, rate of consumption and PU total input transmit power. Therefore the an harvested energy E_i can be written as:

$$E_i = \sum_{i=1}^{N} P_{PUtx} \cdot \left|f_{3,j}\right|^2 \cdot \eta \cdot \alpha \cdot T$$

$$\Rightarrow \qquad E_i = Z_1 \cdot \eta \cdot \alpha \cdot T \tag{4.8}$$

Now, the expression for energy harvesting E_{hs} shall be given as,

$$E_{hs} = min\ [B_{max}\ , E_i\ ] \tag{4.9}$$

Now, from Equation (4.5) and (4.7), the expression for outage probability can be summarized as

$$P_{out} = P\left(\frac{P_s \cdot X_1}{Z_2 + 1} < \gamma_{th}\right)$$

$$P_{out} = P\left\{\frac{\min\left(\frac{E_{hs}}{(1-\alpha)\ \cdot\ T}, \frac{P_I}{Y_1}\right)\ \cdot\ X_1}{Z_2 + 1} < \gamma_{th}\right\}$$

…(4.10)

To simply the equation complexity, let us define a new random variable V,

$$V \triangleq \frac{E_{hs}}{(1-\alpha)\ \cdot\ T}$$

…(4.11)

$$\Rightarrow \qquad V \triangleq \frac{min\ [B_{max}\ , E_i\ ]}{(1-\alpha)\ \cdot\ T}$$

…(4.12)

$$V \triangleq \frac{min\ [B_{max}\ , Z_1 \cdot \eta \cdot \alpha \cdot T\ ]}{(1-\alpha)\ \cdot\ T}$$

$\therefore$

$$P_s = \min\left(V, \frac{P_I}{Y_1}\right)$$

…(4.13)

Substituting Equation (4.10) and (4.11) in Equation (4.13), we get

$$P_{out} = P\left\{\frac{\min\left(V, \frac{P_I}{Y_1}\right) \cdot X_1}{Z_2 + 1} < \gamma_{th}\right\}$$

…(4.14)

$$P_{out} = P\left\{\min\left(V, \frac{P_I}{Y_1}\right) \cdot X_1 < \gamma_{th} \cdot (Z_2 + 1)\right\}$$

$$P_{out} = P\left\{\min\left(V, \frac{P_I}{Y_1}\right) < \frac{\gamma_{th} \cdot (Z_2 + 1)}{X_1}\right\}$$

…(4.15)

Let us consider

$$\xi \triangleq \frac{\gamma_{th} \cdot (Z_2 + 1)}{X_1}$$

$\Rightarrow$ $$P_{out} = P\left(\min\left(V, \frac{P_I}{Y_1}\right) < \xi\right)$$

$\therefore$ $$P_{out} = P(V < \xi) + P\left(\frac{P_I}{Y_1} < \xi\right) - P\left(V < \xi, \frac{P_I}{Y_1} < \xi\right)$$

…(4.16)

The closed-form of outage probability can be found in Appendices (Appendix 1,2 and 3).

4.1.2 THROUGHPUT

The throughput is evaluated in delay-sensitive mode. It determines the efficiency of the network to successfully transmit a signal to the receiver. Throughput is always expected to be large (or increasing graph) for a reliable network. The evaluation of throughput provides insight into practical implementations and challenges of EH cognitive relay network.

$$\Gamma_{ds} = (1 - \alpha) \cdot R_{ds} \cdot [1 - P_{out}(\gamma_{th})]\ bits/s/Hz \quad (4.17)$$

Where R_{ds} is defined as the information rate from SS to SD and given by,

$$R_{ds} = log_2(1 + \gamma_{th})\ bits/s \quad (4.18)$$

4.1.3 CHANNEL CAPACITY

It is defined as the rate (bits per sec) below which a signal can be reliably transmitted over the channel, and it is given by the formula below:

$$C = B \cdot log_2\left(1 + \frac{Signal\ Power}{Interference\ Noise\ Power}\right)$$

$$\Rightarrow \qquad C = B \cdot log_2(1 + \mathrm{r}_{SD})\ bits/s/Hz \qquad (4.19)$$

4.2 SUMMARY

Small value of outage probability is required for a reliable network model. Outage denotes that the receiver didn’t receive the packet due to insufficient signal power or we can say noise dominance. Outage probability is highly affected by the interference power P_I. Thus, a signal is pre-processed to have a high amplitude and good range to travel without getting attenuated by noise during the transmission. On the other hand, the throughput of the network defines the performance of the overall cycle i.e., whether the signal has been received completely at the receiver.

Channel capacity determines the amount of information a model can carry. It should be very large for a reliable network. In general, there are large number of users in this type of communication system. More users imply that the network consists of a large set of distances and channel gains which contribute to an efficient network.

CHAPTER 5

SIMULATION AND RESULTS

In this chapter, we discuss the simulation of the EH-CRN model and various system parameters which determine the efficiency of the overall system. Also, we define the positional coordinates at which we place PU and SU, by virtue of which the exact distribution of the channel gain coefficients is determined. We show the outage probability and the throughput as functions of P_I, P_{PUtx}, and the position of PU_{tx}. For slight changes in parameters, we present promising results to implement this model in a practical scenario.

