INVESTIGATION OF COGNITIVE WIRELESS AND POWER LINE NETWORK USING INTERNET OF THINGS

By

Onimesh Roy
15321001
Md Atique Shahriar
15321023
Shakib Mahmud
15321019
Tanjim Ahmed Komol
15321025

A thesis submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering
Brac University
August 2019

Declaration

It is hereby declared that the thesis submitted is our own original work while completing degree at Brac University. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution. We have acknowledged all main sources of help.

Student's Full Name & Signature:

Onimesh Roy 15321001	**Md Atique Shahriar** 15321023
Shakib Mahmud 15321019	**Tanjim Ahmed Komol** 15321025

Approval

The thesis/project titled "Investigation of Cognitive Wireless and Power Line Network using Internet of Things (IoT)" submitted by

1. Onimesh Roy (15321001)
2. Md Atique Shahriar (15321023)
3. Shakib Mahmud (15321019)
4. Tanjim Ahmed Komol (15321025)

of Summer, 2019 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of B.Sc. In Electrical and Electronic Engineering on August 29, 2019.

Examining Committee:

Supervisor:
(Member)

____

Dr. Saifur Rahman Sabuj
Assistant Professor
Department of Electrical and Electronic Engineering
Brac University

Program Coordinator:
(Member)

____

Dr. Saifur Rahman Sabuj
Assistant Professor
Department of Electrical and Electronic Engineering
Brac University

Departmental Head:
(Chair)

____

Dr. Shahidul Islam Khan
Professor and Chairperson
Department of Electrical and Electronic Engineering
Brac University

Abstract

Now a days, smart grid is getting more popularity than the electric power grid because of its two-way communication between consumers and utilities. Using internet of things (IoT), smart grid is monitoring the both way communication which is one of the major tasks of smart grid. So, in this thesis, we observed the cognitive wireless and power line network using IoT. To do that, we have set-up a system model consisting of transmitter, receiver, and different relays. Besides, we have formulated equations for signal to noise ratio for relay network, cumulative distribution function (CDF) and probability density function (PDF). Likewise, we have analyzed the spectrum sensing of cognitive radio, throughput of wireless channel and the path loss model. In addition, we have also derived the equations of the throughput for cognitive wireless channel with and without the interference. Finally, from all the equations and data, numerical results that the efficiency increases for both wireless and power line communication. The efficiency increases with the increase of path loss exponent, transmission power, distance of transmitter and receiver for wireless networks. On the other hand, the capacity improves significantly with the increase of signal to noise ratio (SNR) and transmission power of secondary user for power line communication (PLC).

Keywords: Smart Grid, IoT, Cognitive Radio Network, PLC.

Acknowledgement

In the very beginning, we would like to thank Almighty for giving us the strength to pursue this thesis which has been a great learning opportunity to us. By the virtue of Almighty, we were able to work hard and successfully completed it on time. Secondly, we would like to thank and show our gratitude to our supervisor Dr. Saifur Rahman Sabuj for help and guidance during whole this time and writing the report. Also, we would like to thank our parents, friends and well-wishers who helped us directly or indirectly while conducting this thesis. We would also like to appreciate the help that we received from the previous researches and contents over the internet. Finally, we would like to show our courtesy to Brac University for providing us the opportunity to conduct this thesis and for the opportunity to complete the Bachelor degree.

Table of Contents

List of Acronyms

IoT	Internet of things
CDF	Cumulative Distribution Function
PDF	Probability Density Function
SNR	Signal to Noise Ratio
PLC	Power Line Communication
AMI	Advanced Metering Infrastructure
QoS	Quality of Service
DRM	Demand Response Management
HAN	Home Area Network
NAN	Neighborhood Area Network
WAN	Wide Area Network
PU	Primary User
SU	Secondary User
SG	Smart Grid
WSN	Wireless Sensor Network
CRSN	Cognitive Radio Sensor Network
CRN	Cognitive Radio Network
EH	Energy Harvesting

Chapter 1

Introduction to Cognitive and Power Line Network

1.1 Introduction

The electrical power grid mainly consists of generators, transformers, relays, power lines for communications. Basically, it supplies the utility to the customers through long distance power lines which causes different power losses. Besides, increasing demand and greenhouse gas emission become a concern for global warming. Normally the power flows only one direction from the grid to the customers. To achieve the greater reliability smart grid has been introduced. It uses two-way communication between consumers and utilities with intelligent computing technologies.

Smart grid has upgraded power generation, distribution, transmission with higher efficiency, reliability and security [19],[20],[21]. It creates a closed loop with the customers with improved digital communication and smart metering. Some main elements of smart grid are advanced metering infrastructure (AMI), demand response management (DRM) and fault tolerance with quality of service (QoS). Here, AMI builds communication setup between utilities and consumers. It passes data through wide area network. So, for transmitting and receiving data, it needs a bigger bandwidth. Besides, DRM develop the system efficiency and act as control unit. Basically, maintaining the demand and supply balance, consumers can synthesize their energy expenses through smart grid. It offers the real time demand and supply monitoring. Moreover, it offers transmission, sensing and control [35].

Most of the AMI communication builds of 2.4 GHz industrial, scientific and medical (ISM) bands. Smart grid communication consists of Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN) [22]. Wireless communication is necessary for connecting these networks. Wireless communication communicates without any wire. It mainly uses electromagnetic signals. Now a days, it has become very popular. Wireless communication needs different frequency bands. These bands are limited to licensed user or primary user (PU) who are the owner of these bands and no permission for unlicensed or secondary user (SU) for reuse it [14]. When PU are absent, SU can use it by changing the parameters. Cognitive radio can improve the network performance using the spectrum sensing. By spectrum sensing, smart meters can provide data on licensed user or the unlicensed user. It also improves the quality of secondary users. But data transmission and spectrum sensing cannot be executed together. Smart grid demands QoS, resource efficiency and bandwidth. For communicating in the application of smart grid needs more research and solution.

One of the main uses of smart grid is smart monitoring which can be done using IoT. IoT is a digital communication system where many computing devices, multiple technologies and a wide range of applications like sensor, mechanical and digital meters can be interconnected. Addition of IoT in smart grid is a great approach because it gears up the data transmission of power system. It improves the two-way communication of smart grid and make it smarter. The population of the world is increasing and demand of the utilities also increasing side by side. So, introducing smart grid with IoT will balance the demand supply management through DRM. Basically, the IoT works through internet exchanging information from one place to another place and it is using wireless communication for connecting different targets. IoT using in the smart grid are following the ISM band and standards used in the IoT are IEEE 802.11 and IEEE 802.15.4 for local areas [36].

The main elements of IoT are wireless sensors which are very important components of smart grid. Wireless sensor network (WSN) are getting more popularity in electric power network for its low cost and efficient operation. By setting these sensors to different power plants, transmission and distribution lines, substations, we can collect information of real time problems. These sensors monitor the power system and identify different problems. As a result, systems reliability and efficiency increases and also decreases the outage. But these sensors create some problem for smart grid like bit error rate, channel capacity variation, power capability of sensors and reliability. Moreover, some environmental elements like dust, humidity, vibration may cause some problem for smart grid. Likewise, different smart grid requires different QoS.

Usually wireless communication is used for IoT but now a days, smart grid network has more developed and PLC has more improvement for using in IoT system. PLC uses subsists power cables to transfer data. It uses for long distance communication where the radio frequency doesn’t work. Different PLC uses different frequency bands. The advantages of PLC are low cost, easy installation and easy to use [23]. Besides, for security support, PLC is the trustworthy and one of the most reliable system. The PLC system does not need any extra wire for controlling and monitoring devices. PLC can control and monitor devices which are connected with it. One of the main problems with PLC is the wire have constant frequency controlling ability. But for AC connection of household elements, PLC is necessary.

Many attempts have been tried to figure out both wireless and PLC in IoT but wireless sensors and power line communication sensors cannot communicate with each other within an IoT. PLC needs wire connection to the grid which creates difficulty for mobile users. Similarly, there are some household equipment’s which needs AC supply. For that reason, wireless communication is not suitable for home networks. Besides, long distance transmission creates problem for both PLC and wireless communication as there will be some signal loss [24],[25].

1.2 Related Works

M.W. Khan & M. Zeeshan described that cognitive wireless and power line networks requires multi-way communication throughout power generation and power distribution. The whole system involves many networks in which energy pass through the transmitter to receiver and multiple applications with various QoS requirements. Cognitive Radio (CR), has been considered as a favorable solution to fill up these requirements. Efficient spectrum utilization and distribution is offered by CR. They proposed a dynamic channel selection algorithm, selecting the most appropriate available idle channel with desired bandwidth, minimum required SNR and probability of miss detection. To reduce the re-transmission probability and thus achieve the desired throughput, they proposed a novel approach to select the channel with closest possible parameters [1].

R. Yu et al. presented an unprecedented cognitive-radio-based communications architecture was identified for the smart grid, which is mainly motivated by the explosive data volume, diverse data traffic, and need for QoS support area network, depending on the service ranges and potential applications. They focused on dynamic spectrum access and sharing in each subarea. The designing was made to intelligently allocate spectra to support the communication requirements in the smart grid [2].

A. Ghassemi et al. introduced that one of the key basics of smart grid (SG) is a reliable communications infrastructure which is a multi-layer network. It carries different classes of data. To accommodate the present energy management requirements as well as the possible demand of future applications SG infrastructures needs to be designed. They proposed the application of CR based on the SG WANs. The planned scheme can work as a secondary radio particularly in urban areas as well as a backup in disaster management [3].

J. Huang et al. described that, smart grid can be imagined as a smart control system over sensors and communication platforms. To reduce the communication interferences and improve the bandwidth efficiency for smart grid communication, CR networks have been identified as a key wireless technology. Various characteristics of smart grid traffic including multimedia and propose a priority-based traffic scheduling approach for CR communication infrastructure is consider in this paper. Taking into consideration of channel switch and spectrum sensing errors, and solve a system utility optimization problem for smart grid communication system, we improve a CR channel allocation schemes. Their simulation and data can offer significant scope for future CR system [4].

Y. Zhutian et al. proposed in their paper that, for overcoming radio spectrum shortages in wireless communications, cognitive radio technology plays a vital role in smart grid applications. They focused on the investigation of the receiver-based routing protocol for enhancing QoS in cognitive radio-enabled networks. A new routing practice with two purposes is proposed: one is to address the real-time requirement while another protocol focuses on how to meet energy efficiency requirements, for practical requirements of smart grid uses. As a special feature of cognitive radio technology, the protocol has the mechanism of protecting PU (licensed) whilst meeting the requirements of SU. System-level estimation shows that the proposed routing protocol can achieve better performances compared with existing routing protocols [5].

E. U. Ogbodo et al. stated, the cognitive radio-based sensor network (CRSN) is planned as a strong driver in the development of modern power system SGs. This can overcome the spectrum drawback in the sensor nodes due to interference cause by other wireless devices operating on the same unlicensed frequency in the Industrial, Scientific and Medical band. A reliable SG communication network architecture is required for transferring. Hence, their paper investigates and explores the CRSN theoretical structure, and SG communication architecture with its applications; vis-à-vis the communication access technologies, including application design with quality of service support. This paper also studies about the research gap in the field of SG networks [6].

