INVESTIGATION AND PERFORMANCE ANALYSIS OF COGNITIVE WIRELESS SENSOR NETWORK

By

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

Electrical and Electronic Engineering
Brac University
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Declaration

It is hereby declared that

1. The project submitted is my own original work while completing degree at Brac University.
2. The project does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The project does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.
5. I would like to request the embargo of my project for 8M from the submission date due to the publication.

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Approval

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Of Fall, 2019 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering (M. Engg) in EEE on 26 September 2019

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Ethics Statement

It is hereby declared that this project or any part of it has not been submitted elsewhere for the award of any degree or diploma. We have published a paper titled ‘Analysis of delay sensitive performance in cognitive wireless sensor network’ Internet Technology Letters, Wiley, 2019.

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Abstract

Cognitive wireless sensor networks (CWSN) have recently attracted significant research attention owing to their promise for application in the cellular communication. In this study, an analytical uplink modeling for CWSN is introduced. Detailed mathematical analysis of the outage probability, throughput, affected area and delay sensitive area spectral efficiency (DASE) for fixed network is defined and also the outage probability and affected area is derived in random network considering of the probabilities of unoccupied by the channel selection and successful transmission for imperfect detection. The numerical results for fixed network are analyzed depending on theoretical expression which shows that optimal transmission power is efficient to find the maximum value of DASE and for this reason the RF pollution is low.

Keywords: cognitive wireless sensor network, energy efficiency, optimization technique, delay sensitive area efficiency.

Dedication

This project is dedicated for my parents.

Acknowledgement

I would like to express sincere thanks to my thesis supervisor, Dr. Saifur Rahman Sabuj, Assistant Professor, Dept. of Electrical & Electronic Engineering (EEE), BRAC University, for his supervision to make a successful completion of the thesis. I am also grateful to BRAC University for providing me the necessary help for the successful completion of this project.

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List of Acronyms

IoT	Internet of Things
M2M	Machine to Machine
WSNs	Wireless Sensor Networks
CWSNs	Cognitive Wireless Sensor Networks
BS	Base Station
CR	Cognitive Radio
DASE	Delay Sensitive Area Efficiency
SINR	Signal to Interference plus Noise Ratio

Chapter 1

Introduction

1.1 Cognitive wireless sensor networks (CWSN) :

Cognitive wireless sensor networks (CWSN) is a a type of sensor networks where the sensors have cognitive abilities and they can change and adapt their communication parameters in accordance to the change to the nearby environment and this is major difference with the conventional wireless sensor networks (WSN) [1]. The different between WSN and CWSN is shown in Fig. 1.1.

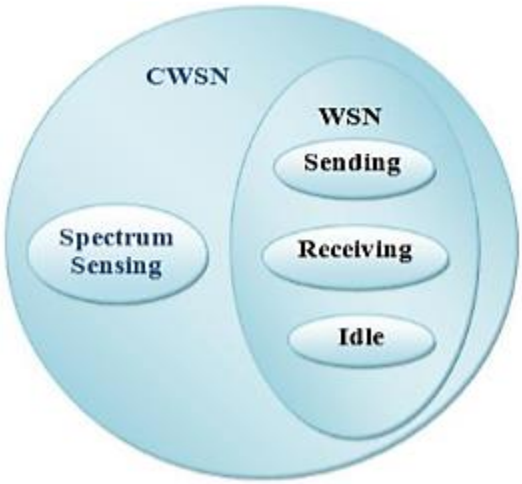

Figure 1.1: CWSN vs WSN [2]

A CWSN is a special network, which has many obedience compared to traditional wireless network. They key enabling for this technology is the spectrum sensing they can provide efficient spectrum utilization which enables opportunistic access to the spectrum [3].

1.1.1 Advantages of CWSN:

The main potential advantages introduced by CWSN are

- Improving spectrum utilization,

- Increasing communication quality,
- Effective Spectrum usage,
- Effective Transmission Quality,
- High Communication range,
- Low node count ,
- Low Energy utilization,
- Maximum Network Lifetime

1.1.2 Architecture of CWSN:

CWSN constructs of various number of compact and cheap sensor nodes that are constrained by resources as shown in Fig. 1.2 .The nodes simply transmit and receive the data or in the idle state as well as sensing state. The sensor nodes sense the desired area and transmit the data to base station (BS) [2]. At emergent part of CIoT depends on CWSN which can improve spectral density as well as reduce power consumption and electromagnetic pollution drastically in cellular networks.

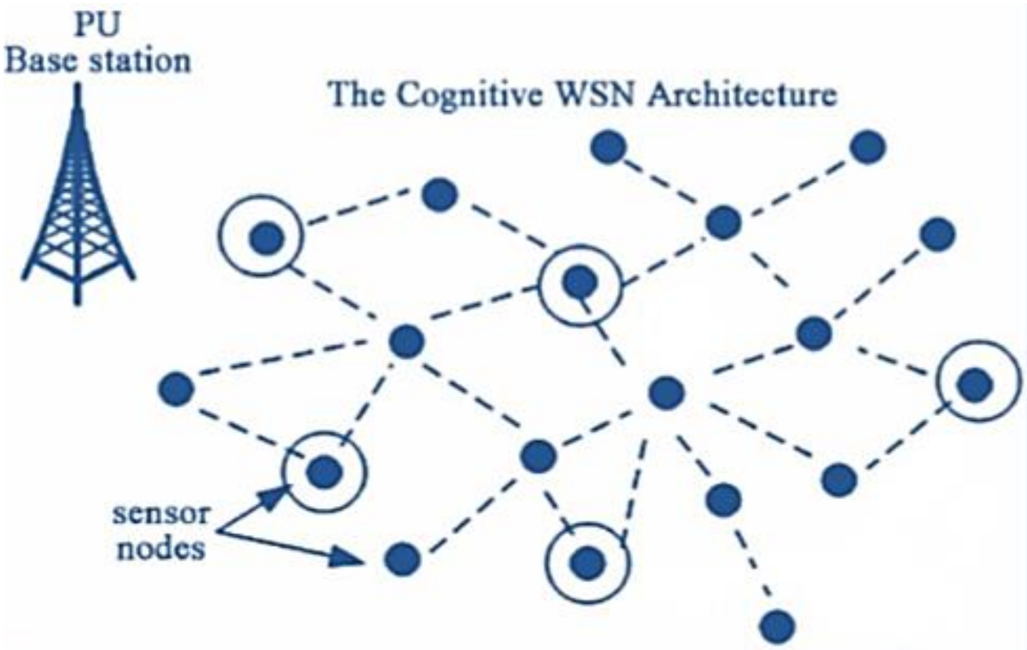

Figure 1.2: Architecture of CWSN [2]

1.2 Review of Previous Works and Observation

There have been research efforts in the area of CIoT systems to address the challenges in energy efficient cognitive networks in the past few years. A short review of the state-of-the-art in this field is presented by this section

Rawat P. present is a metering paper which is based on cognitive radio (CR) to integrate machine-to-machine (M2M) and IoT. This paper considers Several M2M and IoT applications with CR such as smart grid, health care, and medical applications, military applications to assuage spectrum shortage problem. Likewise authors goal in developing the existing rules and protocols used for cognitive M2M communications [4].

Aijaz A and Aghvami AH introduced a paper is audited that proposed model alleviates delay traffic by 38% and interference to PU receiver by 50% [5]. To help performance of network level and defined a new performance metric link successful probability for CIoT networks a central architecture was proposed by Afzal and coworkers for CIoT model [6].

Dynamic spectrum sensing for CR enabled low-power wide area networks are established by B. Moon and the blocking probability of the licensed users, the mean dwell time of the unlicensed user and the total carried traffic and service quality of licensed and unlicensed users are observed [7]. By using a matrix geometric approach, the simulation and the numerical analysis for the strategy are presented.