5.1 SIMULATION DATA

In the designing of the network model, we have four major nodes which are assigned with their respective coordinates.

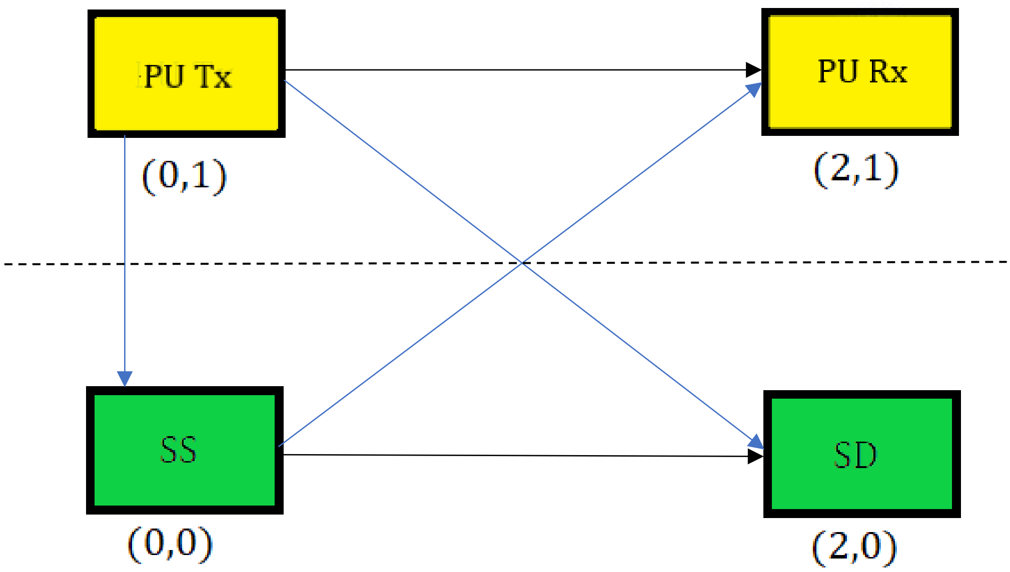

Figure 5.1 Coordinate Model of Proposed System

The nodes represent the PU transmitter, PU receiver, SS and SD. The coordinates which are $(0,1), (2,1), (0,0), (2,0)$ respectively. The schematic arrangement of the network can be neatly illustrated from Fig. 5.1.

The arbitrary parameters such as time slot for EH, conversion efficiency and other critical definitions which are assigned a constant value are also listed in the table below.

Table 5.1 Parameters Name, Symbol and Value Assignment

Parameter Name	Symbol	Relation	Value
EH-IT time slot	α	-	0.5
Conversion efficiency	η	-	0.8
Rho	ρ	$\frac{2\eta\alpha}{(1-\alpha)}$	1.6
Path loss factor	m	-	2
Total transmitter power	P_{PUtx}	-	0dB or 1W
Total number of PU transmitters	N	M	3 (variable to 10)
Total number of PU receivers	M	N	3 (variable to 10)
Noise variance	σ_n^2	-	1
Distance from SS to SD	d5	-	2
Distance from PU Tx to PU Rx	d4	-	2
Distance from SS to PU Tx	d3	-	1
Distance from SS to PU Rx	d2	-	$\sqrt{5}$
Distance from PU Tx to SD	d1	-	$\sqrt{5}$

We assume that $\alpha = 0.5, \eta = 0.8$, and $M = N$ for all data simulations. A cognitive network model is constructed on MATLAB, which describes a similar relation as mentioned in the above schematic (see Fig. 5.1). Each distance is more than unity and contributes to the channel characteristics. As discussed earlier in Chapter 3, we know that the channel is exponentially distributed over frequency. The location of PU_{tx} make considerable change in performance of network. On the contrary, it is suggested that the location of PU_{tx} should be (0,1) i.e., there is a cluster of a number of transreceivers located near the signal source for faster communication and reducing transit time between nodes. Change in the location of PU_{tx} signifies that if a transmitter is moving in such a direction that it will eventually move out of a certain radius r, then the system will not be able to produce sufficient input power to transmit the input signal without getting attenuated. Thus a suitable size of cluster should be defined so that each transmitter can successfully transmit.