N. Ghasemi & S. M. Hosseini described that, CRs have recently attracted attentions as an alternative to the problem of spectrum shortage. The main aspect of Smart grids is making use of digital technologies to save energy, reduce cost and increase reliability and transparency in order to enhance the exploitation of the available resources. Since scarcity of resources is the crisis of both communication systems and electrical energy systems, in this paper solutions for the problem of spectrum scarcity will be explored. The main principle of these radio networks is opportunistic access to the spectrum holes mainly licensed to PUs [7].

Z. Yang et al. stated that, AMI networks are practically deployed as a static multihop wireless mesh network. Recently, routing solutions for AMI networks have attracted a lot of attention in the literature. On the other hand, it is expected that the use of cognitive radio will be essential in near future. This paper investigates a worldwide optimization-based routing protocol for enhancing quality of service in CR-enabled AMI networks. This protocol utilizes a global optimization algorithm to select the best route from the whole network. In addition, the system protects PU (licensed) while meeting the utility requirements of the secondary network [8].

B. Khalfi et al. studied that, an optimal power allocation analysis for a point-to-point wireless system when powered by a smart grid is proposed in this paper. They propose to minimize the total power consumption cost while ensuring individual and total extent limitations. Systematic solutions are derived for each pricing model [9].

S. Alam et al. described SG is an evolution of conventional electricity grid in solving the electricity shortages, escalation in electricity prices, power quality issues and need for using environment friendly green energy resources. The purpose of this research article is to provide a detailed survey on SGCN in terms of communication network requirements, architecture, technologies and applications. This paper first discusses the communication requirements, followed by an overview of SG applications using a multi-layer approach of dividing the communication layer [10].

R. C. Qiu et al this paper analytically studies the novel idea of applying the next generation wireless technology, cognitive radio network, for the smart grid. Both power flow and information flow supporting by a microgrid testbed is also proposed. Control strategies and security considerations are discussed. To recover data from the simultaneous smart meter wireless transmissions in the presence of strong wideband interference, the concept of independent component analysis (ICA) in combination with the robust principal component analysis (PCA) technique is employed in the study [11].

X. Huang & N. Ansari stated that, wireless telecommunications is facing a massive saturation of wireless devices and an exponential growth in wireless applications. They present a new radio resource exchange scheme for a smart grid connected cognitive radio system, in order to accommodate the expected service requirements with the available radio resources. The secondary system will gain spectrum usage by either forwarding primary data or transferring energy credit directly to the primary system. The utilities of both systems are optimized by jointly designing the sub channel assignment scheme with power control, to exploit the overall energy saving while meeting the throughput requirement [12].

A. A. Khan et al. described; traditional power grids are presently being altered into SGs. Multi-way communication among energy generation, transmission, distribution, and usage facilities are features of SG. The complex power system needs to integrate into SG to monitor transformation. Though some issue in complexity wireless communication is an important linked with SG system. Cognitive radio networks (CRNs) is very promising in SG system to utilize the spectrum network in power line. In this paper CRN based communication technology and system is described with potential applications of this system in near future [13].

R. Deng et al. stated that, Smart grid is considered a future potential power transformation system where generation, transformation, application is organized systematically. DRM is recognized as a control unit of the smart grid, with the attempt to balance the real-time load as well as to shift the peak-hour load. A cognitive radio into the smart grid to improve the communication quality is introduced in this paper. By means of spectrum sensing and channel switching, the usage of spectrum for primary as well as secondary channel can be controlled. In order to solve the problem of communication with vast expenses it will be appropriate to use grin energy smart grid in near future. Also, communication outage on the control performance of DRM reduces the profit of power provider and the social welfare of the smart grid, although it may not always decrease the profit of power consumer. With energy detector the sensing of controlled user channels and it's allocating frequency also taken in attention in this discussion [14].

M Ozger et al. described the IoT gives the connectivity to the object to monitor and sense the digital world. Interoperability, connectivity, etc from IoT is beneficial to SG. Harsh channel conditions and limited battery power, may be resolved by connecting IoT with the Cognitive Radio network and Energy harvesting (EH) approach. Hence, combination of EH and CR reveals a new networking model for IoT-enabled SG. They firstly introduced CR usage in IoT and then EH to the wireless devices in the IoT enabled SG. Procedure and node architecture of energy harvesting cognitive radios, and network architecture of the IoT-enabled SG are described to clarify details of our networking model in the paper [15].

S. Althunibat et al. studied that, a reliable, accurate and effective communication link between the distributed meters and the control center is required from SG operation. However, due to the spectrum shortage problem, dedicating a portion of the spectrum is difficult. For the efficiency and flexibility, CR technology has been nominated as a good candidate for SG communications. Indeed, channel selection in CR based SG systems is still an open issue, and it is studied in this paper. The paper proposes a fresh channel selection appliance that is able to adapt the selection criteria based on the type of transmitted data. The proposed mechanism will try to provide high performance compared to the non-adaptable system [16].

T. N. Le et al. described that now a days, power grids are facing demands for generation and supply. Also, these power generation company are facing lot of pressure for increasing global warming and greenhouse gas emission. As a result, smart grid has introduced because it can communicate two ways and helps to match the demand of the consumers. Smart grid also transfers a large amount of information with security, reliability and efficiency [17].

Q. Li stated that wireless communication network with spectrum resources is needed for real time DRM. But the spectrum is fulfilling with local and civil dimensions. To solve this security problem, cognitive radio and dynamic spectrum sharing have been proposed. Here, DRM and outage relationship has been executed. The outage causes from noise, interference and lack of resources. Smart grid network is divided into two regions: Temporal spectrum sharing region (TSSR) and free spatial spectrum sharing region (Free-SSSR). Here TSSR can use the licensed spectrum when PU is absent. Besides, Free-SSSR can share this network without using power [18].

1.3 Objective of the Thesis:

The goal of this research is to investigation of Cognitive Wireless and Power Line Network using IoT. To meet this goal the following objectives have been finalized.

1. To set-up a system model consisting of transmitter, receiver, and different relays.
2. To derive the equations for SNR for relay network, CDF, PDF, spectrum sensing of cognitive radio, throughput of wireless channel and capacity of PLC channel with and without the interference.
3. To analyzed the numerical result of throughput and capacity for both wireless and PLC.
4. To compare false alarm probability/detection alarm probability (p_f /p_d), path-loss exponent (n), Secondary user transmission power (P_s), distance (d) between transmitter and receiver with Throughput.

1.4 Organization of the thesis:

Chapter-1 is basically introducing chapter. It comprises of different previous works, uses and restrictions of PLC, wireless communication, smart grid using IoT.

Chapter 2 is the combination of six parts. Firstly, the system model of a typical IoT formed with PLC and wireless sensors. Secondly, performance Analysis with a combination of SNR of relay network and receiver architecture. Thirdly, the spectrum sensing of cognitive radio in which to find out the presence of primary user, energy detection method is used. Moreover, Effective throughput and interference throughput equations are formed in throughput of wireless channel. Furthermore, channel gain was considered to discuss the path loss model of the system. Finally, in the capacity of PLC channel, combining the capacity of PLC channel with interference and without interference to get the average capacity.

Chapter 3 describes about the numerical results and MATLAB simulation of our equations and graphs.

Chapter 4 contains the summary of all the previous chapters and future works.

Chapter 2

2.1 System Model

We review a typical IoT system, formed together wireless and Power line Communication PLC sensors in this chapter. In this model PLC sensors are positioned in the electrical loads and meters. The proposed sensors network builds as an Ad Hoc as sensors can perform as pathway or final nodes. The proposed model is shown in Fig. 2.1.

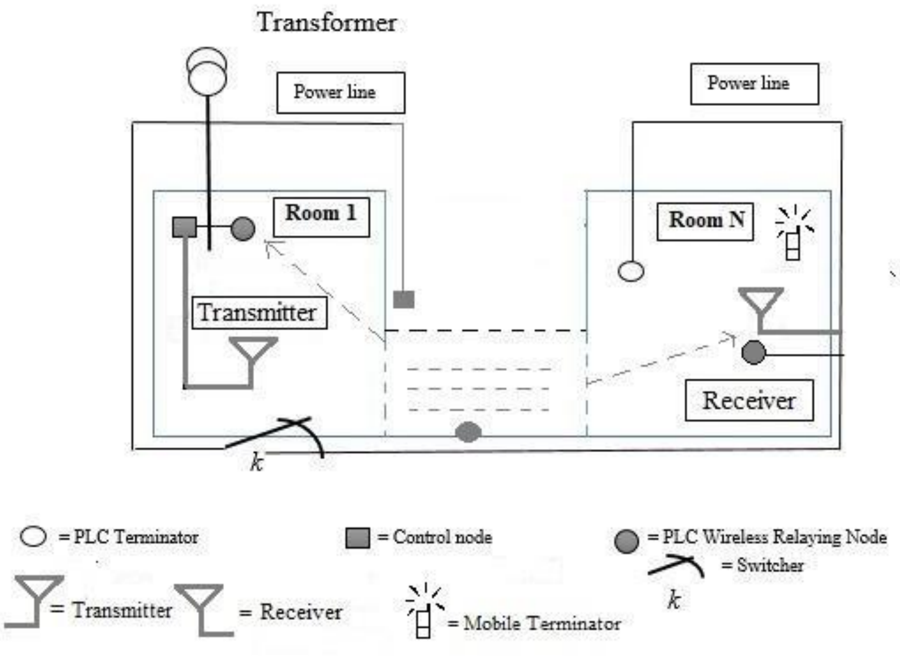

Fig. 2.1: The model of an emblematical IoT system combining relaying nodes, that also have a PLC interface and wireless interface. Various rooms are distributed by wireless and PLC sensors whereas electrical loads are occupied by PLC sensors and connected by power line cables [26].

Generally, PLC and wireless communication can be unbalanced via long power line which lies between sensors when transceivers have a number of walls in between them. In order to manage up this unbalancing the double-interface relaying nodes, a wireless and PLC interface are placed in this model. Usually, the double-interface relaying nodes are placed in some chosen and important point of the network. For instance, in Fig 2.1, room 1 and room N cannot communicate directly for their high space between the two rooms. There lies an nth number of rooms between them. Room 1 and room N are also free Ad Hoc. In this situation, to support communication a relay with PLC wireless interface is connected for sensors in the two networks. As dual-interface makes high investment and energy cost we cannot equip all sensors with them. That's why only some nodes with the double -interface are placed near the double -interface relaying nodes. As a result, the network can give convenient access to both mobile terminals and stabled PLC sensors. Also, the sensors network can be provided robust communication by this dual-interface relaying model, as one communication can maintain the network connection if other one is out of work.

In relying model of Fig. 2.1, via relaying node R, a generation node S in room 1 communicates with the target edge D. The relaying node R works in half - duplex mode. The communication includes two hops from S to D. It is showed in Fig. 2.1.