Kim et al. researched conditional interference distribution issue in CR devices for measuring interference at sensors. cognitive random access algorithm to develop transmission probability of sensors were completed by them. Here a new recovery scheme consisting of timeout and vaccine model to raise transmission probability of SU are presented by Cheng et al [8]. and also end-to-end transmission authenticity for flooding scheme considering outage obedience for both PUs and SUs are explored. In this excercised huts new light on solution of recovery-assisted flooding schemes in CRAHNs and allocates performance appraisal of cognitive IoT services built upon CRAHNs.

Besides authors in Reference 9 studied the uplink and downlink coverage probability of radio frequency (RF) energy harvested IoT devices where each time slot is divided into three subslots for power and information transmission. To derive tight approximation for this joint coverage probability, dominant BS based entrance is improved. Hu et al. investigated the secure communication between IoT device and destination via wireless energy harvested relay. Simultaneously they developed the coverage of an IoT device in CIoT network.

Tervonen et al. carried out the design and improvement of wireless sensor network and actuators for IoT solutions and protocols, challenges, solution related to intra cognitive and inter cognitive is also discussed here. Through several case experiments in different application domains, the present and future roles of info communications in the design of IoT solutions are indicated [10].

Makki et al. investigated the design and improvement of wireless sensor and actuator networks that enable Internet-of-Things (IoT) solutions from the view point of cognitive info communications. The reasons, requirements, and issues related to adaptive systems and architectures are presented by them. The corresponding intra-cognitive and inter cognitive communications are also examined here. In the design of IoT solutions the current and future roles of info communications are reported via different case experiments in different application domains [11].

A study proposed a paper which is based on a stochastic geometry framework with a single-tier uplink model the coverage probability and spectral efficiency of a cognitive radio network are discussed. The mathematical expressions for the coverage probability and spectral efficiency of this network is also defined and in this paper the locations of cognitive transmitters, cognitive receivers, primary transmitters, and primary receivers are modeled as independent Poisson point processes. When the cognitive receiver is outside the primary exclusion region the coverage probability is higher and the spectral efficiency is higher which are confirmed by authors in numerical results [12].

Sabuj et al. presented a comprehensive study of energy harvesting cognitive radio network where locations of primary users and secondary networks follow a Poisson point process is studied by authors and they focused on the two-slope path-loss function so as to have a realistic scenario of propagation environments [13]. Under a particular outage probability constraint, the harvested energy maximization problem is observed and an optimal solution of transmission power is obtained in this study. Simultaneously the result shows for outage probability, harvested energy, and maximization of harvested energy for appreciation of the function and characteristics of this network [15].

Followed by a thorough literature review on the areas of successful probability, blocking probability and coverage probability works have been done. However, studies based on outage probability and delay sensitive area efficiency (DASE) in CWSN remain unexplored. In this project, we have investigated the DASE and obtained an optimal solution of transmission power and code rate.

1.3 Objective of the Thesis

The main achievement of this research study is to observe the DASE maximization problem and optimal solution of transmission power and code rate are obtained. To meet the goal, the following objectives have been recognized.

- To derive the mathematical expression of outage probability, throughput, affected area, delay-sensitive area spectral efficiency (DASE).
- To evaluate the mathematical analysis of DASE in CWSN.
- To determine the optimal transmission power and code rate for maximizing DASE and evaluate the performance of DASE.

1.4 Organization of the Thesis

Chapter 1 is an introductory chapter where i describe how the Cognitive wireless sensor network (CWSN) had the potential to play a key role in the solutions of most intelligent challenges. The back ground and necessity of CWSN are discussed and related previous works of CWSN are reported. A short review of CWSN are also presented.

Chapter 2 provides the fundamental concept of Internet of Things (IoT) with its previous history and the merits and demerits of IoT. A short description of CIoT is also presented.

Chapter 3 presents the system model and mathematical model for fixed network. System models contain network model, channel model and transmission model. In mathematical model of fixed network, the theoretical expressions of outage probability and delay sensitive area efficiency are defined.

Chapter 4 shows the system model and mathematical model for random network. In random network, considering four assumption the theoretical expressions of outage probability and affected area are analyzed to get noise limited environment in the CWSN.

Chapter 5 is all about the results and discussion on the curves obtained from MATLAB programs for original, optimal transmission and optimal code. More specifically, the performance of DASE are considered and DASE for maximum transmission power, propagation constant, distance and maximum code rate are compared with each other for their performances. Numerical results are illustrated only for fixed networks.

Chapter 6 presents the concluding observations of all the chapters and highlights some possible promising avenues of further development.

Chapter 2

Internet of Things

2.1 Introduction to Internet of Things

The Internet of Things (IoT) is expanding at a rapid rate in internet technology right now. One of the most progressive and exciting developments in information and communications technology is the advent of IoT. IoT is a network in which all physical objects are connected to the internet through wireless communication technology and facilitates sharing or information among them. This technology is epitomized in a spacious spectrum of networked products, systems, and sensors, which receive benefit of improvements in computing power, electronics miniaturization, and interconnections of network to offer new abilities not previously possible [16].

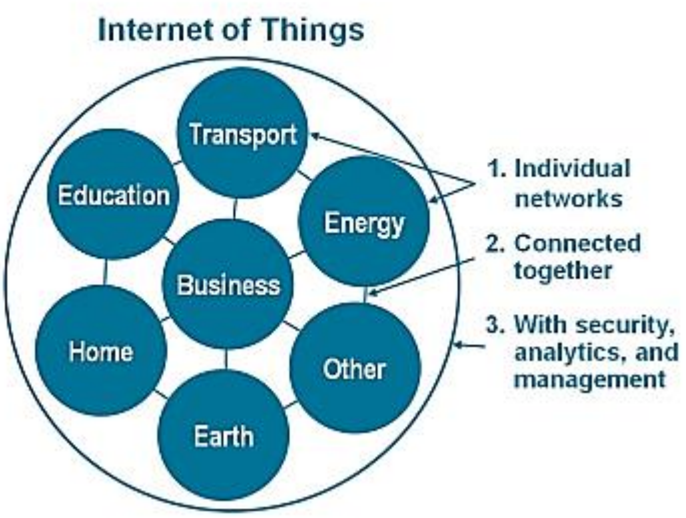

Figure 2.1: Basic concept of Internet of things (IoT) [17]

The most emergent properties of IoT cover artificial intelligence, connectivity, sensors, active engagement, and small device use. IoT vitally establishes actually anything "smart", meaning it improves every sector of life with the capability of simulated intelligence algorithms, networks and data collection [18]. Briefly, the IoT is a network of networks as shown in Fig.2.1. New enabling technologies for networking and especially IoT networking indicate networks are no prolonger only tied to major providers. IoT creates networks and it can remain on a much smaller and inexpensive scale while still being practical between its system devices [20]. IoT acts like defining devices which can use the transformation technique of IoT from a standard inoperative network of devices into an effective system able of real-world integration which is shown in Fig.2.2 and loses its variety except sensors. Through passive engagement, much of today's interaction with connected technology is happened. IoT establishes a new illustration because of active content, product, or service engagement and utilizes purpose-built small devices to offer its limpidity, scalability, and versatility [19].