5.2 RESULTS AND DISCUSSIONS

a) Outage Probability vs Interference Power

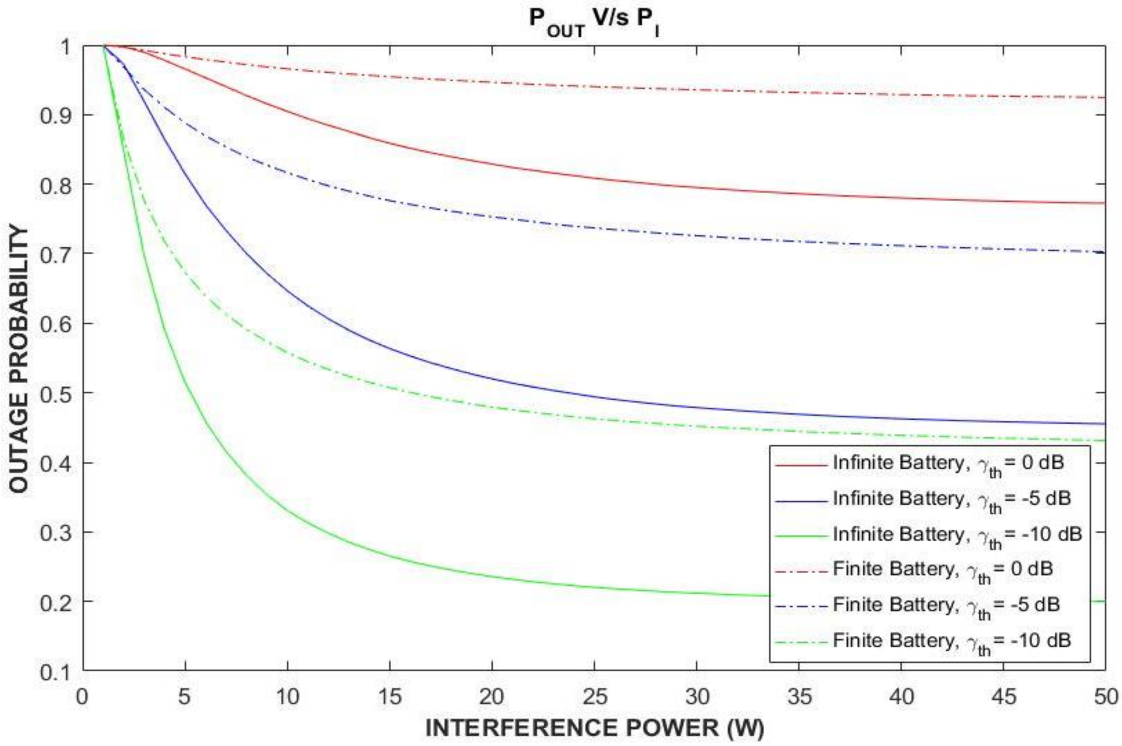

Figure 5.2 Outage Probability (P_{out}) as a function of Interference Threshold Power (P_I)

Above graph shows that with an increase in interference threshold, outage probability decreases. This is because as interference threshold power P_I increases, SS can tolerate larger interference power and there is a greater chance of signal being received at the SD, thus outage probability decreases.

b) Throughput vs Interference Power

As interference threshold power increases, the occurrence of an outage at SD decreases. Less outage is a sign of successful reception of more number of samples per cycle at the SD which is nothing but Throughput. Outage probability and throughput of a system are always inversely related. It can be observed in Fig. 5.3.

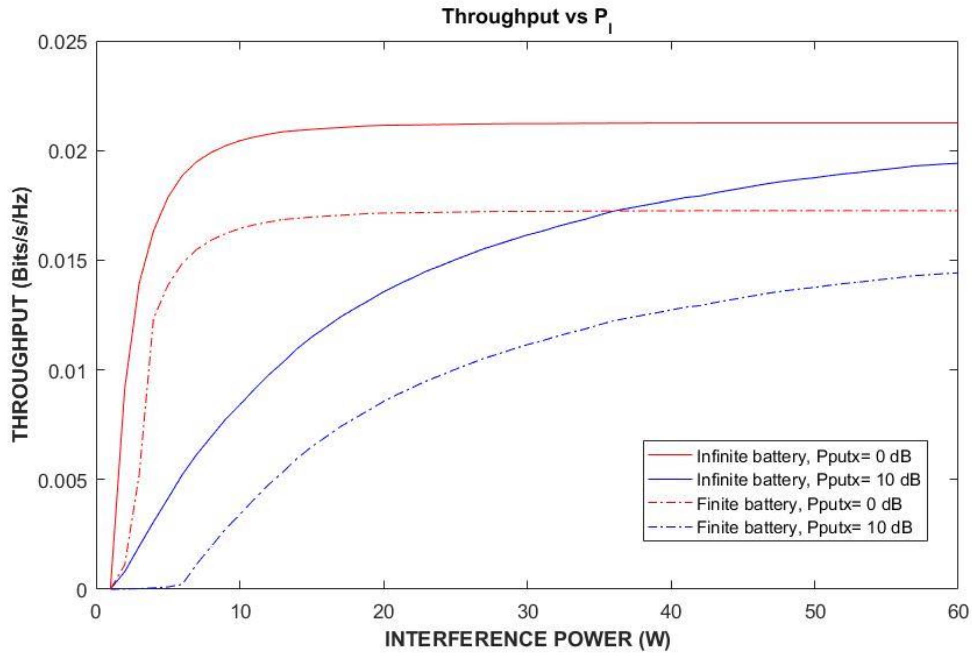

Figure 5.3 Throughput (Γ_{ds}) as a function of Interference Threshold Power (P_I)