2.2 Performance Analysis:

2.2.1 Signal to noise ratio of Relay Network:

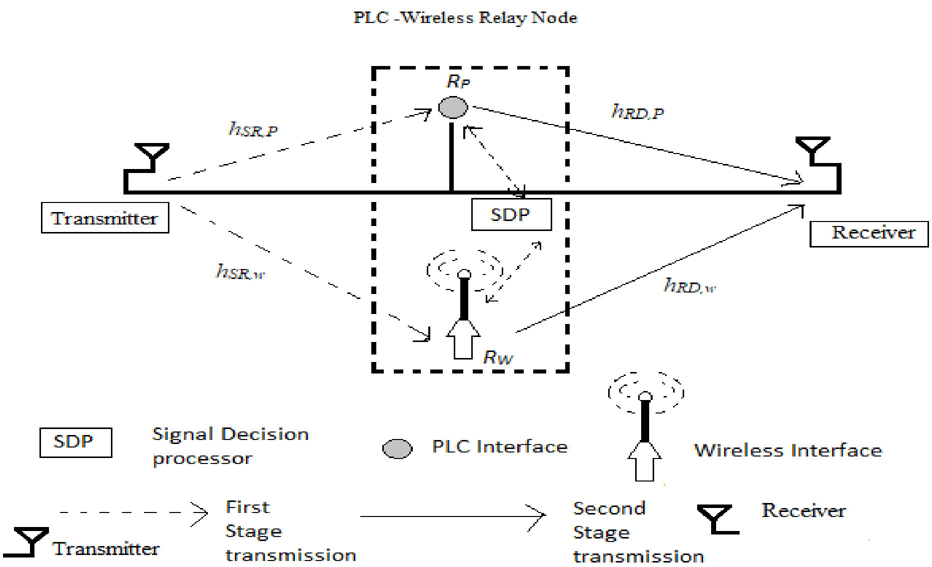

Fig. 2.2: The logical model of a typical HWPLC relaying model. It has a two-stage relay transmitting protocol, R_p an R_w are the PLC and wireless interface. Here, signal decision processor is SDP which can pick the signal with upper SNR from the two interfaces. Channel gains from S to R are h_{SRp} and h_{SRw} via PLC and wireless channel. Similarly, h_{RDp} and h_{RDw} are PLC and wireless channel gain from R to D [26].

In Fig. 2.2: during transmission there are two stages. Each one has their own time slot. The information through wireless and PLC channels is broadcasted by S to the relaying node. The adopted signal at the relaying node can be expressed as

$$\begin{bmatrix} y_{SRp}(t) \\ y_{SRw}(t) \end{bmatrix} = \begin{bmatrix} \sqrt{P_S} & 0 \\ 0 & \sqrt{P_S} \end{bmatrix} \begin{bmatrix} h_{SRp} & 0 \\ 0 & h_{S,w} \end{bmatrix} \begin{bmatrix} x(t) \\ x(t) \end{bmatrix} + \begin{bmatrix} n_{SRp}(t) \\ n_{SRw}(t) \end{bmatrix} \ldots\ldots\ldots\ldots\ldots \text{(2.1)}$$

Here, transmitted symbol is *x(t).* Also h_{SRp} and h_{SRw} are the channel gains from *S* to *R* over PLC and wireless channel. PLC and wireless channel are donated by subscripts *p* and *w* in the equation. Transmission power is indicated by $P_{s.}$ Noise over the PLC channel and wireless channel are indicated by $n_{SRp}(t)$ and $n_{SRw}(t)$.

A signal decision processor (SDP) module is used in order to get better performance. The upper adopted SNR to forward the adopted information is selected with the interface by SDP in the relaying node. PLC and wireless interface received the information through their communication channels in each time block. After that the received SNRs is calculated and imputed to the SDP. SDP module chooses an ideal relaying channel from the PLC and wireless channels between the two input SNRs. Therefore, at the relaying node the received SNR can be written as

y_{SR} = max { $P_S h^2_{SRp} / \sigma_p^2$, $P_S h^2_{SRw} / \sigma_w^2$ }………………………………………………….. (2.2)

Here, $\boldsymbol{\sigma_p^2}$ and σ_w^2 are variance of the noise over the PLC channel and wireless channel respectively.

During the second time slot at the destination the adopted signals can be expressed like

$$\begin{bmatrix} y_{RDp}(t) \\ y_{SRw}(t) \end{bmatrix} = \begin{bmatrix} \sqrt{P_R} & 0 \\ 0 & \sqrt{P_R} \end{bmatrix} \begin{bmatrix} h_{RDp} & 0 \\ 0 & h_{DRw} \end{bmatrix} \begin{bmatrix} y_{SR}(t) \\ y_{SR}(t) \end{bmatrix} + \begin{bmatrix} n_{RDp}(t) \\ n_{RDw}(t) \end{bmatrix} \ldots\ldots\ldots \text{(2.3)}$$

Here, chosen signal at the relaying node is $y_{SR}(t)$. The channel gains from *R* to *D* over the PLC channel and wireless channel are h_{RDp} and h_{RDw}. Furthermore, the transmission power of the relaying node is $P_{R.}$ Noise over the PLC channel and wireless channel are indicated by $n_{RD_p}(t)$ and $n_{RD_w}(t)$ respectively.

Next, the interface with higher adopted SNR is chosen at the terminal D. The received SNR at D is expressed as

y_{RD} = max { $P_R h^2_{RD,w} / \sigma_p^2$, $P_R h^2_{RD,w} / \sigma_w^2$} ………………………………………… ...(2.4)

In this system, *S* and *R* transmit symbol is assumed with unit power, which is $P_S = PR = 1$.

2.2.2 Receiver Architecture:

We consider the PLC system with the several divisions of varieties combining receiver in this portion. It is shown in Fig. 3. PLC transmitter has a buffer which store and collect data from the source node. Next, the stored data is transmitted by the transmitter as binary shift keying (BPSK). It is modulated over L correlated PLC-sub channel. The modulated data can be coupled from frequency, time and space. To avoid the cross-channel interface, all the PLC-sub channels has various sub-frequency bands with appropriate separation. We guess that the receiver is well synchronized with the transmitter. Lastly in our model there is a buffer at the receiver to store adopted data. Receiver can join the correlated adopted signals from the L PLC sub-channels.

2.2.3 Cumulative Distribution Function & Probability Density Function:

The l^{th}, $(1 \leq l \leq L)$, PLC sub-channels received signal at receiving node is

$$y_l = h_l x_l + z_l \,,\; 1 \leq l \leq L \,, \quad \ldots\ldots \quad (2.5)$$

Here, h_l is the received noise and x_l and h_l are the transmitted signal and channel gain respectively over the l^{th} sub-channel.

Since a PLC sub-channel is subjected to the composition of the thermal and impulsive noises which are independent (12), the Bernoulli-Gaussian sample can be taken as noise model for PLC channels, that is

$$z_l = n_G + n_B * n_l \,, \quad \ldots\ldots \quad (2.6)$$

Here, n_G and n_l are the Gaussian random variables with zero mean. Their respective variances are σ_G^2 and σ_I^2 . Also n_B is the Bernoulli random sequence having parameter p.

The variances of the PLC channel noise $\sigma_{p,l}$ can be more explained in details as

$$\sigma_{p,l}^2 = E(n_G^2) + E(n_B^2) \times E(n_I^2)$$

$$= \sigma_G^2 + p\sigma_l^2 \quad \ldots\ldots \quad (2.7)$$

The noises in sub-channels are independent and identical as L sub-channels are anticipated interference free with each other. Thus, we have $\sigma_p = \sigma_{p,1} = \cdots = \sigma_{p,L}$.

As in [27] and [28], the PDF or Probability density function of h_l is lognormal and can be expressed as

$$f_{h_l}(x) = \frac{1}{\sqrt{2\pi\sigma^2}\,x}\, e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} \quad \text{.......} \quad (2.8)$$

Here, μ and σ2 are the average and discord of a general random variable ln(hl) .

Different sub-channels transmit the input signal from S to D. The MRC is accepted to get the optimal adopted SNR over the PLC sub-channel [29] and that is,

$$\gamma_{SR_P} = \frac{(\sum_{l=1}^{L} w_l h_l)^2}{\sum_{l=1}^{L} w_l^2 \sigma_{p,l}^2} = \frac{1}{\sigma_{p,l}^2}\, \frac{(\sum_{l=1}^{L} w_l h_l)^2}{\sum_{l=1}^{L} w_l^2} \quad \text{.......} \quad (2.9)$$

Weight over the lth sub-channel is w_l and adopted SNR of the chain from S to R over PLC Channels However,w_l is balanced to the channel gain in MRC and there is no loss of generality, we can say $w_l = c * h_l$. Here, c is a constant. The adopted SNR now can be written as

$$\gamma_{SR_P} = \frac{1}{\sigma_{p,l}^2}\, \frac{c^2(\sum_{l=1}^{L} h_l^2)^2}{c^2 \sum_{l=1}^{L} h_l^2} = \sum_{l=1}^{L} \frac{h_l^2}{\sigma_{p,l}^2} \quad \text{.......} \quad (2.10)$$

In addition, the received SNR can be expressed as

$$\gamma_{SR_P} = \gamma_p \sum_{l=1}^{L} \frac{h_l^2}{\sigma_{p,l}^2} \quad \text{.......} \quad (2.11)$$

in equation (2.11) the transferred SNR over the *l*th PLC sub-channel $\gamma_p \triangleq \frac{1}{\sigma_p^2}$. Here, h_l^2 pursues the lognormal distribution with average 2μ and discord σ^2. Let's assume $\mu_\gamma = 2\mu$ and $\sigma_\gamma = \sigma$ we can find the PDF of h_l^2 as

$$f_{h_l^2}(x) = \frac{1}{\sqrt{2\pi\sigma_\gamma^2 x}}\, e^{-\frac{(\ln\ln x-\mu_\gamma)^2}{2\sigma_\gamma^2}} \quad \text{.......} \quad (2.12)$$

According to (2.11), lognormal sum distribution is followed by the adopted SNR of the PLC channel. That's why the formation of the CDF of SNR for PLC channels require to revolve am integral of the lognormal count. This is a difficult task. For this case we approximate the PDF of γ_{SR_P} as [30]

$$f\gamma_{SR_{,p}}(x) \approx \frac{v_1 v_2 \left(\frac{x}{\gamma_p}\right)^{-(\frac{v_2}{\lambda+1})}}{\sqrt{2\pi}\,\lambda_{\gamma_p}} * e^{\left(-\frac{\left(v_0 - v_1\left(\frac{x}{\gamma_p}\right)^{\left(-\frac{v_0}{\lambda}\right)}\right)^2}{2}\right)} \quad \text{.......} \quad (2.13)$$

Here, $\lambda = \frac{\ln(10)}{10}$ and v_0, v_1 and v_2 are constant. Based on the equation (2.13), the CDF of the $\gamma_{SR_{,p}}$ can be found as

$$F_{\gamma_{SR_{,p}}}(x) = \Phi\left[\ (v_0 - v_1\left(\frac{x}{\gamma_p}\right)^{-\frac{v_2}{\lambda}}\right] \quad \text{.......} \quad (2.14)$$