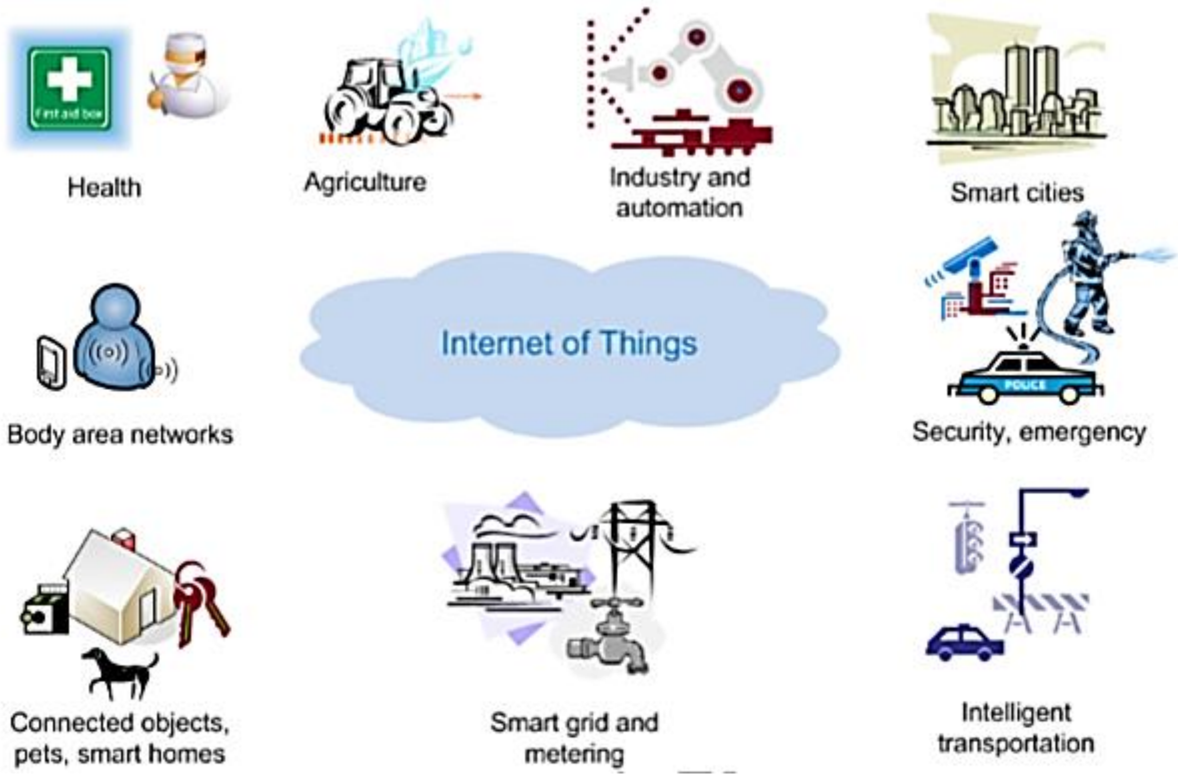

Figure 2.2: Uses of Internet of things (IoT) [21]

2.1.1 Advantages

There are many advantages of incorporating IoT into our lives that can help individuals, businesses and society on a daily basis as shown in Fig. 2.3.

IoT emboldens the communication between devices which is widely known as Machine-to-Machine (M2M) communication. As a result of this, the physical devices are capable to keep connected and therefore the total transparency is obtainable with lesser incompetences and higher quality [22].

According to the point above, IoT makes easier communication between electronic devices; it helps people in daily tasks and transfers data packets over a connected network save time and money. The same data that would take a long time to transfer can now be done much faster.

Avoiding human involvement, the IoT allows automating and controlling the tasks of daily basis [18]. To aid the quality of services and reduce the level of human intervention are helped by the tasks of Automating in a business.

IoT is used in the section for patient monitoring in where various types of wireless sensors are situated on the patient body that communicates with the IoT network and provides all the necessary information of the patient under treatment. All the applications of this technology culminate in enhanchmented comfort, opportunity, and better management, thereby developing the quality of life [20].

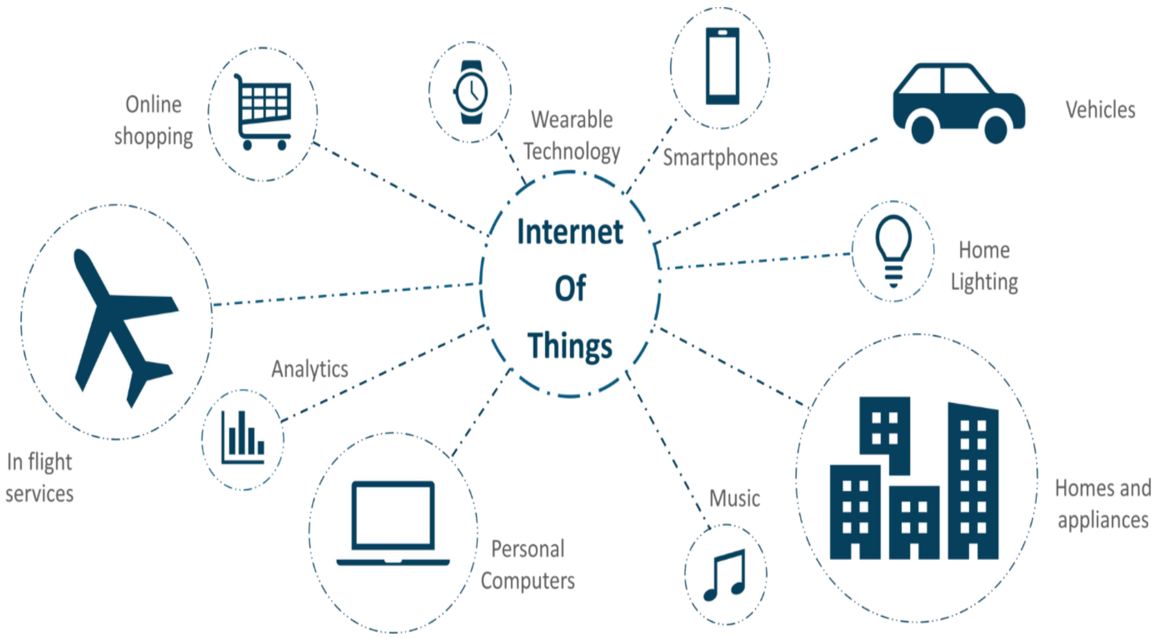

Figure 2.3: IoT applications in different sector [23]

2.1.2 Disadvantages

The IoT consists of multiple technologies whose configaration are dissimilar than one another. Any kind of defeat or bugs in the software or hardware will have serious results. Even power failure can reason of a lot of disturbance.

This may need expert workers requiring knowledge of multiple techniques and to hire and keep such employees should be paid high by IoT service provider. For the reason of every task being automated, the demand for human labour will reduce drastically [22]. This will have a direct effect on employability.

There is no hesitation that technology is controlling our regular lifestyle, reflecting a human's dependability on technology. The younger generation is already addicted to technology for every little thing of daily life and we should have to determine how much of our daily lives are controlled by technology and we intending to mechanize [31].

2.1.3 Literature review:

The history of Internet goes back to the evolvement of communication between two computers through a computer network in the late 1960s. In 1995, the term Internet of Things (IoT) has first been introduced by Bill Gates. MIT raised the early improvement of IoT: 1) Based on radio frequency identification (RFID), MIT determined to give each good a unique numbering and RFID realize unique identification in 1998; 2) The Center for Automatic Identification Technology (Auto ID Center) is founded by MIT which proposed the concept of Electronic Product Code (EPC), and consecrated RFID system in 1999 [24]. As the title of a presentation, the Internet of Things (IoT) firstly coined by Kevin Ashton in 1999 [25].

Then, In 2001 the MIT Auto-ID center represented their Internet of Things (IoT) vision. In 2005, the International Telecommunication Union (ITU) released ITU Internet Report 2005 that presents that IoT can understand the interconnection of thing to thing and depends on sensors and other equipments [16]. The core of IoT is to achieve interconnection, communication between things and exchange of information. The definition and scope of IoT have changed and its coverage has been greatly expanded.