c) Finite Battery Status

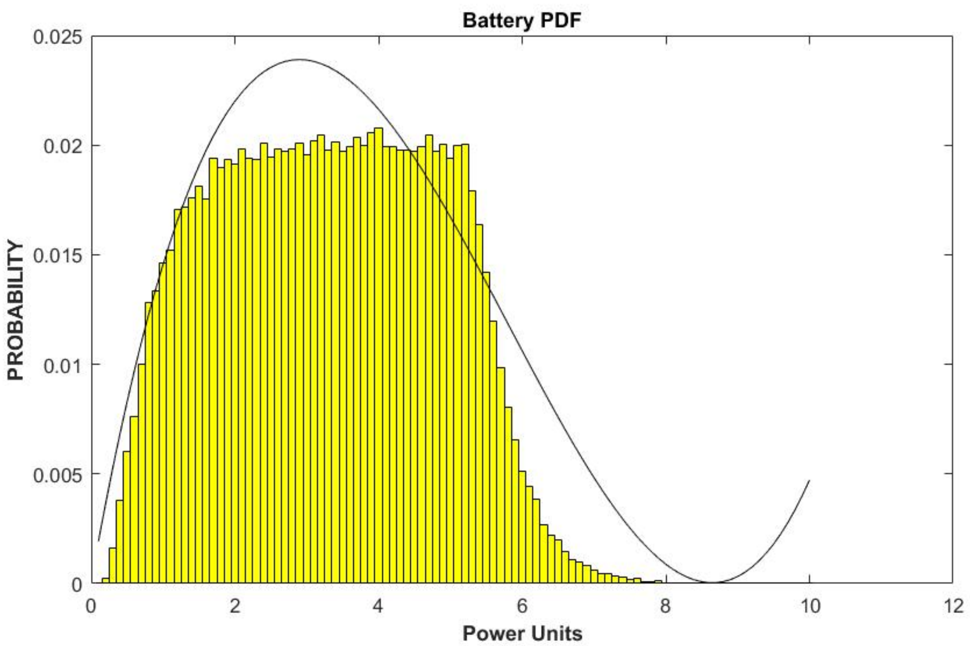

Figure 5.4 Finite Battery PDF

A finite battery with total storage power of 10 units is implemented at the SS. From Fig. 5.4, it can be observed that for most of the cases the battery is neither fully charged nor fully discharged during the transmission period. Its PDF is distributed over 10 units and maximum in 2-6 power units. An infinite battery model as in [1], always transmits signal from SS whereas a finite battery model only transmits when there is sufficient power (in this case 4 units) in battery at SS. The outage probability increases by battery implementation because, for a successful transmission two conditions are required which are as follows:

(i) SNR at SD should be greater than a sufficient threshold.
(ii) SS should have sufficient power to transmit the signal.

Therefore we can manage other parameters to obtain better performance.

d) Outage Probability vs Total Input Transmitted Power

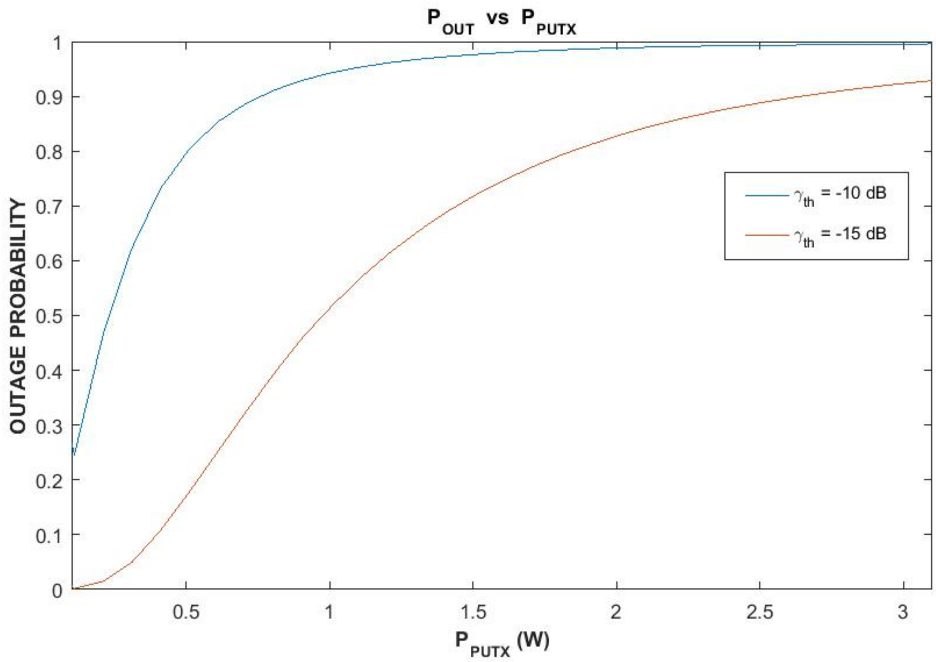

Figure 5.5 Outage Probability (P_{out}) as a function of total input transmitted power (P_{PUtx})

SS harvests energy which is a function of P_{PUtx} (from eq. 4.9), therefore as P_{PUtx} increases then there is more power harvested at the SS, since power transmitted from SS to SD is a function of P_{PUtx} (from eq. 4.13), thus as P_{PUtx} increases the power transmitted by SS is considerably large. This large transmitted power at SS causes interference to the PN. Therefore, as P_{PUtx} increases, outage probability increases.