Here, $\Phi = \int_0^x \frac{1}{\sqrt{2\pi}}\ e^{-\frac{t^2}{2}}dt$ is the Gaussian function with zero average and tune discord. As both the periods of the relaying model are free, we can get the same CDF and PDF of $\boldsymbol{\gamma_{RD,p}}$, which are $f\gamma_{RD,p} \approx f\gamma_{SR,p}$ and $F\gamma_{RD,p} \approx F\gamma_{SR,p}$, where $f\gamma_{SR,p}$ and $F\gamma_{RD,p}$ are the PDF and CDF of the adopted SNR at D. The value of Φ can be further simplify by integrating with respect to t in Matlab with an interval of {0, $v_0 - v_1(\frac{x}{\gamma_p})^{-\frac{v_2}{\lambda}}$ } Which is,

$$\Phi\ (\mathrm{x}) = \frac{\pi^{\frac{1}{2}} * erf\left[\left(\frac{2^{\frac{1}{2}} * v_0}{2}\right) - \left(\frac{2^{\frac{1}{2}} * v_1}{2\left(\frac{x}{\gamma_p}\right)^{\frac{v_2}{\lambda}}}\right)\right]}{2\pi^{\frac{1}{2}}} \quad \text{.......} (2.15)$$

[Equation 2.15 we find from MATLAB Software]

Here, erf(•) = error function

Equation (2.14) can be simplified from Matlab by differentiating with respect to x. It is,

$$F_{\gamma_{SR,p}} = \frac{2^{\frac{1}{2}} * v_1 * v_2}{2 * \mu^{\frac{1}{2}} * \gamma_p * \lambda * e^{\left(\frac{2^{\frac{1}{2}} * v_0}{2} - \frac{2^{\frac{1}{2}} * v_1}{\left(2\frac{x}{\gamma_p}\right)^{\frac{v_2}{\lambda}}}\right)^2} \left(\frac{x}{\gamma_p}\right)^{\frac{v_2}{\lambda}+1}} \quad \text{.......} (2.16)$$

[Equation 2.16 we find from MATLAB Software]

Here, v_0, v_1 and v_2 are constants.

Next, we consider a statistical character of the wireless channel. Generally, for the practical IoT networks, the Nakagami-m model is adopted as the distribution for the wireless channel gain $\boldsymbol{h_w}$. Its PDF can be obtained as

$$f_{h_w}(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m}\ e^{(-\frac{m}{\Omega}x^2)} \quad \text{.......} (2.15)$$

Here, $m = \frac{E^2(x)^2}{\sigma(x)^2}$, $\Omega = E\ (x)^2, \Gamma(x) = \int_0^\infty t^{x-1}e^{-t}\mathrm{dt}$ and E (.) is the statistical expectation operator. Transmit SNR for the wireless channel $\gamma_w \triangleq \frac{1}{\sigma_w^2}$ and we have $\gamma_{SR,w} = \gamma_w h_w^2$. From (2.15) we can find the PDF of the received SNR for wireless channel at relay as

$$f_{\gamma_{SR,w}}(x) = \frac{(\frac{m}{\gamma_w \Omega})^m x^{m-1}}{\Gamma(m)}\ e^{(-\frac{m}{\gamma_w \Omega}x)} \quad \text{.......} (2.16)$$

Moreover, it follows that [31]

$$\int_0^u x^{v-1}e^{-\mu x}\ dx = \mu^{-v}\Upsilon(v, \mu u) \quad \text{.......} (2.17)$$

Here, $\Upsilon(\alpha, x) = \sum_{n=0}^{\infty} \frac{(-1)^n \, x^{\alpha+n}}{n!(\alpha+n)}$

By substituting (2.16) and (2.17) the received SNR's CDF over the wireless channel can be obtain as

$$F\gamma_{SR,w}(\text{x}) = \frac{(\frac{m}{\gamma_W \, \Omega})^m}{\Gamma(m)} \int_0^x t^{m-1} e^{-\frac{m}{\gamma_W \, \Omega} t} dt$$

$$= \frac{\Upsilon\,(m, \frac{m}{\gamma_W \, \Omega} x)}{\Gamma(m)} \quad \text{……………………………………………………………..……..(2.18)}$$

$\int_0^x t^{m-1} e^{-\frac{m}{\gamma_W \, \Omega} t} \, dt$ is calculated from MATLAB and the result is,

$$\frac{\Gamma m - \Gamma\left(m, \frac{mx}{oy}\right)}{\left(\frac{m}{oy}\right)^m}$$

2.3 Spectrum Sensing in Cognitive Radio Network:

To find out the appearance of PU, energy detection method is used. By comparing the energy statistics with present threshold, energy detection confirms the appearance of primary user. We assume the received signal is

$$Y(m) = \mu s(m) + h(m) + n(m) \quad \text{………… ……………(2.19)}$$

Here, m =1, 2, 3……M

μ = indicator of primary user (if μ=1, primary user is present and if μ=0, primary user is absent)

h(m) = channel sample

n(m) = noise sample

s(m) = signal sample

M = number of samples = $t_s \, f_s$; [f_s = sample frequency]

Now the energy statistics of sample signal,

$$E(y) = \frac{1}{M}\sum_{m=1}^{M}(y(m))^2 \quad \text{(2.20)}$$

When M is very large, it follows the Gaussian distribution.

If μ = 0, then the false alarm probability, P_f (θ) = P_r (E(y) > λ|μ=0)

$$=Q\left(\left(\frac{\lambda}{\sigma^2}-1\right)\sqrt{\theta\frac{r\,f_s}{v}}\right) \quad \text{(2.21)}$$

If μ = 1, then the detection probability, P_d (θ) = P_r (E(y) > λ|μ=1)

$$= Q\left(\left(\frac{\lambda}{\sigma^2(1+\gamma)}-1\right)\sqrt{\theta\frac{r\,f_s}{v}}\right) \quad \text{(2.22)}$$

Here, γ = Signal to noise ratio (SNR)

σ^2 = Noise power

θ = sensing angle

λ = sensing threshold

Q(x) = Q function = $\frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp\left(-\frac{u^2}{2}\right)du$

λ can be found by fixing detection probability,

$$\lambda = \sigma^2(1+\gamma)\left[Q^{-1}\left(P_d\right)\sqrt{\frac{v}{r\;f_s\;\theta}}+1\right] \quad \text{(2.23)}$$

So the false alarm probability will be

$$P_f = Q\left(Q^{-1}\left(P_d\right)(1+\gamma)+\gamma\sqrt{\frac{r\;f_s\,\theta}{v}}\right) \quad \text{(2.24)}$$

When the primary user is absent, the accurate detection probability is $P_r(\mu = 0)(1- P_f)$ and when primary user is absent, the miss detection probability is $P_r(\mu = 1)(1- P_d)$

2.4 Throughput of Wireless Channel:

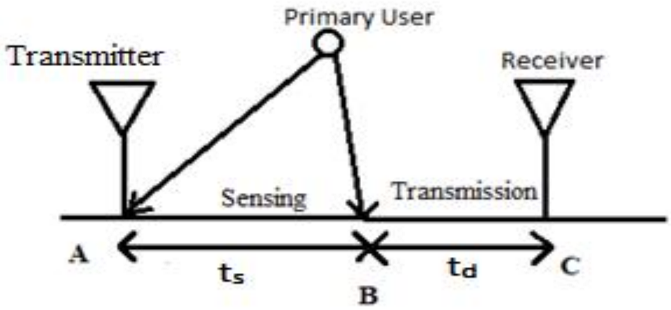

Fig 2.3: Sensing time and Transmission time slot [26]

Now we assume spectrum sensing through a straight line where initial point is A, final point is C and distance between A to C is S. Time taken from A to B is sensing time, t_s and B to C is transmission time, t_d . Here data will transmit when the primary user is absent. If sensing time is, t_s then the transmission time, $t_d = \frac{S - t_s v}{v}$ and S = ($t_s + t_d$).

Applying the value of S, we find v = 1.

So, the effective throughput is

$$R_d(t_s) = \frac{t_d}{t_s + t_d} P_r(\mu=0)\,(1 - P_d)$$

$$= \frac{t_d}{t_s + t_d} P_r(\mu=0)\,(1 - P_d)\,\log_2\left(1 + \gamma_s\right)$$

$$= \frac{t_d}{t_s + t_d} P_r(\mu=0)\,(1 - P_d)\,\log_2\left(1 + \frac{P_t h^2}{\sigma_n^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.25)}$$

Where

$\gamma_s = \frac{p_t\ h^2}{\sigma^2}$ = Secondary User SNR

γ_p = Primary User SNR

P_t = transmission power

And interference throughput is

$$R_i\,(t_s) = \frac{t_d}{t_s + t_d}\,\mathrm{P}_r\,(\mu{=}1)\,\left(1 - P_f\right)$$

$$= \frac{t_d}{t_s + t_d}\,\mathrm{P}_r\,(\mu{=}1)\,\left(1 - P_f\right)\log_2\left(1 + \frac{\gamma_s}{1 + \gamma_p}\right)$$

$$= \frac{t_d}{t_s + t_d}\,\mathrm{P}_r\,(\mu{=}1)\,\left(1 - P_f\right)\log_2\left(1 + \frac{P_t h^2}{\sigma_n^2 (1 + \gamma_p)}\right) \quad \text{... (2.26)}$$

2.5 Path Loss Model:

For path loss model first off all we have to consider channel gain. Assuming the channel gains between PT_x and SR_x is g_p, between ST_x and SR_x is g_s. During the transmission is going on, all channel gains are assumed to be independent. Also, all the channel state information is available during transmission. So, the feedback of the large-scale path loss in the channel gains is,

$$g_{xy}(d_{xy}) = \frac{1}{\sqrt{PL_{xy}(d_{xy})}} \quad \text{.. (2.27)}$$

Here, *x* and *y* indicate two different nodes which are air and ground. Path loss in linear form between *x* and *y* is $PL_{xy}(d_{xy})$ which is isolated by distance d_{xy}.