The first international conference on the IoT was held in Zurich in 2008.The idea of "smarter planet" which consists of the IoT is proposed by the CEO of IBM. In August 2009, Chinese Premier Jiabao Wen establish forward the idea of "Sensing China", that made the IoT become the national strategy of China [5] and IoT European Research Cluster (IERC) represented a record of IoT strategic research roadmap on future experiment and improvement until 2015 and beyond 2020. a comprehensive document on the vision and challenges for realizing the IoT was published one year later [22]. The IoT has gained importantly increasing attention from academia as well as industry, comprehensive surveys can be found in the past couple of years. The research study focusses on developing the understanding of Internet of Things (IoT) shown in Fig. 2.4.

Therefore, we proposed a new concept of Cognitive Internet of Things (CIoT) through integrating cognition into IoT that is integrated to develop performance and attain intelligence [22]. CIoT can admire present business types and network situation, explore the perceived information based on the previous knowledge, prepare smart decisions, and perform adaptive and monitoring actions. The aim of CIoT is to maximize network performance and complete the application requirement [26].

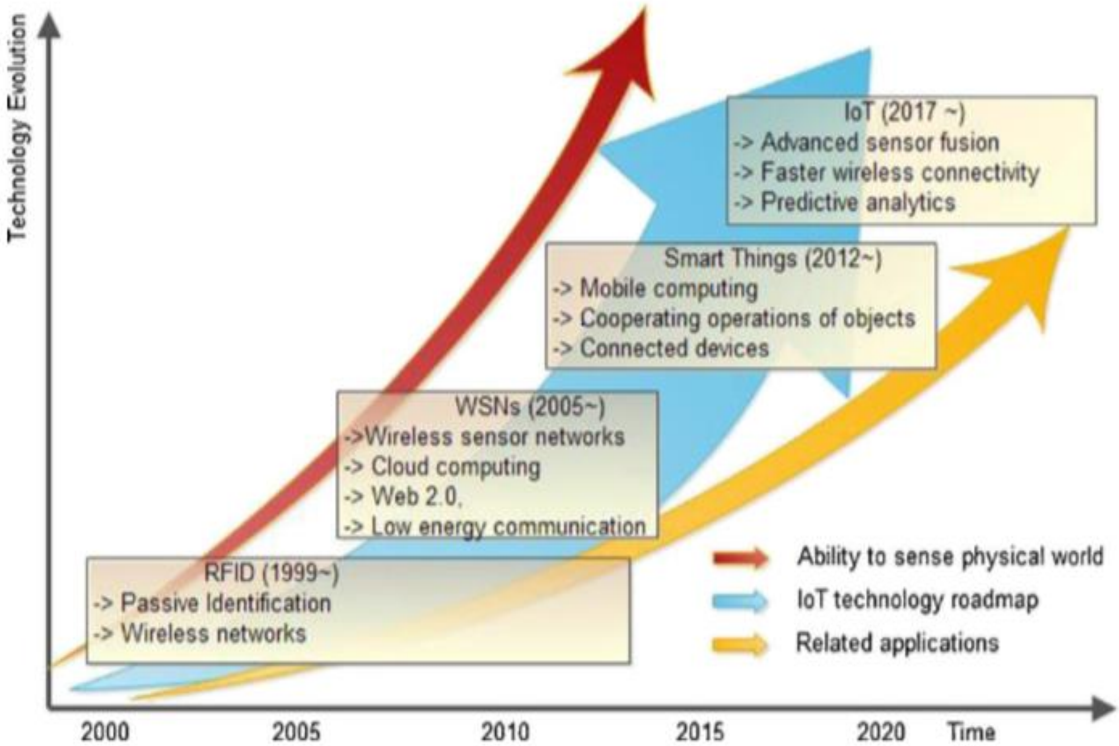

Figure 2.4: Evaluation of Internet of Things (IoT) [31]

2.2 Wireless Sensor Network:

One of the most effective perspective of wireless sensor networks (WSNs) is their capability to gather and method massive quantity of information in parallel with the support of tiny, power limited devices enabling their use in surveillance, target detection and several other controlled applications [28]. Recently, new concepts have been introduced to reveal CWSNs to prolong awareness about the network and take adaptive decisions based on the application goals.

WSNs consist of hundreds of WS nodes deployed entirely the sensor field and the distance between two surrounding WS nodes is usually moderated to few meters. Because of collecting the data from the WS nodes in single or multiple-hop manner a sink node or base station is responsible. The sink node then transmits the collected data to the users via a gateway, often using the internet or any other communication channel. Figure 2.5 shows the scenario of conventional WSNs.

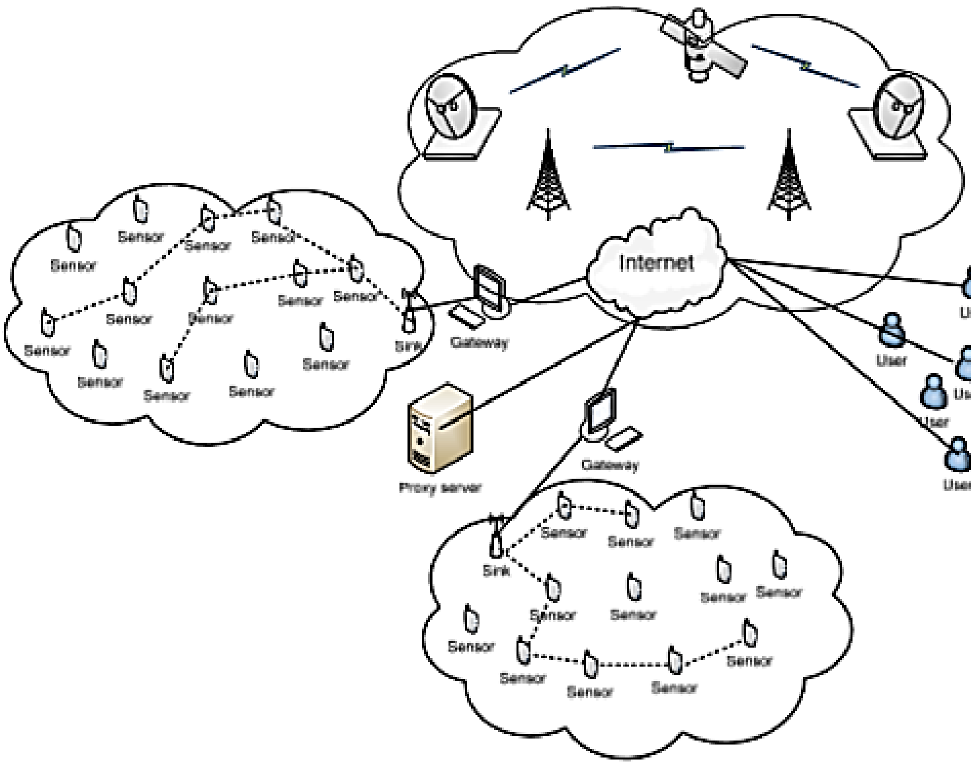

Figure 2.5. Conventional wireless sensor networks [14]

2.3 Cognitive Internet of Things:

A new idea of Cognitive Internet of Things (CIoT) through integrating cognition into IoT which is integrated to develop performance and acquire intelligence. The technology of

Cognitive Internet of Things (IoT) characteristics developed machine intelligence toward developed data sensing and solution which is particularly appealing to applications involving sensor networks [3].

To fully incorporate CIoT technology in sensor networks, smart and effective medium access control protocols enabling the coexistence of sensor networks with current wireless infrastructure and simultaneously optimizing the performance of IoT applications are important challenges. Hence, in addition to cognitive power in data sensing and computation, in order to fully deploy CIoT another crucial factor toward cognitive sensor networks is the cognition in spectrum access [29].