(e) Outage Probability vs EH time interval

It is interesting to note that the variation in outage probability after $\alpha = 0.4$ is very less. We observe in Fig. 5.6 that, vale of EH interval should be large that provides low value of Outage Probability. EH duration should be larger than the signal transmission duration. For further validity of simulation theoretical results are required which can be future scope of the work.

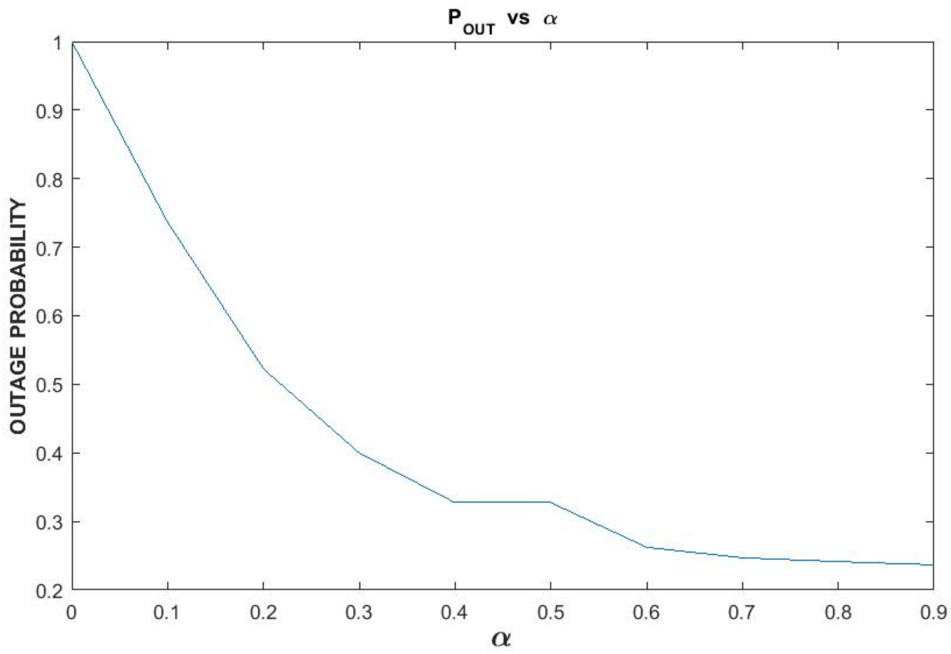

Figure 5.6 Outage Probability (P_{out}) as a function of EH time interval (α)

5.3 APPLICATIONS

Some of the other cognitive abilities include determining its location, sensing spectrum use by neighbouring devices, change in frequency, the adjustment in output power or even altering transmission parameters and characteristics. All of these capabilities and others yet to be realized will provide wireless spectrum users with the ability to adapt to real-time spectrum conditions, offering regulators, licenses and the general public flexible, efficient and comprehensive use of the spectrum.

Some of the applications are:

1. Emergency and public safety communications by utilizing white space.
2. Military applications such as battlefield surveillance, intelligent assistant, targeting, etc.
3. Health care e.g., telemedicine.
4. Real-time surveillance applications such as traffic monitoring, environmental condition monitoring, etc.
5. Indoor applications such as home monitoring systems, factory automation, personal entertainment, etc.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

A wireless energy harvesting protocol for an underlay cognitive non-relay network with multiple primary users (PUs) was examined. Expressions for the Outage Probability, Channel capacity, and the Throughput for delay-sensitive mode were studied. For a sufficiently large network, we applied a finite battery model at SS which provided a pragmatic outage probability of the system. Throughput is also improved as it is dependent on the outage probability as well. The value chosen for α greatly impacts the outage probability and the throughput of the secondary network. As the value of α increases from 0 to 1, the duration of EH at SS in each time slot increases and naturally, the remaining duration of the time slot to transmit information decreases. In other words, more energy may be available at SS but less time is available to transmit the information. It is desired to find a value of α for which throughput can be maximized.

A non-relay energy harvesting cognitive radio network is useful in short distance communication. The network is equipped with a finite battery which gave a practical scenario results for outage probability and throughput. These results are necessary to make suitable changes in other parameters to obtain relatively better performance.

6.2 FUTURE SCOPE

A wireless network is prone to eavesdropping attack which may results in loss of secrecy, hence to improve the physical layer security, a network can be equipped with sensor nodes which can evaluate secrecy outage probability [27]. Secrecy outage probability shall give an idea about security of the network for given parameters thus the analysis shall be helpful to design a network in the best way possible. Furthermore, the variation of parameters like link gain coefficients, distances, conversion efficiency, EH time interval also makes a considerable change in outage probability analysis and therefore, an adaptive system may be designed within the network to ensure optimum results.