Two types of channels of the structure we have acknowledged in this model. These are air-to-ground channel and ground-to-ground channel. Both non-fading line of sight component and fading non-line of sight component are present in case of Air to Ground channel. We have considered that Line of Sight links, with a certain probability p_{xy}^{LoS} between UAVs and BSs. So, the path loss between Air to Ground is stated as,

$$PL_{xy}(d_{xy}) = aPL_{xy}^{LoS} + (1 - a)PL_{xy}^{NLoS}\ [dB] \quad \text{...(2.28)}$$

Here, *a* is the probability of available Line of Sight between Air to Ground nodes. From, (2.26) the Line of Sight free path loss is expressed as,

$$PL_{xy}^{NLoS} = 10n\log_{10}\left(\frac{4\pi d_{xy}}{\lambda}\right) + L_{LoS}\ [dB] \quad \text{..(2.29)}$$

Here, path loss component is n and $c = f\lambda$ where f is the carrier frequency and c represent light speed. The average supplementary loss because of Line of Sight link is L_{LoS}. Only NLoS between the ground nodes are assumed in case of Ground to Ground scenario. Hence, the free space path loss can be denoted as,

$$PL_{xy}^{NLoS} = 10n \log_{10}\left(\frac{4\pi d_{xy}}{\lambda}\right) + L_{NLoS}\ [dB] \quad \ldots\ldots(2.30)$$

2.6 Capacity of PLC Channel:

The capacity of the PLC channel is, [32], [33]

$$C_P(\gamma) = \sum_{i=0}^{1} p_i \log_2(1 + \gamma_s \alpha_i)$$

So, the capacity of the PLC channel without interference will be

$$C_{p,0}(\gamma) = P_0 \log_2\left(1 + \gamma_s\alpha_0\right) + P_1 \log_2\left(1+\gamma_s\alpha_1\right)$$

$$= (1\text{-}P) \log_2(1 + \gamma_s\alpha_0) + P\ (1 + \gamma_s\alpha_1)$$

$$= \log_2(1 + \gamma_s\alpha_0) - P\log_2(1 + \gamma_s\alpha_0) + P \log_2(\gamma_s\alpha_1)$$

$$= \log_2(1) + \log_2(\gamma_s\alpha_0) - P \log_2(1) - P \log_2(\gamma_s\alpha_0) + P \log_2(\gamma_s\alpha_1)$$

$$= 0 + \log_2(\gamma_s\alpha_0) - P\log_2(\gamma_s\alpha_0) + P \log_2(\gamma_s\alpha_1)$$

$$= (1\text{-}P) \log_2(\gamma_s\alpha_0) + P \log_2(\gamma_s\alpha_1)$$

$$= (1\text{-}P) \log_2(\gamma_s) + (1\text{-}P) \log_2(\alpha_0) + P \log_2(\gamma_s) + P \log_2(\alpha_1)$$

$$= ((1 - P)\log_2(\alpha_0) + P\log_2(\alpha_1)) + \log_2(\gamma_s) + P\log_2(\gamma_s) - P \log_2(\gamma_s)$$

$$= \Theta(p) + \log_2\left(\gamma_s\right) \quad \ldots\ldots (2.31)$$

Here, $\Theta(p) = (1 - P)\log_2(\alpha_0) + P\log_2(\alpha_1)$

And the capacity of the PLC channel with interference will be

$$C_{p,1}(\gamma) = P_0 \log_2\left(1 + \frac{\gamma_s\alpha_0}{1+\gamma_p}\right) + P_1 \log_2\left(1 + \frac{\gamma_S\alpha_1}{1+\gamma_P}\right)$$

$$= P_0 \log_2\left(\gamma_s\alpha_0\right) - P_0 \log_2(1 + \gamma_P) + P_1 \log_2(\gamma_s\alpha_1) - P_1 \log_2(1 + \gamma_P)$$

$$= P_0 \log_2\left(\gamma_s \alpha_0\right) - P_0 \log_2(\gamma_P) + P_1 \log_2(\gamma_S \alpha_1) - P_1 \log_2(\gamma_P)$$

$$= (1-P)\log_2\left(\gamma_s \alpha_0\right) - (1-P)\log_2(\gamma_P) + P\log_2(\gamma_S \alpha_1) - P\log_2(\gamma_P)$$

$$= \log_2\left(\gamma_s \alpha_0\right) - P\log_2\left(\gamma_s \alpha_0\right) - \log_2(\gamma_P) + P\log_2(\gamma_P) + P\log_2(\gamma_S \alpha_1) - P\log_2(\gamma_P)$$

$$= \log_2\left(\gamma_s \alpha_0\right) - P\log_2\left(\gamma_s \alpha_0\right) - \log_2(\gamma_P) + P\log_2(\gamma_S \alpha_1)$$

$$= \left((1-P)\log_2\left(\alpha_0\right) - P\log_2(\alpha_1)\right) + \log_2(\gamma_S) - \log_2(\gamma_P)$$

$$= \Theta(\mathrm{p}) + \log_2\left(\frac{\gamma_s}{\gamma_p}\right) \quad \ldots\ldots (2.32)$$

Here, Θ (p) = $(1-P)\log_2(\alpha_0) + P\log_2(\alpha_1)$

γ_s = Unlicensed User SNR

γ_p = Licensed User SNR

P_0 = (1- P) , P_1 = P

$\alpha_0 = (1+P\eta)$, $\alpha_1 = \frac{1+P\eta}{1+\eta}$

Where, $\eta \triangleq \frac{\sigma_1^2}{\sigma_G^2}$ [26]

So, the average capacity,

$$C_{SR,p} = \int_0^\infty C_p(\gamma)\, d F_{\gamma SR,p}(x) \quad \ldots\ldots (2.33)$$

Now, substituting the value of $C_{p,0}(\gamma)$ and $C_{p,1}(\gamma)$ to (2.33),

$$C_{SR,p0} = \int_0^\infty C_{p,0}(\gamma_s)\, d F_{\gamma SR,p}(x)$$

$$= \Theta(p) + \int_0^{\infty} \log_2(\gamma_s)\, d\phi \left(v_0 - v_1 \left(\frac{x}{\gamma_p} \right)^{\frac{-v_2}{\lambda}} \right)$$

$$= \Theta(p) + \int_0^{\infty} \log_2(\gamma_s) \frac{\sqrt{2} v_1 v_2}{2\sqrt{\pi}\gamma\lambda \exp\left(\left(\frac{v_0}{\sqrt{2}} - \frac{v_1}{2\left(\frac{x}{\gamma_p}\right)^{\frac{v_2}{\lambda}}} \right)^2 \right) \left(\frac{x}{\gamma_p} \right)^{\left(\frac{v_2}{\lambda}+1\right)}}$$

$$= \Theta(p) + \int_0^{\infty} \log_2(\gamma_s) \frac{\sqrt{2} v_1 v_2}{2\sqrt{\pi}\gamma\lambda \exp(m^2) \left(\frac{x}{\gamma_p} \right)^{\left(\frac{v_2}{\lambda}+1\right)}} \quad \text{.................................(2.34)}$$

Here, $\lambda = \frac{\ln 10}{10}$ and

$v_0, v_1, v_2 =$ Constants.

Let, m = $\left(\frac{v_0}{\sqrt{2}} - \frac{v_1}{2\left(\frac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}} \right)$

$$Now,\ dm = \frac{V_1 V_2}{\sqrt{2}\lambda\gamma_p \left(\frac{x}{\gamma_p} \right)^{\left(\frac{V_2}{\gamma}+1\right)}} dx$$

So, $dx = \frac{\sqrt{2}\lambda\gamma_p \left(\frac{x}{\gamma_p} \right)^{\left(\frac{v_2}{\gamma}+1\right)}}{v_1 v_2} dm$ ....(2.35)

Therefore, x = $\left(\dfrac{v_1}{v_0 - \sqrt{2}m}\right)^{\frac{\lambda}{v_2}} \gamma_p$

According to [34],

$$\int_{-\infty}^{\infty} f(x)\, e^{-x^2}\, dx \approx \sum_{i=1}^{N} \omega_i\, f(x_i)$$

So,

$$\int_{0}^{\infty} f(x)\, e^{-x^2}\, dx \approx \frac{1}{2}\sum_{i=1}^{N} \omega_i\, f(x_i)$$

Here, N= Hermite polynomial order

$\omega_i = i$ th weight = $\dfrac{2^{n-1} n! \sqrt{\pi}}{n^2 \left(H_{n-1}(x_i)\right)^2}$

x_i = i th zero of the Hermite polynomial

Therefore, $C_{SR,p0} = \Theta(\text{p}) + \int_0^{\infty} \log_2(\gamma_s) \dfrac{\sqrt{2} v_1 v_2}{2\sqrt{\pi}\gamma\lambda \exp\left(m^2\right)\left(\dfrac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}}$

$$= \Theta(\text{p}) + \int_0^{\infty} \log_2(\gamma_s) \frac{\sqrt{2} v_1 v_2 \exp\left(m^{-2}\right)}{2\sqrt{\pi}\gamma\lambda\left(\dfrac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}}$$

$$= \Theta(\text{p}) + ½ \sum_{i=1}^{N} \omega_i \frac{\log(\gamma_s)}{\sqrt{\pi}\left(\dfrac{v_1}{v_0 - \sqrt{2}m}\right)^{\left(\lambda/v_2\right)}\left(\dfrac{x_i}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}\right)}} \quad \text{………………} (2.36)$$

$$C_{SR,P1} = \int_0^\infty c_{P,1}(\gamma)\, d F_{\gamma SR,\, p}(x)$$

$$= \Theta(\mathrm{p}) + \int_0^\infty \log_2\left(\frac{\gamma_s}{\gamma_p}\right) d\phi\left(v_0 - v_1\left(\frac{x}{\gamma_p}\right)^{\frac{-v_2}{\lambda}}\right)$$

$$= \Theta(\mathrm{p}) + \int_0^\infty \log_2\left(\frac{\gamma_s}{\gamma_p}\right) \frac{\sqrt{2} v_1 v_2}{2\sqrt{\pi}\gamma\lambda \exp\left(\left(\frac{v_0}{\sqrt{2}} - \frac{v_1}{2\left(\frac{x}{\gamma_p}\right)^{\frac{v_2}{\lambda}}}\right)^2\right)\left(\frac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}}$$

$$= \Theta(\mathrm{p}) + \int_0^\infty \log_2\left(\frac{\gamma_s}{\gamma_p}\right) \frac{\sqrt{2} v_1 v_2}{2\sqrt{\pi}\gamma\lambda \exp\left(m^2\right)\left(\frac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}}$$

$$= \Theta(\mathrm{p}) + \int_0^\infty \log_2\left(\frac{\gamma_s}{\gamma_p}\right) \frac{\sqrt{2} v_1 v_2}{2\sqrt{\pi}\gamma\lambda \exp\left(m^2\right)\left(\frac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}} \quad \text{………………..………..(2.37)}$$

According to [34],

$$C_{SR,P1} = \Theta(\mathrm{p}) + \int_0^\infty \log_2\left(\frac{\gamma_s}{\gamma_p}\right) \frac{\sqrt{2} v_1 v_2 \exp\left(m^{-2}\right)}{2\sqrt{\pi}\gamma\lambda\left(\frac{x}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}+1\right)}}$$

$$= \Theta(\mathrm{p}) + \tfrac{1}{2} \sum_{i=1}^{N} \omega_i \frac{\log\left(\frac{\gamma_s}{\gamma_p}\right)}{\sqrt{\pi}\left(\frac{v_0 - \sqrt{2}m}{v_1}\right)^{\left(\frac{\lambda}{v_2}\right)} \left(\frac{x_i}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}\right)}} \quad \text{……………………......... (2.38)}$$