CIoT not only connect each and every devices to the Internet, but also it will supply the decision making capability to each and every devices connected in the network. Cognitive Internet of Things support that only inter connection is not efficient for Internet of Things but the devices should be intelligent enough to make the decision [6]. Each devices in CIoT should be susceptible to perform following five cognitive tasks-

(i) they should be capable to understand the data from environment

(ii) they will sense their surroundings and collect the data and they should be able to analyze those solid data after getting data

(iii) after analyzing those data they should be able to detect the knowledge

(iv) they will also perform knowledge discovery, then based on the detected data they will make the decision and according to the user requirements finally they will provide the services.

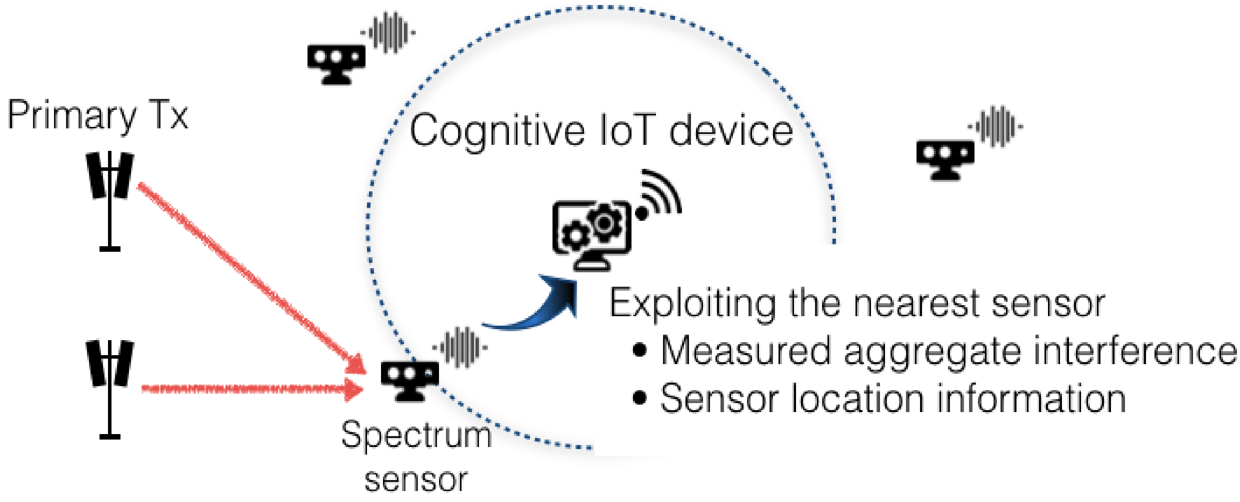

Fig. 2.6: Cognitive IoT networks-with-spectrum-sensors [7]

2.3.1 Key components of CIoT

The key components of Cognitive Internet of things are -

I. **Sensors**: Sensor is the one thing which can to collect data from the environment in Internet of Things. A Sensor device can detect and converts the physical parameter. There are different types of sensor which can be used in Cognitive Internet of Things are –

1. Temperature Sensor: The information about temperature from the environment is gathered by a temperature sensor which can convert that into electrical form and other device can understand that form.
2. .Pressure Sensor : To measure pressure, typically of liquids or gases like fiber optic a pressure sensor is used.
3. Accelerometers Sensor : Accelerometer Sensors are based on the MEMS(Micro Electro Mechanical Sensor) technology.
4. Image Sensors : This type of Sensor is mainly used in cameras, traffic, security, biometrics and is build based on the CMOS technology.

5. Motion Sensors : A motion sensor is created based on the InfraRed radar technology/ microwave, Ultrasonic . They are used in light activation and security detection.

II. **Actuators**: An Actuator is not only converts the electrical signal to a physical parameter but also monitoring the other devices based on the data available and can make decision and perform actions.

III. **Human**: Man power can be used in Cognitive Internet of Things. The volunteers will be accountable for collecting the information about current status in certain areas of the city. Assume there is an accident on the high way, the volunteer present in that are will take an image or a video and instantly transmit it to the central server. After certain interval he will maintain dating the information in server [31].

Chapter 3

System model and mathematical model for fixed network

3.1 System model for fixed network

3.1.1 Network Model:

Here, we consider the uplink scenario of cognitive IoT model and assume cognitive wireless sensor network (CWSN) where secondary system (SS) shares the licensed spectrum resources of PUs and Secondary user's (SUs) consists a number of sensor node (SNs) and base stations (BSs) shown in Fig. 3.1. Here, we assume that all sensor node are transmitting with the same power Ps in the uplink and the transmission power of the PTs is P_p . In this system, sensor node act as a Secondary transmits (ST) and base station act as a secondary receiver (SR) [8].

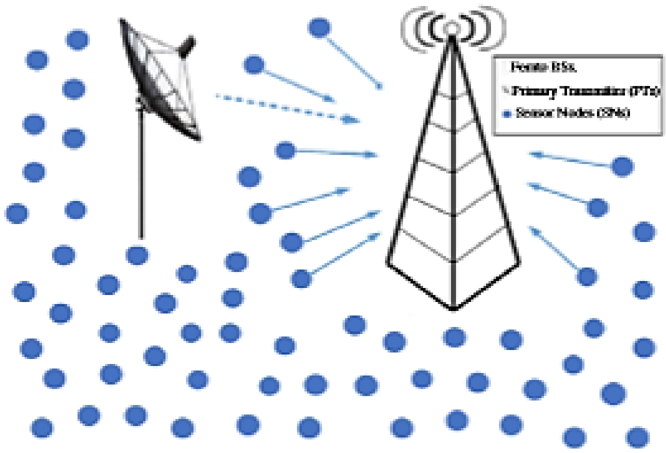

Figure 3.1: CWSNs where femto BSs, PTs, and SNs are deployed [8]

3.1.2 Channel Model:

In this model, we consider the effect of path loss and small scale fading. The Rayleigh fading model is supposed for the small scale fading which is presented by $f_x(g) = exp(-g)$ and

$f_x(.)$ presents the probability density function of a random variable of x. Channel fading factor follows exponential distribution with unit mean. The transmission power decays at a rate of $\|r\|^{-\alpha}$ in where propagation distance r and path loss exponent α. So the general channel gain is considered as h$r^{-\alpha}$ and background noise N in our channel model.

3.1.3 Transmission model:

In the proposed model, we focus on CIoT communication of uplink transmission in secondary system network. PU are the legimate owners of the licensed channels. When PU are not using licensed channel, the channels are unoccupied. The unoccupied channels are empty which are referred to as idle channels. In case SNs perform spectrum sensing, power consumption of SNs is high for searching idle channels. Therefore it is simple to implement spectrum sensing technique in femto BSs. After finding idle channels, femto BSs inform to SNs and SNs transmit the data in the idle channels on the principle of acceptance of femto BSs [8].

3.2 Mathemetical model for fixed network:

We derive the mathematical expressions of the outage of coverage probability which depends on the signal-to-interference-plus-noise ratio (SINR) of each BS in CWSN. When its SINR is greater than a predefined threshold or code rate, a transmitted signal is decoded successfully.

Outage probability is the probability which a conferred information rate is not accepted for changeable channel capacity. The probability that information rate is less than the necessary threshold information rate defines outage probability and it is the probability that an outage will occur within a specified time period.