Appendix 1

$$I_1 = P(V < \xi)$$

where, $V \triangleq \frac{min\,[B_{max}\,, E_i\,]}{(1-\alpha)\cdot T},\ \xi \triangleq \frac{\gamma_{th}\cdot(Z_2 + 1)}{X_1}$

$$\Omega_1 = 0.25, \Omega_2 = 0.2\,, \Omega_3 = 1\,, \Omega_4 = 0.2$$

$\Rightarrow$ $$I_1 = P\left\{\frac{min\,[B_{max}\,, Z_1 \cdot \eta \cdot \alpha \cdot T\,]}{(1-\alpha)\ \cdot\ T} < \ \xi\right\}$$

$$I_1 = P\,\{\,min\,[B_{max}\,, Z_1\eta\alpha T\,] < \ \xi(1-\alpha)\,T\,\}$$

Let $\xi' \triangleq \ \xi(1-\alpha)T$

$$Z_1 = W$$

$$Z_2 = Z$$

$$X_1 = X$$

$\therefore$ $$I_1 = P\left\{\,min\left[B_{max}\,, W\cdot\eta\cdot\alpha\cdot T\,\right] < \ \xi'\,\right\}$$

$$\begin{aligned}
I_1 &= P\,\{\,B_{max} < \ \xi' \ \cap\ B_{max} < \ W\eta\alpha T\,\} \\
&\qquad + \ P\,\{\,W\eta\alpha T \ < \ \xi' \ \cap\ W\eta\alpha T \ < B_{max}\,\} \\
&= \ P\left(B_{max} < \frac{\gamma_{th}(Z + \ 1)(1-\alpha)T}{X} \ \cap\ B_{max} < \ W\eta\alpha T\right) \\
&\qquad + \ P\ \left(W\eta\alpha T \ < \ \frac{\gamma_{th}(Z + \ 1)(1-\alpha)\,T}{X} \cap\ W\eta\alpha T \ < B_{max}\right) \\
&= \ P\left(X < \frac{\gamma_{th}(Z + \ 1)(1-\alpha)T}{B_{max}} \ \cap\ W > \frac{B_{max}}{\eta\alpha T}\right) \\
&\qquad + \ P\ \left(X < \ \frac{\gamma_{th}(Z + \ 1)(1-\alpha)\,T}{W\eta\alpha T} \cap\ W < \frac{B_{max}}{\eta\alpha T}\right) \\
&= \ P\left(X < \frac{\gamma_{th}(Z + \ 1)(1-\alpha)T}{B_{max}}\right) \times P\left(\ W > \frac{B_{max}}{\eta\alpha T}\right) \\
&\qquad + \ P\ \left(X < \ \frac{\gamma_{th}(Z + \ 1)(1-\alpha)\,T}{W\eta\alpha T} \cap\ W < \frac{B_{max}}{\eta\alpha T}\right)
\end{aligned}$$

$$= E_Z\left\{\left[1 - exp\left(-\frac{\gamma_{th}(Z+\ 1)(1-\alpha)T}{B_{max}\ \Omega_1}\right)\right]\right.$$

$$\left.\times\left[1 - \frac{\Gamma\left(N, \frac{B_{max}}{\eta\alpha TP_{PUtx}\ \Omega_3}\right)}{\Gamma(N)}\right]\right\}$$

$$+ E_{ZW}\left\{1 - exp\left(-\frac{\gamma_{th}(Z+\ 1)(1-\alpha)T}{W\eta\alpha T\Omega_1}\right)\right\} \mid W < \frac{B_{max}}{\eta\alpha T}$$

(i) Consider, $E_Z\left\{\left[1 - exp\left(-\frac{\gamma_{th}(Z+1)(1-\alpha)T}{B_{max}\ \Omega_1}\right)\right] \cdot \left[1 - \frac{\Gamma\left(N, \frac{B_{max}}{\eta\alpha TP_{PUtx}\ \Omega_3}\right)}{\Gamma(N)}\right]\right\}$

$$= \left[1 - \frac{\Gamma\left(N, \frac{B_{max}}{\eta\alpha TP_{PUtx}\ \Omega_3}\right)}{\Gamma(N)}\right]$$

$$\times\left[\int_0^\infty 1 \cdot f_z(z)\ dz\right.$$

$$\left.- \int_0^\infty \frac{e^{-\frac{\gamma_{th}(1-\alpha)T}{B_{max}\ \Omega_1}} \cdot e^{-\frac{\gamma_{th}Z(1-\alpha)T}{B_{max}\ \Omega_1}} \cdot z^{N-1} \cdot e^{-\frac{Z}{P_{PUtx}\ \Omega_2}}}{\Gamma(N)(P_{PUtx}\ \Omega_2)^N}\ dz\right]$$

$$= \left[1 - \frac{\Gamma\left(N, \frac{B_{max}}{\eta\alpha TP_{PUtx}\ \Omega_3}\right)}{\Gamma(N)}\right]$$