So,

$C_{av} = 2\Theta(p) +$

$$\tfrac{1}{2}\sum_{i=1}^{N}\omega_i \frac{\log(\gamma_s)}{\sqrt{\pi}\left(\frac{v_1}{v_0 - \sqrt{2}m}\right)^{\left(\lambda/v_2\right)}\left(\frac{x_i}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}\right)}} + \tfrac{1}{2}\sum_{i=1}^{N}\omega_i \frac{\log\left(\frac{\gamma_s}{\gamma_p}\right)}{\sqrt{\pi}\left(\frac{v_0 - \sqrt{2}m}{v_1}\right)^{\left(\frac{\lambda}{v_2}\right)}\left(\frac{x_i}{\gamma_p}\right)^{\left(\frac{v_2}{\lambda}\right)}}$$

Chapter 3

Results and Discussion

In this section, we are going to discuss about the result of Cognitive Wireless system. We have used MATLAB for simulation and compared the numerical efficiency in each figure. There are some parameters have been used in the MATLAB simulation given below,

Parameters for Fig. 3.1, 3.2, 3.3 and 3.4

f_c	2×10^9
c	3×10^8
n	4
L_LOS	3
L_NLOS	10
t_d	3
t_s	1
P_d	0.5
P_f	0.5
σ	$10^{-3}\times10^{\frac{-174}{10}}$

Parameters for Fig. 3.4 and 3.5

N_p	2
λ	$\frac{log10}{10}$
V_2	0.02
V_1	12.37
V_0	8.21
a_0	0.1
p	0.5
a_1	0.9

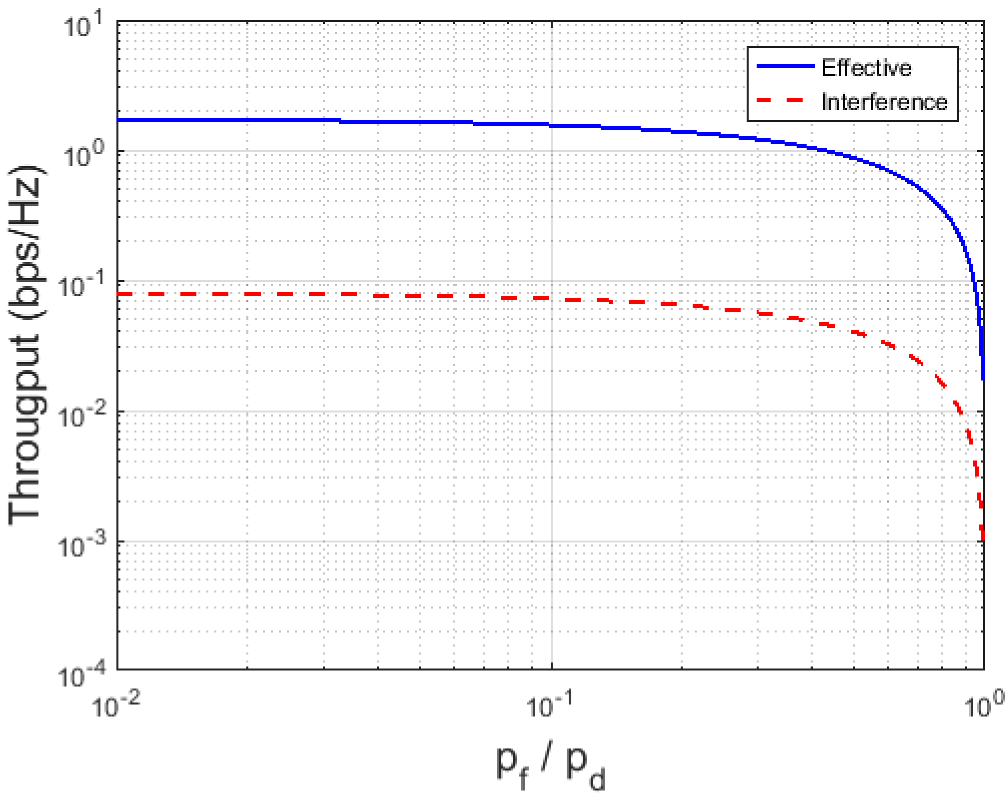

Fig 3.1: Throughput vs P_f/P_d

In fig. 3.1 we are going to talk about throughput vs P_f / P_d (false alarm probability/detection alarm probability) and also its changing efficiency with P_f / P_d . Furthermore, for a single point of ration of p_f / p_d we are getting different effective throughput and interference throughput.

To begin with, if P_f / P_d =0.02, then we are getting effective throughput of 1.7 bps/Hz and interference throughput of 0.08 bps/Hz and the efficiency is 4.7 %. After that, if we it has been moved further in P_f / P_d axis and take the value of P_f / P_d =0.45 then effective throughput is 0.95 bps/Hz and interference throughput is 0.044 bps/Hz and the efficiency for this point of P_f / P_d is going to be 4.63 %. Furthermore, if we are to take P_f / P_d =0.85 then effective throughput is 0.26 bps/Hz and interference throughput is 0.012 bps/Hz and for this point of P_f / P_d , the efficiency is going to be 4.61 %. Finally, we can say that in fig. 3.1 simulation the efficiency decreases with the increasing value of P_f / P_d .

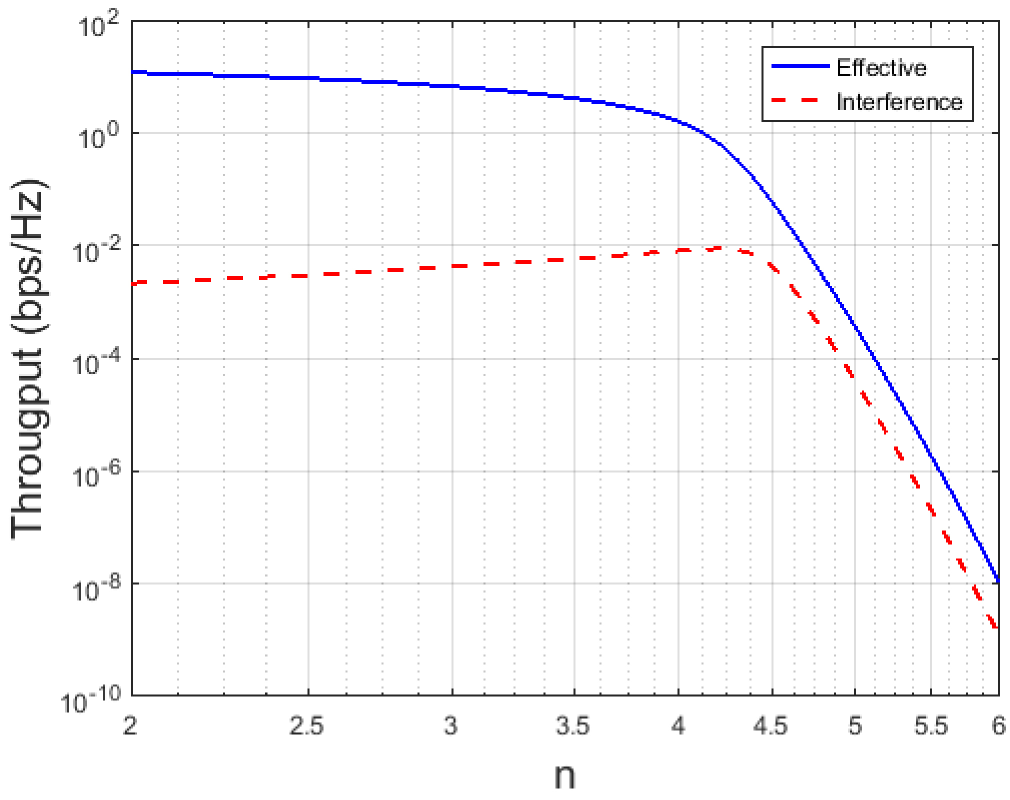

Fig 3.2: Throughput vs n

Throughput vs path-loss exponent (n) and its efficiency is going to be analyzed in fig. 3.2. To begin with, for a single point of path exponent value, we are getting effective throughput and interference throughput respectively. Let's say, n=2.15 and for this value, effective throughput going to be 10.92 bps/Hz and interference throughput going to be 0.0023 bps/Hz and the efficiency is 0.02%.Furthermore, if n=2.85, we get effective throughput of 7.37 bps/Hz and interference throughput of 0.0038 bps/Hz and for this value of path-loss exponent, we get the efficiency of 0.05%. Moving forward, if n=4.16, then the value of effective throughput and interference throughput is 0.82 bps/Hz and 0.0086 bps/Hz respectively, for this throughput values the efficiency will be 1.049%. Finally, with the values of efficiency we can say that it increases with the increasing values of path-loss exponent.

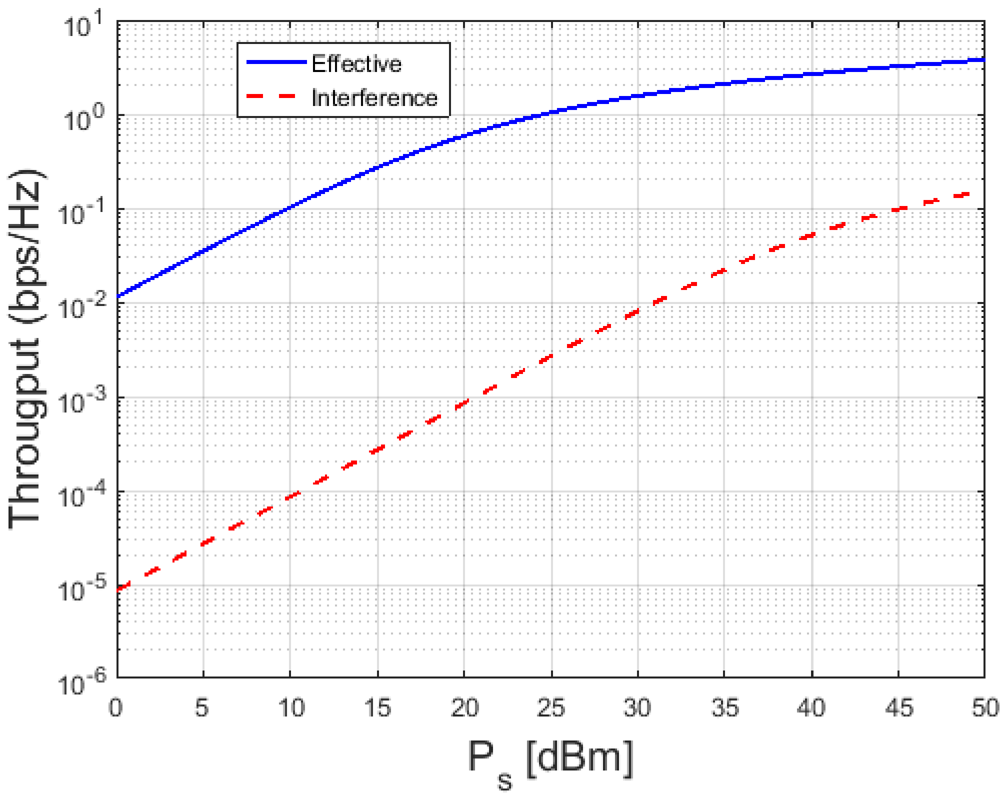

Fig 3.3: Throughput vs P_s

Throughput vs Secondary user transmission power has been discussed in fig. 3.3, Ps [dBm]. For this section, we are also going to evaluate the efficiency with the increasing value of secondary user transmission power. To begin with, if Ps=5 dBm is taken then effective throughput and interference throughput are 0.035 bps/Hz and 2.72×10^{-5} bps/Hz respectively and the efficiency is 52.36%. Furthermore, if we are to take Ps=10 dBm then we get the efficiency of 56.52% with the help of effective throughput and interference throughput values of 0.1024 bps/Hz and 8.59×10^{-5} respectively. However, if we start to increase the value of Ps at this point, let's say Ps =11 dBm then then efficiency suddenly drops to 0.07% and then it starts to increase again with the increasing value of Ps. For example, if Ps=20 dbm is taken in figure, then the efficiency is 0.144% and after that, if we have taken Ps=45dBm then the efficiency is 3.01%. So, after analyzing this simulation, we can say that, efficiency for this figure is high at the beginning and when secondary user transmission power is 11 dbm then it decreases significantly and then again it starts to increase linearly.