In accordance with the worst-case scenario, the SINR of the BS at a distance r from the typical SN can be presented as,

$$\text{SINR}=\frac{P_s h_s r^{-\alpha}}{I_s+I_p+N} \tag{3.1}$$

where Ps is SN transmission power in idle channel, h_s is the channel gain from SN to corresponding BS and the noise power is N , the interference at the BS transmitted from other SNs is I_s, and I_p is the interference at the BS transmitted from PTs. In accordance with Reference14, the mathematical expressions of I_s and I_p can be defined as

$$I_s=\sum_{j\in N_{s\backslash\{0\}}} P_{sj}\, h_{sj} r_j{}^{\propto} , \tag{3.2}$$

$$I_p=\sum_{j\in N_{p\backslash\{0\}}} P_{pj}\, h_{pj} d_j{}^{\propto} , \tag{3.3}$$

where the number of SNs except typical SN is N_s and the number of PTs is Np . the channel gain between PT and corresponding BS is h_p . the distance between between PT and corresponding BS is d. Following assumption are observed depending on the interference.

Assumption 1

Signals are orthogonal for SU, then SINR of the BS (ie, Equation (3.1)) reduces to

$$\text{SINR}=\frac{P_s h_s r^{-\alpha}}{I_s+N} \tag{3.4}$$

Assumption 2

When Signals are considered as orthogonal for PU, then SINR of the BS (ie, Equation (3.1)) reduces to

$$\text{SINR}=\frac{P_s h_s r^{-\alpha}}{I_p+N} \tag{3.5}$$

Assumption 3

When both signals are considered as orthogonal, then SINR of the BS (ie, Equation (3.1)) reduces to

$$\text{SINR}=\frac{P_s h_s r^{-\alpha}}{N} \tag{3.6}$$

When the SINR of BS is below than predefined code rate (R) a cognitive wireless link between the SN and BS suffers from outage. The mathematical expression of outage probability can be defined as

$$O_p = P_r(\ln(1+\text{SINR}) < R)$$

$$= 1-P_r\left(\ln\left(1+\frac{P_s h_s r^{-\propto}}{I_s+I_p+N}\right) > R\right)$$

$$=1-\exp\left(\frac{\left(\exp(R-1)\left(I_s+I_p+N\right)r^{\propto}\right)}{P_s}\right) \tag{3.7}$$

3.2.1 Throughput

The rate of information successfully transmitted over a channel network, is defined as throughput and as an average and measured in bits per second (bps) is usually represented. Throughput is a significant indicator of the performance and quality of a network connection.

Throughput is affected by a number of factors and is involved with the code rate and outage probability. Code rate is explained as number of bits or nats sent per unit time to a receiver via a channel and as R=K/L nats-per-channel-use (npcu) presents it where K is the number of nats per codeword and L is the codeword length. The expression of system throughput which is mathematically defined can be expressed as

$$T_p=\frac{K}{L}\left(1-o_p\right)$$

$$\Rightarrow T_p = R\left(1-\left(1-\ \exp\ \left(\frac{(\exp(R-1)(I_s+I_p+N)r^{\propto})}{P_s}\right)\right)\right)$$

$$\Rightarrow T_p = R\left(\exp\ \left(-\frac{(\exp(R-1)(I_s+I_p+N)r^{\propto})}{P_s}\right)\right) \tag{3.8}$$

3.2.2 Affected Area

Lot of SNs transmit data to femto BSs in CWSNs, and RF pollution in the surrounding area is effected by SNs. as the surrounding area of SNs where SINR is greater than predefined threshold value (T) defines the affected area. The expression of affected area which is mathematically defined can be expressed as

$$A = \int_0^{2\pi}\int_0^{\infty}\int_{\frac{T(I_s+I_p+N)r^{\alpha}}{P_s}}^{\infty} f_g(x) r dr\, dx\, d\theta \tag{3.9}$$

$$= 2\pi\int_0^{\infty} r(1-F_g\left(\frac{T(I_s+I_p+N)r^{\alpha}}{P_s}\right))dr$$

$$= \frac{2\pi P_s^{\frac{2}{\propto}}\,\Gamma\left(\frac{2}{\propto}\right)}{\propto T^{\frac{2}{\propto}}\ (I_s+I_p+N)^{\frac{2}{\propto}}} \tag{3.10}$$

Where x is the integration variable that presents channel gain random variable and $F_g(\cdot)$ is the cumulative distribution function of x. Gamma function that express as $\Gamma(q)$ - $=\int_0^{\infty} t^{q-1}\, e^{-t}dt$.

The detailed derivation of A is given in Appendix A.

3.2.3 Delay-Sensitive Area Spectral Efficiency

The ratio of the achievable throughput to the affected area, measured in npcu/m^2 can be expressed as DASE .The objective is to maximize DASE, i.e., develop the throughput while remaining the radio pollution in the surrounding area limited. In the meantime limiting the RF pollution a DASE optimized setup may reduce the system throughput. This is the motivation which is for defining DASE as a metric taking the throughput, power consumption, delay and RF pollution into account. The expression of DASE which is mathematically defined can be expressed as

$$\mathrm{D_{ASE}} = \frac{\mathrm{T_p}}{\mathrm{A_a}} \tag{3.11}$$

where T_p is the probable throughput of the CWSN and A_a denotes the affected area. Substituting the value of Equations (3.8) and (3.10) into Equation (3.11), DASE is presented as

$$\mathrm{D_{ASE}} = \frac{\propto \mathrm{R} \mathrm{T}^{\frac{2}{\propto}} \mathrm{I_n}^{\frac{2}{\propto}} \exp\left(\frac{-(\exp(\mathrm{R})-1)\mathrm{I_n}\, \mathrm{r}^{\propto}}{\mathrm{P_s}}\right)}{2\pi \mathrm{P_s}^{\frac{2}{\propto}}\, \Gamma\left(\frac{2}{\propto}\right)} \tag{3.12}$$

where, $\mathrm{I_n}=\mathrm{I_s}+\mathrm{I_p}+\mathrm{N}$

3.2.4 Optimal Transmission Power

Due to the CWSN, the expression of optimal transmission power which is mathematically defined can be presented by setting the derivative of Equation (3.12) with respect to Ps. This means that, $\frac{\partial D_{ASE}}{\partial P_s} = 0$

$$P_s^{*} = \arg\{ \frac{\partial (D_{ASE})}{\partial P_s} = 0\}$$

$$\Longrightarrow P_s^{*} = \frac{\propto(\exp(\mathrm{R})-1)\mathrm{I_n}\ \mathrm{r}^{\propto}}{2} \tag{3.13}$$

The detailed derivation of P_s^{*} is given in Appendix B.

Now substituting the value of Equation (3.13) into Equation (3.12), the maximum achievable D_{ASE} is represented as

$$D_{ASE}\ (P_s^{*}) = \frac{\propto \mathrm{R}(2\mathrm{T})^{\frac{2}{\propto}} \exp\left(-\frac{2}{\propto}\right)}{2\pi \propto^{\frac{2}{\alpha}} \mathrm{r}^2\, \Gamma \frac{2}{\propto} (\exp(\mathrm{R})-1)^{\frac{2}{\alpha}}} \tag{3.14}$$

3.2.5 Optimal Code Rate:

By setting the derivative of Equation (3.12) with respect to R, the optimal code rate is established and that is, $\frac{\partial D_{ASE}}{\partial R} = 0$

Due to the CWSN, the expression of optimal code rate that is mathematically defined can be expressed as,

$$R^* = \arg\{\frac{\partial (D_{ASE})}{\partial R} = 0\}$$

$$\Longrightarrow R^* = W\left(\frac{\mathrm{P_s}}{\mathrm{I_n\, r^{\alpha}}}\right) \tag{3.15}$$

Where $\mathrm{W}(.)$ is the Lambert fuction.

The detailed derivation of R^* is given in Appendix C.