$$\times\left[1 - \int_0^\infty \frac{e^{-\frac{\gamma_{th}(1-\alpha)T}{B_{max}\ \Omega_1}} \cdot e^{-\frac{\gamma_{th}Z(1-\alpha)T}{B_{max}\ \Omega_1}} \cdot z^{N-1} \cdot e^{-\frac{Z}{P_{PUtx}\ \Omega_2}}}{\Gamma(N)(P_{PUtx}\ \Omega_2)^N}\ dz\right]$$

$$= \left[1 - \frac{\Gamma\left(N, \frac{B_{max}}{\eta\alpha TP_{PUtx}\ \Omega_3}\right)}{\Gamma(N)}\right]$$

$$\times\left[1 - \frac{e^{-\frac{\gamma_{th}(1-\alpha)T}{B_{max}\ \Omega_1}}}{\Gamma(N)(P_{PUtx}\ \Omega_2)^N}\int_0^\infty e^{-z\left(\frac{\gamma_{th}(1-\alpha)T}{B_{max}\ \Omega_1} - \frac{1}{P_{PUtx}\ \Omega_2}\right)} \cdot\ z^{N-1}\ dz\right]$$

(ii) Consider, $E_{ZW}\left\{1 - exp\left(-\frac{\gamma_{th}(Z+1)(1-\alpha)T}{W\eta\alpha T\,\Omega_1}\right)\right\} \mid W < \frac{B_{max}}{\eta\alpha T}$

$$= \int_0^{\infty}\int_0^{\frac{B_{max}}{\eta\alpha T}} 1 \cdot f_z(z)\,dz\, f_w(w)\,dw$$

$$- \left(\int_0^{\frac{B_{max}}{\eta\alpha T}} \left[\int_0^{\infty} exp\left(-\frac{\gamma_{th}(Z+1)(1-\alpha)T}{W\eta\alpha T\,\Omega_1}\right) f_z(z)\,dz\right] f_w(w)\,dw\right)$$

(iii) Consider, $\int_0^{\infty}\int_0^{\frac{B_{max}}{\eta\alpha T}} 1 \cdot f_z(z)\,dz\, f_w(w)\,dw$

$$= \int_0^{\infty}\left[\int_0^{\frac{B_{max}}{\eta\alpha T}} \frac{e^{-\left(\frac{w}{P_{PUtx}\,\Omega_3}\right)}\; w^{N-1}}{\Gamma(N)(P_{PUtx}\,\Omega_3)^N}\,dw\right] f_z(z)\,dz$$

Using property 3.351.3, in [28]

$$\int_0^{s} e^{-ux}\cdot x^n\,dx = \frac{\Upsilon(n+1, us)}{u^{n+1}}$$

$$= \int_0^{\infty} \frac{\Upsilon\left(N, \frac{B_{max}}{P_{PUtx}\,\Omega_3\,\eta\alpha T}\right)}{\Gamma(N)(P_{PUtx}\,\Omega_3)^N}\,(P_{PUtx}\,\Omega_3)^N\; f_z(z)\,dz$$

$$= \int_0^{\infty} \frac{\Upsilon\left(N, \frac{B_{max}}{P_{PUtx}\,\Omega_3\,\eta\alpha T}\right)}{\Gamma(N)}\; f_z(z)\,dz$$

$$= \frac{\Upsilon\left(N, \frac{B_{max}}{P_{PUtx}\,\Omega_3\,\eta\alpha T}\right)}{\Gamma(N)} \int_0^{\infty} f_z(z)\,dz$$

$$= \frac{\Upsilon\left(N, \frac{B_{max}}{P_{PUtx}\,\Omega_3\,\eta\alpha T}\right)}{\Gamma(N)}$$

(iv) Consider, $\left(\int_0^{\frac{B_{max}}{\eta\alpha T}} \left[\int_0^{\infty} exp\left(-\frac{\gamma_{th}(Z+1)(1-\alpha)T}{W\eta\alpha T\Omega_1}\right) f_z(z)\,dz\right] f_w(w)\,dw\right)$

$$= \int_0^{\frac{B_{max}}{\eta\alpha T}} \frac{e^{-\frac{\gamma_{th}(1-\alpha)T}{W\eta\alpha T\Omega_1}}}{\Gamma(N)(P_{PUtx}\,\Omega_2)^N} \left[\int_0^{\infty} e^{-z\left(\frac{\gamma_{th}(1-\alpha)T}{W\eta\alpha T\Omega_1}+\frac{1}{P_{PUtx}\,\Omega_2}\right)s} \cdot z^{N-1}\ dz\right] f_w(w)\,dw$$

Using property 3.351.3, in [28]

$$\int_0^{\infty} e^{-ux} \cdot x^n\,dx = \frac{n!}{u^{n+1}}$$

$$= \int_0^{\frac{B_{max}}{\eta\alpha T}} \frac{e^{-\frac{\gamma_{th}(1-\alpha)T}{W\eta\alpha T\Omega_1}}}{\Gamma(N)(P_{PUtx}\,\Omega_2)^N} \times \frac{(N-1)!}{\left(\frac{\gamma_{th}(1-\alpha)T}{W\eta\alpha T\Omega_1}+\frac{1}{P_{PUtx}\,\Omega_2}\right)^N} f_w(w)\,dw$$