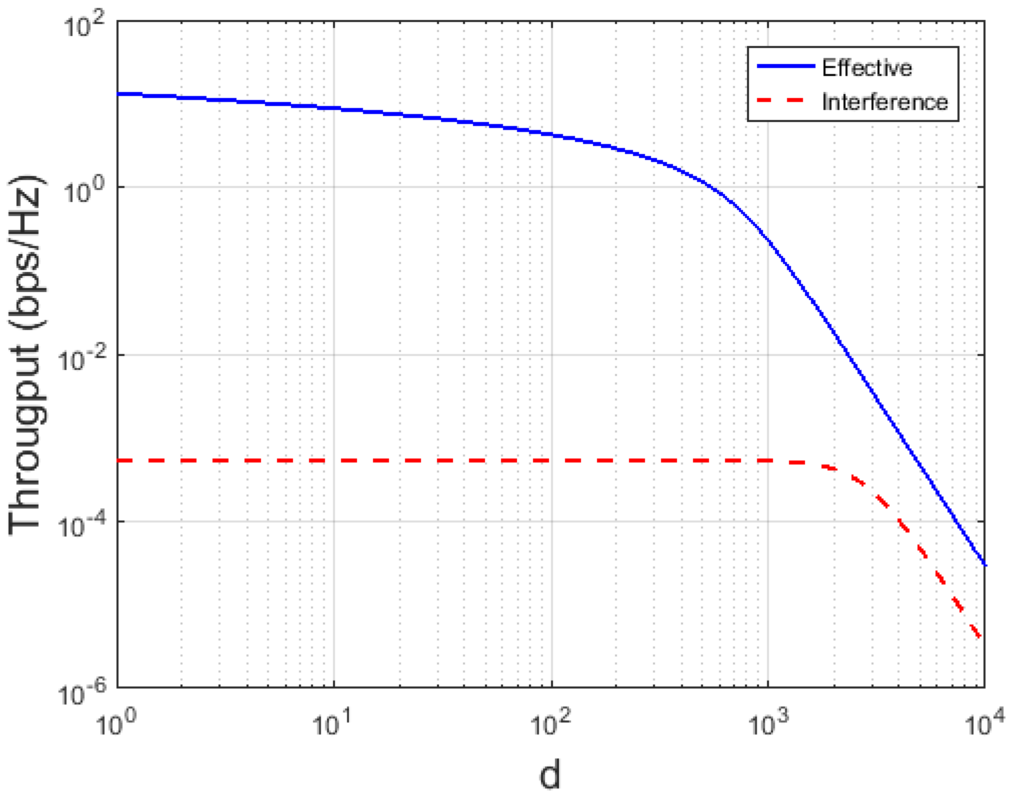

Fig 3.4: Throughput vs d

In fig. 3.4 we are going to discuss about throughput vs distance between transmitter & receiver, d. Furthermore, we are also going to evaluate the efficiency of this figure with the increasing values of d. To begin with, if d=3 is taken then effective throughput is 11.06 bps/Hz and interference throughput is 0.00054 bps/Hz and for this value we get the efficiency of 4.88×10^{-3} %. Moving forward, if d=54 has been taken then we get effective throughput of 5.43 bps/Hz and interference throughput of 0.00054 bps/Hz and for this we get efficiency of 9.944×10^{-3} %. Furthermore, if we have to increase the value of d again and take d=801 then the effective throughput and interference throughput will be 0.44 bps/Hz and 0.00053 bps/hz respectively and we get the efficiency of 0.120 %. Finally, after this discussion we can say that, efficiency is increasing with the increasing value of d.

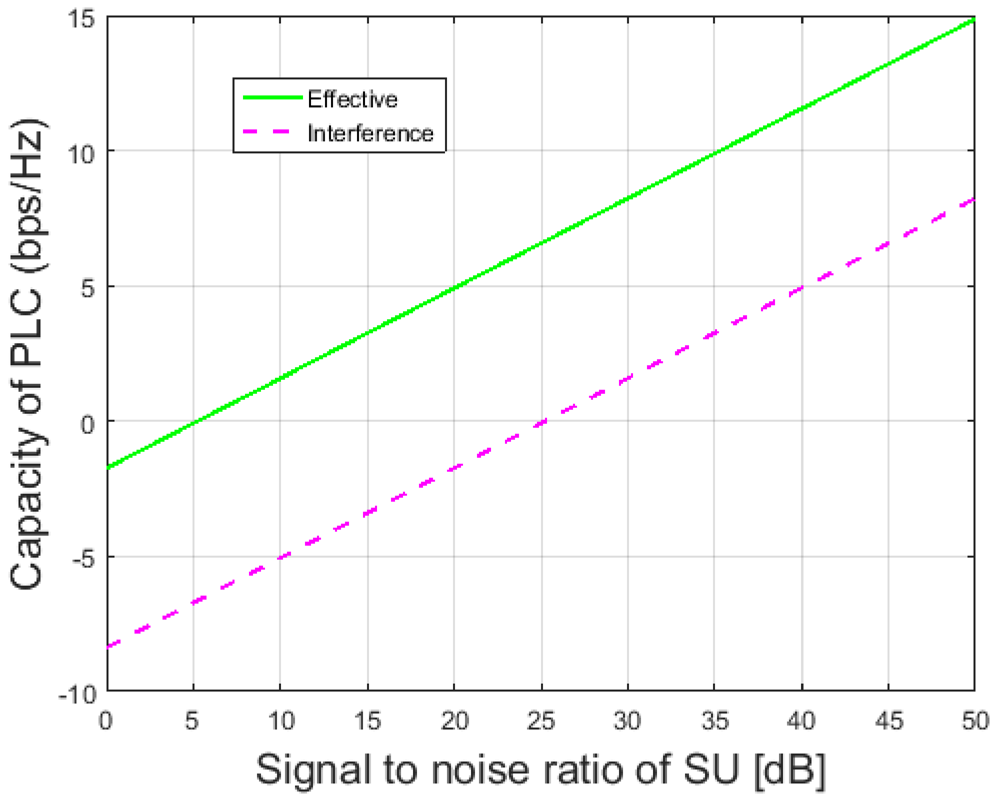

Fig 3.5: Capacity of PLC vs Signal to noise ratio of SU

In this section, we are going to discuss about Capacity of PLC (bps/Hz) vs signal to noise ratio of SU (dB).Firstly, Signal to noise ratio of SU has been taken 5 dB and because of that we are getting effective capacity of PLC -0.076 bps/Hz and interference capacity of PLC of -6.72 bps/Hz .So, the improvement at this point has been taken 6.644 bps/Hz. Afterwards, we have taken 30 dB signal to noise ratio of SU and resultant for this point, we have been found is 8.229 bps/Hz effective capacity of PLC and 1.585 bps/Hz interference capacity of PLC respectively. Furthermore, the improvement for 30 dB SNR of SU point has been measure to be 6.644 bps/Hz. Moving forward, 45 dB signal to noise ratio of SU has been taken for measurement and we have found 13.21 bps/Hz effective capacity of PLC and 6.568 bps/Hz interference capacity of PLC. Finally, for this point, we have improvement of 6.642 bps/Hz

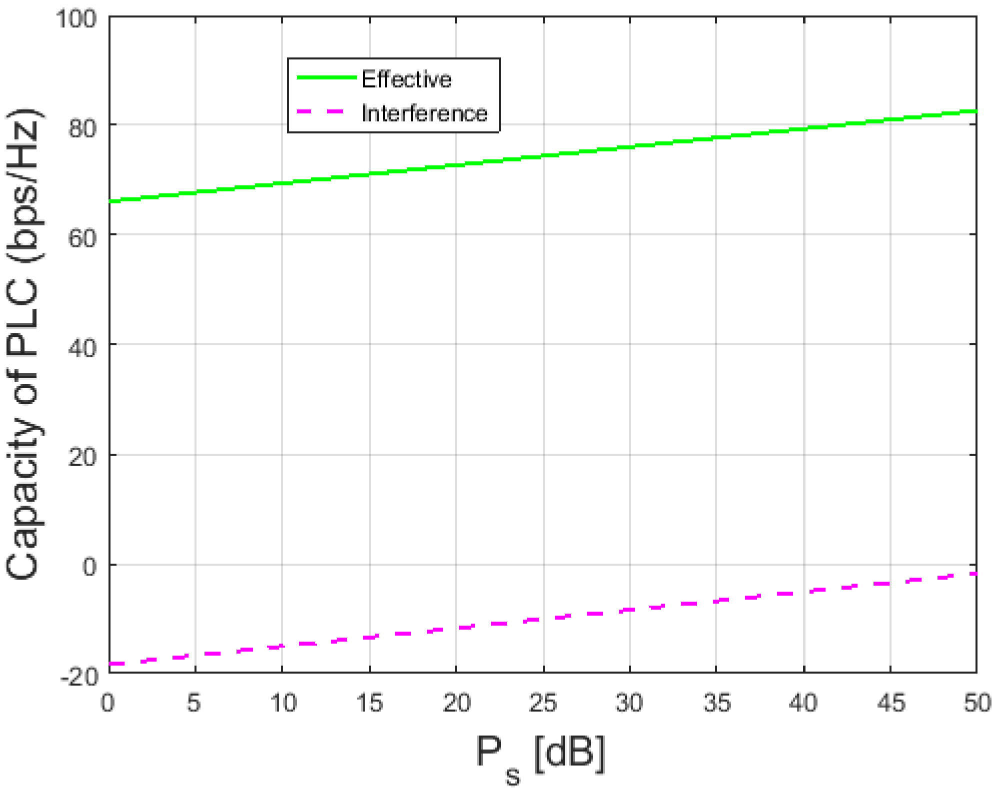

Fig 3.6: Capacity of PLC vs P_s

Capacity of PLC vs Secondary user transmission power ($P_{s)}$ is going to be analyzed in this part. Firstly, P_s=5 dB has been taken so we have found effective capacity of PLC 67.69 bps/Hz and interference capacity of PLC -16.69 bps/Hz and improvement has been found to be 84.38 bps/Hz. Furthermore, P_s =30 db has been taken so effective capacity of PLC 76 bps/Hz and interference capacity of PLC -8.38 bps/Hz has been found and improvement for this point is 84.38 bps/Hz.