Now substituting the value of Equation (3.15) into Equation (3.19), the maximum achievable D_{ASE} is expressed as

$$D_{ASE}\,(R_s{}^*)=\frac{\propto \mathrm{T}^{\frac{2}{\propto}} \mathrm{I_n}^{\frac{2}{\propto}}\, \mathrm{W}\left(\frac{\mathrm{P_s}}{\mathrm{I_n\, r^{\alpha}}}\right)\exp(-\mathrm{v})}{2\pi \mathrm{P_s}^{\frac{2}{\alpha}}\, \Gamma\left(\frac{2}{\propto}\right)} \tag{3.16}$$

Where, $v = \frac{\left(\exp\left(\mathrm{w}\left(\frac{\mathrm{P_s}}{\mathrm{I_n r^{\propto}}}\right)\right)-1\right)\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}$

Chapter 4

System model and mathematical model for random network

4.1 System model for random network

4.1.1 Network model:

We consider an uplink transmission in a CWSNs where ST, SRs,BSs, and SN are randomly located in the r[2] plane. An independent homogeneous PPP $\Phi_{BS} = \{s_i : \forall i\}$ with density λ_s , models the base station. According to an independent homogeneous PPP $\Phi_{SN} = \{r_i : \forall i\}$ with density λ_p the locations of SNs are allocated. With density λ_p the PTs are composed following an independent homogeneous PPP $\Phi_{PT} = \{p_i : \forall i\}$ and with density $\lambda_p{}'$ the PRs are organized as an independent PPP $\Phi_{PR} = \{q_i : \forall i\}$.

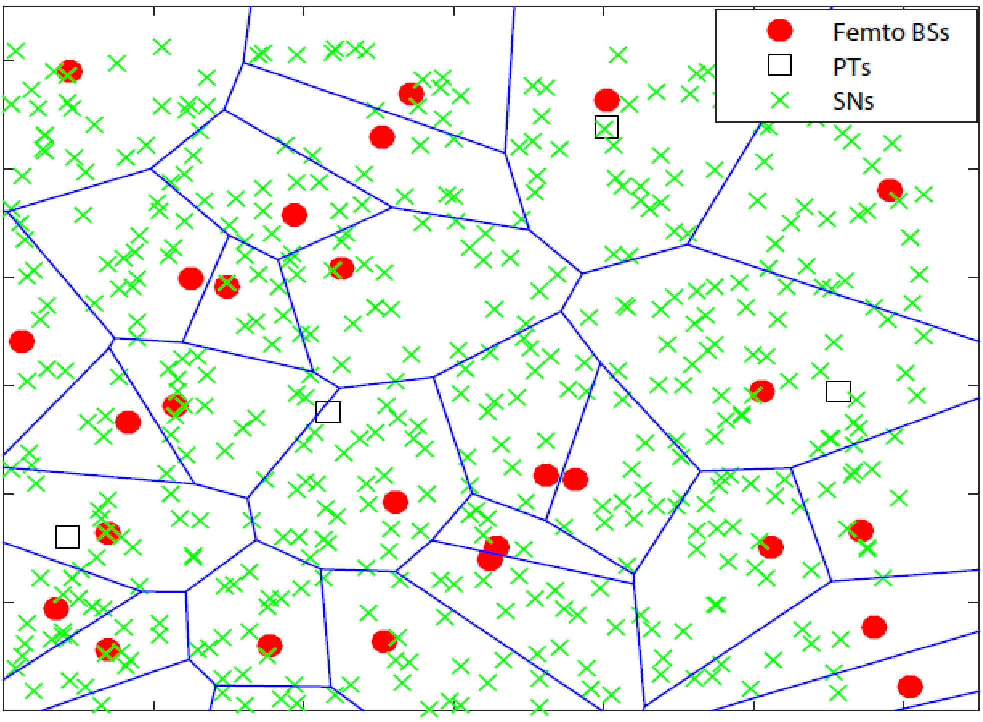

Figure 4.1: Locations of the BSs are denoted by red circles, SNs by green crosses, PTs by black squires

4.1.2 Channel model:

We consider a general path loss model where the signal power transmitted by the BSs decays at a rate of $r^{-\alpha}$ where r is the distance between transmitter and receiver pair. The path loss exponent of transmission is presented by α. Here, Rayleigh fading is adoped in this model and power gains are presented by h_s for BS-SN pain and h_p for PT-SN pair respectively. Power gains are exponential distributed random variables with unit mean.

4.2 Mathematical model for random network:

4.2.1 Outage probability:

Outage probability of random network is defined as the probability that information rate is less than the required threshold information rate and it is the probability that an outage will occur within a specified time period. In this network, the outage probability can be expressed as equation (3.7). where $s_s = \frac{\exp(R-1)r^{\propto}}{P_s}$ and $\mathcal{L}_{IS}(s_s)$, $\mathcal{L}_{IP}(s_s)$ are the laplace transforms of the probability density functions of the interference I_s and I_p respectively.

$$O_p{}^{a} = 1- \exp\left(\frac{(\exp(R-1)(I_s+I_p+N)r^{\propto})}{P_s}\right)$$

$$=1- \exp\left[\frac{\exp(R-1)r^{\propto}}{P_s}\left(I_s + I_p + N\right)\right] \quad \left[\therefore\ s_s = \frac{exp(R-1)r^{\propto}}{P_s}\right]$$

$$=1-\exp\left(\frac{\exp(R-1)r^{\propto}N}{P_s}\right) \mathcal{L}_{IS}(s_s)\mathcal{L}_{IP}(s_s) \tag{4.1}$$

Because of spectrum sensing, there are four assumptions for the perfect and imperfect detection of PT-to-BS and SNs-to-BS links:

(i) Complete detection of SNs-to-BS and PT-to-BS links: in this case, the Laplace transforms of interferences are equal to one, i.e., $\mathcal{L}_{IS}(s_s) = 1$ and $\mathcal{L}_{IP}(s_s) = 1$.

(ii) Complete detection of SNs-to-BS link and imperfect detection of PT-to-BS links: the Laplace transforms of the interferences are $\mathcal{L}_{IS}(s_s) = 1$ and $\mathcal{L}_{IP}(s_s) \neq 1$.

(iii) Incomplete detection of SNs-to-BS link and perfect detection of PT-to-BS links: the Laplace transforms of the interferences are are $\mathcal{L}_{IS}(s_s) \neq 1$ and $\mathcal{L}_{IP}(s_s) = 1$.

(iv) Incomplete detection of SNs-to-BS and PT-to-BS links: the Laplace transforms of the interferences are not equal to one, i.e., $\mathcal{L}_{IS}(s_s) \neq 1$ and $\mathcal{L}_{IP}(s_s) \neq 1$.

Conforming the four assumptions, in assumption (i) considers a noise-limited environment [12]. in accordance with this consideraton, the outage probability and area spectral efficiency are noise limited in which interference is negligible. Besides, interfering SNs and PT do not affect the tagged BS.

but the other assumptions i.e., (ii), (iii), and (iv) correspond to noise-plus-interference-limited. Interfering SNs and PT cause interference on the tagged BS. Thus, the outage probability and area spectral efficiency are noise-plus-interference-limited for these assumptions.

In this section, we explore the theoretical expressions of outage probability for all assumptions in the CWSN. The four assumptions of the outage probability and affected area are given by the following lemmas.