As, $\Gamma(N) = (N-1)!$

$$= \int_0^{\frac{B_{max}}{\eta\alpha T}} \frac{e^{-\frac{\gamma_{th}(1-\alpha)T}{W\eta\alpha T\Omega_1}}}{(P_{PUtx}\,\Omega_2)^N\,\Gamma(N)(P_{PUtx}\,\Omega_3)^N} \times \frac{e^{-\left(\frac{w}{P_{PUtx}\,\Omega_3}\right)}\ w^{N-1}}{\left(\frac{\gamma_{th}(1-\alpha)T}{W\eta\alpha T\Omega_1}+\frac{1}{P_{PUtx}\,\Omega_2}\right)^N}\ dw$$

Appendix 2

$$I_2 = P\left(\frac{P_I}{Y_1} < \xi\right)$$

where, $\xi \triangleq \frac{\gamma_{th}\cdot(Z_2+1)}{X_1}$

$$\Rightarrow \qquad I_2 = P\left(\frac{P_I}{Y_1} < \frac{\gamma_{th}\cdot(Z_2+1)}{X_1}\right)$$

Let $\quad X_1 = X$

$$Z_2 = Z$$

$$Y_1 = Y$$

$$= P\left(\frac{P_I}{Y} < \frac{\gamma_{th}(Z+1)Y}{X}\right)$$

$$= P\left(X < \frac{\gamma_{th}(Z+1)Y}{P_I}\right)$$

$$= E_{YZ}\left[1 - F_X\left(\frac{\gamma_{th}(Z+1)Y}{P_I}\right)\right]$$

$$= E_Y\left[1 - \frac{e^{-\frac{\gamma_{th}Y}{P_I\,\Omega_1}}}{\Gamma(N)(P_{PUtx}\,\Omega_2)^N}\int_0^{\infty} e^{-z\left(\frac{\gamma_{th}Y}{P_I\,\Omega_1}+\frac{1}{P_{PUtx}\,\Omega_2}\right)}\cdot\ z^{N-1}\ dz\right]$$

Using property 3.351.3, in [28]

$$\int_0^{\infty} e^{-ux}\cdot x^n\,dx = \frac{n!}{u^{n+1}}$$

$$= E_Y\left[1 - \frac{e^{-\frac{\gamma_{th}Y}{P_I\,\Omega_1}}}{\Gamma(N)(P_{PUtx}\,\Omega_2)^N}\times\frac{(N-1)!}{\left(\frac{\gamma_{th}Y}{P_I\,\Omega_1}+\frac{1}{P_{PUtx}\,\Omega_2}\right)^N}\right]$$

As, $\Gamma(N) = (N-1)!$

$$= E_Y\left[1 - \frac{e^{-\frac{\gamma_{th}Y}{P_I\,\Omega_1}}}{(P_{PUtx}\,\Omega_2)^N}\times\frac{1}{\left(\frac{\gamma_{th}Y}{P_I\,\Omega_1}+\frac{1}{P_{PUtx}\,\Omega_2}\right)^N}\right]$$

$$= \int_0^\infty \left(1 - \frac{e^{-\frac{\gamma_{th} Y}{P_I\,\Omega_1}}}{(P_{PUtx}\,\Omega_2)^N} \times \frac{1}{\left(\frac{\gamma_{th} Y}{P_I\,\Omega_1} + \frac{1}{P_{PUtx}\,\Omega_2}\right)^N} \right) f_Y(y)\,dy$$

$$= \int_0^\infty \left(1 - \frac{e^{-\frac{\gamma_{th} Y}{P_I\,\Omega_1}}}{(P_{PUtx}\,\Omega_2)^N} \times \frac{1}{\left(\frac{\gamma_{th} Y}{P_I\,\Omega_1} + \frac{1}{P_{PUtx}\,\Omega_2}\right)^N} \right)$$

$$\cdot \frac{M}{\Omega_4} \sum_{k}^{M-1} \binom{M-1}{k} (-1)^k \, e^{-\left(\frac{k+1}{\Omega_4}\right) y}\,dy$$

Appendix 3

$$I_3 = P\left(V < \xi , \frac{P_I}{Y_1} < \xi \right)$$

where, $V \triangleq \frac{min\,[B_{max}, E_i\,]}{(1-\alpha)\cdot T}$, $\xi \triangleq \frac{\gamma_{th}\cdot(Z_2+1)}{X_1}$

Let $X_1 = X$

$Z_2 = Z$

$Y_1 = Y$

Since V, ξ, Y are independent random variables as their channel distribution and thereby link gain coefficients are independent to each other. Therefore, we can write the above equation as:

$$I_3 = P(V < \xi) \times P\left(\frac{P_I}{Y} < \xi\right)$$

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