Chapter 4

4.1 Conclusion

In this paper, we have investigated a Cognitive Wireless and Power Line Networks using IoT. Here, we have used both wireless and PLC sensors with a system of IoT. Basically, PLC and wireless sensors can be unbalanced for long line. For that reason, we have used dual interface relaying nodes to overcome unbalancing problem. This provides strong connections. Besides, we have executed CDF and PDF of the SNR that we obtained for both wireless and PLC. Finally, with the help of simulation result we have observed,

i) The efficiency of Cognitive Wireless system and the improvement of the Capacity of PLC system.

ii) The efficiency increases with the increase of path loss exponent, transmission power, distance of transmitter and receiver and the ratio of P_f and P_d for cognitive wireless system.

iii) The capacity improves significantly with the increase of SNR and transmission power of SU for the PLC system.

4.2 Future Work

1. In future we will work with the cognitive wireless sensor networks to examine the delay sensitive contribution [37].
2. We will also work with MIMO-OFDM which is very good for wireless communication when the data rate is high [39].
3. Moreover, we will inspect the energy harvesting in cognitive radio network of dual slope path loss model. Basically, energy harvesting makes the network more complex but it still reduces the use of cell which is very much nature friendly [38].

References

[1]. M. W. Khan & M. Zeeshan, "QoS-based dynamic channel selection algorithm for cognitive radio based smart grid communication network". Ad Hoc Networks, vol. 87, pp. 61-75, 2019. doi:10.1016/j.adhoc.2018.11.007

[2]. R. Yu, Y. Zhang, S. Gjessing, C. Yuen, S. Xie and M. Guizani, "Cognitive radio based hierarchical communications infrastructure for smart grid", *IEEE Network*, vol. 25, no. 5, pp. 6-14, 2011. Available: 10.1109/mnet.2011.6033030.

[3]. A. Ghassemi, S. Bavarian and L. Lampe, "Cognitive Radio for Smart Grid Communications", *2010 IEEE International Conference on Smart Grid Communications*, 2019.[Online].Available:https://www.academia.edu/5211496/Cognitive_Radio_for_Smart_Grid_Communications. [Accessed: 18- Jul- 2019].

[4]. J. Huang, H. Wang, Y. Qian and C. Wang, "Priority-Based Traffic Scheduling and Utility Optimization for Cognitive Radio Communication Infrastructure-Based Smart Grid", IEEE Transactions onSmart Grid, vol.4, no. 1, pp. 78-86, 2013.Available:10.1109/tsg.2012.2227282.

[5]. Z. Yang, S. Ping, H. Sun and A. Aghvami, "CRB-RPL: A Receiver-Based Routing Protocol for Communications in Cognitive Radio Enabled Smart Grid", IEEE Transactions on Vehicular Technology, vol.66, no. 7, pp. 5985-5994, 2017. Available: 10.1109/tvt.2016.2617874.

[6]. E. Ogbodo, D. Dorrell and A. Abu-Mahfouz, "Cognitive Radio Based Sensor Network in Smart Grid: Architectures, Applications and Communication Technologies", *IEEE Access*, vol. 5, pp. 19084-19098, 2017. Available: 10.1109/access.2017.2749415.

[7]. N. Ghasemi & S. Hosseini "Comparison of Smart Grid with Cognitive Radio: Solutions to Spectrum Scarcity'' 2010. Retrieved July18, 2019.

[8]. Z. Yang, S. Ping, A. Aijaz and A. Aghvami, "A Global Optimization-Based Routing Protocol for Cognitive-Radio-Enabled Smart Grid AMI Networks", *IEEE Systems Journal*, vol. 12, no. 1, pp. 1015-1023, 2018. Available: 10.1109/jsyst.2016.2580616.

[9]. B. Khalfi, M. B. Ghorbel, B. Hamdaoui, & M. Guizani. "Optimal power allocation for smart-grid powered point-to-point cognitive radio system". *2014 IEEE Computers, Communications and IT Applications Conference*. doi:10.1109/comcomap.2014.7017217

[10]. S. Alam, M. Sohail, S. Ghauri, I. Qureshi and N. Aqdas, "Cognitive radio based Smart Grid Communication Network", *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 535-548, 2017. Available: 10.1016/j.rser.2017.01.086.

[11]. R. Qiu et al., "Cognitive Radio Network for the Smart Grid: Experimental System Architecture, Control Algorithms, Security, and Microgrid Testbed", *IEEE Transactions on Smart Grid*, vol. 2, no. 4, pp. 724-740, 2011. Available: 10.1109/tsg.2011.2160101.

[12]. X. Huang and N. Ansari, "Resource Exchange in Smart Grid Connected Cooperative Cognitive Radio Networks", *IEEE Transactions on Vehicular Technology*, vol. 66, no. 7, pp. 6291-6298, 2017. Available: 10.1109/tvt.2016.2642902.

[13]. A. Khan, M. Rehmani and M. Reisslein, "Cognitive Radio for Smart Grids: Survey of Architectures, Spectrum Sensing Mechanisms, and Networking Protocols", *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 860-898, 2016. Available: 10.1109/comst.2015.2481722.

[14]. R. Deng, J. Chen, X. Cao, Y. Zhang, S. Maharjan and S. Gjessing, "Sensing-Performance Tradeoff in Cognitive Radio Enabled Smart Grid", *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 302-310, 2013. Available: 10.1109/tsg.2012.2210058.

[15]. M. Ozger, O. Cetinkaya and O. Akan, "Energy Harvesting Cognitive Radio Networking for IoT-enabled Smart Grid", *Mobile Networks and Applications*, vol. 23, no. 4, pp. 956-966, 2017. Available: 10.1007/s11036-017-0961-3.

[16]. S. Althunibat, Q. Wang and F. Granelli, "Flexible channel selection mechanism for cognitive radio based last mile smart grid communications", *Ad Hoc Networks*, vol. 41, pp. 47-56, 2016. Available: 10.1016/j.adhoc.2015.10.008.

[17]. T. Nghia Le, W. Chin and H. Chen, "Standardization and Security for Smart Grid Communications Based on Cognitive Radio Technologies—A Comprehensive Survey", *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 423-445, 2017. Available: 10.1109/comst.2016.2613892.

[18]. Q. Li, Z. Feng, W. Li, T. Gulliver and P. Zhang, "Joint Spatial and Temporal Spectrum Sharing for Demand Response Management in Cognitive Radio Enabled Smart Grid", *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1993-2001, 2014. Available: 10.1109/tsg.2013.2292528.

[19] M. Amin and B.Wollenberg, “Toward a smart grid: Power delivery for the 21st century,” *IEEE Power Energy Mag*, vol. 3, no. 5, pp. 34–41, Sep.-Oct. 2005.

[20] A. Ipakchi and F. Albuyeh, “Grid of the future,” *IEEE Power Energy Mag*, vol. 7, no. 2, pp. 52–62, Mar.-Apr. 2009.

[21] X. Fang, S. Misra, G. Xue, and D. Yang, “Smart grid the new and improved power grid: A survey,” *IEEE Commun. Surveys Tuts.*, to be published.

[22] H. Farhangi, “The path of the smart grid,” *IEEE Power Energy Mag*, vol. 8, no. 1, pp. 18–28, Jan.-Feb. 2010.

[23] Y. Qian, M. Tian, X. Jian, S. Feng, and J. Li, “Performance analysis for a two-way relaying power line network with analog network coding,” *Frontiers of Information Technology and Electronic Engineering*, vol. 16, no. 10, pp. 892–898, 2015.

[24] N. Kushiro, T. Higuma, M. Nakata, H. Kubota, and K. Sato, “Practical solution for constructing ubiquitous network in building and home control system,” *IEEE Transactions on Consumer Electronics*, vol. 53, no. 4, pp. 1387–1392, 2007.

[25] A. Dubey, R. K. Mallik, and R. Schober, “Performance analysis of a power line communication system employing selection combining in correlated lognormal channels and impulsive noise communications,” *IET Communications*, vol. 8, no. 7, pp. 1072–1082, 2014.

[26] Y. Qian et al., "Design of Hybrid Wireless and Power Line Sensor Networks with Dual-Interface Relay in IoT", *IEEE Internet of Things Journal*, vol. 6, no. 1, pp. 239-249, 2019. Available: 10.1109/jiot.2017.2725451.

[27] A. Dubey, R. K. Mallik, and R. Schober, “Performance analysis of a power line communication system employing selection combining in correlated lognormal channels and impulsive noise communications,” *IET Communications*, vol. 8, no. 7, pp. 1072–1082, 2014.

[28] G. B. L. Lampe and H. Hrasnica, “Power line communication networks for large-scale control and automation systems,” *IEEE Communication Magazine*, vol. 48, no. 4, pp. 1076–113, 2010.

[29] D. G. Brennan, “Linear diversity combining techniques,” in *IEEE Proceeding*, vol. 91, no. 2, 2003, pp. 331–356.

[30] N. C. Beaulieu and F. Rajwan, “Highly accurate simple closed-form approximations to lognormal sum distributions and densities,” *IEEE Communication Letters*, vol. 8, no. 12, pp. 709–712, 2004.

[31] I. S. Gradshteyn and I. Ryzhik, *Table of Integrals, Series, and Products (Seventh Edition))*. Elsevier, 2007.

[32] M. Hosseini, G. Hodtani, and M. Kakhki, “Capacity analysis of power line communication point-to-point and relay channels,” *Transactions on Emerging Telecommunications Technologies*, vol. 27, pp. 200–217, 2016.

[33] A. Dubey and R. K. Mallik, “Effect of channel correlation on multi-hop data transmission over power lines with decode-and-forward relays,” *IET Communications*, vol. 10, no. 13, pp. 1623–1630, 2016.

[34] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables (9th Edition)*. New York: Dover Publications, 1970.

[35] Yu R et al. (2011) Cognitive Radio Based Hierarchical Communications Infrastructure for Smart Grid. IEEE Net- work, 25(5): 6-14.

[36] M. Ozger, O. Cetinkaya and O. Akan, "Energy Harvesting Cognitive Radio Networking for IoT-enabled Smart Grid", *Mobile Networks and Applications*, vol. 23, no. 4, pp. 956-966, 2017. Available: 10.1007/s11036-017-0961-3.

[37] S. Nazneen, M. M. J. Chowdhury, S. R. Sabuj, “Analysis of delay-sensitive performance in cognitive wireless sensor networks”, *Internet Technology Letters, 2019* (pp. e98). John Wiley & Sons.

[38] S. R. Sabuj & M. Hamamura, “Two-slope path-loss design of energy harvesting in random cognitive radio networks”. In *Computer Networks, 2018* (pp. 128–141). Elsevier.

[39] K. J. Chisty, S. M. Islam, S. E. Ullah & S. R. Sabuj, “Scrambled Voice Frequency Signal Transmission in an Amplify and Forward Relaying Based STBC Encoded Cooperative MIMO-OFDM System”, *International Journal of Signal Processing, Image Processing and Pattern Recognition*, *7*(2), 143–152, 2014.