Lemma 1:

Considering assumption (i) , in the single-tier uplink modeling of a CWSN, the outage probability for the tagged SN can be represented as

$$O_p^{ia} = 1 - \exp\left[-\frac{(\exp(R)-1)Nr^{\alpha}}{P_s}\right] \tag{4.2}$$

Lemma 2:

In the single-tier uplink modeling of a CWSN considering interfering SNs, the outage probability for the tagged SN can be indicated as

$$O_p^{iia} = 1 - \exp\left[-\frac{(\exp(R)-1)Nr^{\propto}}{P_s} - \lambda_s b_d P_{is,st}[(\exp(R)-1)r^{\propto}G_s]^{\frac{d}{\alpha}}\,\Gamma\left(1-\frac{d}{\alpha}\right)\right] \quad (4.3)$$

The detailed derivation of $\mathcal{L}_{IS}\,(s_s)$ is given in Appendix D.

Lemma 3:

Considering an interfering PT in the single-tier uplink modeling of CWSN, the outage probability for the tagged SN can be denoted as

$$O_p^{iiia} = 1 - \exp\left[-\frac{(\exp(R)-1)Nr^{\propto}}{P_s} - \lambda_p b_d P_{is,st}\left[(\exp(R)-1)r^{\propto}P_p {P_s}^{-1}G_p\right]^{\frac{d}{\alpha}}\,\Gamma\left(1-\frac{d}{\propto}\right)\right] \quad (4.4)$$

The detailed derivation of $\mathcal{L}_{IP}\left(s_p\right)$ is given in Appendix E.

Lemma 4:

In the single-tier uplink modeling of a CWSN considering interfering SNs and an interfering PT, the outageage probability for the tagged SN can be presented as

$$O_p^{iva} = 1 - \exp\left[-\frac{(\exp(R)-1)Nr^{\propto}}{P_s} - \lambda_s b_d P_{is,st}[(\exp(R)-1)r^{\propto}G_s]^{\frac{d}{\alpha}}\,\Gamma\left(1-\frac{d}{\propto}\right) - \right.$$

$$\left.\lambda_p b_d P_{is,st}\left[(\exp(R)-1)r^{\propto}P_p {P_s}^{-1}G_p\right]^{\frac{d}{\alpha}}\,\Gamma\left(1-\frac{d}{\propto}\right)\right] \quad (4.5)$$

Lemma 4 combines the results of lemmas 2 and 3. For more details, see Appendices D and E.

4.2.2 Affected area:

The surrounding area of SNs where SINR is greater than predefined threshold value (T) defines affected area of random network and the expression which is mathematically defined for affected area of random network can be presented as equation (3.9)

$$A=\int_0^{2\pi}\int_0^{\infty}\int_{\frac{T(I_s+I_p+N)r^{\alpha}}{P_s}}^{\infty} f_g(x) r dr\, dx\, d\theta$$

$$\Rightarrow A= 2\pi\int_0^{\infty} r(1-F_g(\frac{T(I_s+I_p+N)r^{\alpha}}{P_s}))dr$$

$$A_a = 2\pi \int_0^{\infty} \exp\left[-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right] rdr$$

$$\Rightarrow A_a=2\pi \int_0^{\infty} \exp\left(-\frac{TI_s r^{\propto}}{P_s}\right) \exp\left(-\frac{TI_p r^{\propto}}{P_s}\right) \exp\left(-\frac{TNr^{\propto}}{P_s}\right) rdr$$

$$\Rightarrow A_a= 2\pi \int_0^{\infty} \exp\left(-\frac{TI_s r^{\propto}}{P_s}\right) \mathcal{L}_{IS}(s_T)\, \mathcal{L}_{IP}(s_T)\, rdr \qquad (4.6)$$

Here, $s_T = \frac{Tr^{\propto}}{P_s}$

Lemma 1:

In the single-tier uplink modeling of a CWSN considering assumption (i), the affected area for the tagged SN can be expressed as

$$A_a{}^{i} = 2\pi\int_0^{\infty} \exp\left(-\frac{Tr^{\propto}N}{P_s}\right) rdr$$

$$\Rightarrow A_a{}^{i} = \frac{2\pi}{\propto}\left[\frac{\Gamma\left(\frac{2}{\propto}\right)}{\left(\frac{TN}{P_s}\right)^{\frac{2}{\propto}}}\right] \qquad (4.7)$$

Gamma function represents as $\Gamma(q) -=\int_0^{\infty} t^{q-1} e^{-t} dt$

Lemma 2:

Considering assumption (ii), the affected area for the tagged SN can be expressed as

$$A_a^{ii} = 2\pi \int_0^\infty \exp\left(-\frac{Tr^\propto N}{P_s}\right) \mathcal{L}_{IS}\,(s_T) r dr$$

$$\Rightarrow A_a^{ii} = 2\pi \int_0^\infty \exp\left(-\frac{Tr^\propto N}{P_s}\right) \exp\left[-\lambda_s b_d P_{is,st} \left(TG_p\right)^{\frac{d}{\propto}} r^d\, \Gamma\left(1-\frac{d}{\propto}\right)\right] r dr$$

Using this formula,

$$\int_0^\infty \exp\left(-\frac{x^2}{4\beta} - \gamma x\right) dx = \sqrt{\pi\beta}\ \exp(\beta\gamma^2)\left[1-\phi\left(\gamma\sqrt{\beta}\right)\right]$$

we can get,

$$A_a^{ii} = \pi\left[\sqrt{\pi\left(\frac{P_s}{4TN}\right)}\ \exp\left[\frac{\left(\lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)\right)^2}{4\left(\frac{TN}{P_s}\right)}\right]\left[1-\Phi\left[\lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)\sqrt{\frac{P_s}{4TN}}\right]\right]\right] \quad (4.8)$$

The detailed derivation of $\mathcal{L}_{IS}\,(s_T)$ is given in Appendix F and $A_a{}^{ii}$ is given in Appendix H

Lemma 3:

Considering assumption (iii), the affected area for the tagged SN can be expressed as

$$A_a^{iii} = 2\pi \int_0^\infty \exp\left(-\frac{Tr^\propto N}{P_s}\right) \mathcal{L}_{Ip}\,(s_T) r dr$$

$$\Rightarrow A_a^{iii} = 2\pi \int_0^\infty \exp\left(-\frac{Tr^\propto N}{P_s}\right) \exp\left[-\lambda_p b_d P_{ip,pt} \left(Tr^\propto P_p G_p P_s^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)\right] r dr$$

Using this formula,

$$\int_0^{\infty} \exp\left(-\frac{x^2}{4\beta} - \gamma x\right) dx = \sqrt{\pi\beta}\ \exp(\beta\gamma^2)\left[1 - \phi\left(\gamma\sqrt{\beta}\right)\right]$$

We can get,

$$\Rightarrow A_a{}^{iii} = \pi\left[\sqrt{\pi\left(\frac{P_s}{4TN}\right)}\ \exp\left[\frac{\left(-\lambda_p b_d P_{ip,pt}\left(Tr^{\propto} P_p G_p P_s{}^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)\right)^2}{4\left(\frac{TN}{P_s}\right)}\right]\left[1 - \right.\right.$$

$$\left.\left.\Phi\left[-\lambda_p b_d P_{ip,pt}\left(Tr^{\propto} P_p G_p P_s{}^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1 - \frac{d}{\propto}\right)\sqrt{\frac{P_s}{4TN}}\right]\right]\right] \qquad (4.9)$$

The detailed derivation of $\mathcal{L}_{Ip}\ (s_T)$ is given in Appendix G and $A_a{}^{iii}$ is given in Appendix I

Lemma 4:

Considering assumption (iv), the affected area for the tagged SN can be expressed as

$$A_a{}^{iv} = 2\pi \int_0^{\infty} \exp\left(-\frac{Tr^{\propto} N}{P_s}\right) \mathcal{L}_{IS}\ (s_T)\ \mathcal{L}_{Ip}\ (s_T) r dr$$

$$\Rightarrow A_a{}^{iv} = 2\pi \int_0^{\infty} \exp\left(-\frac{Tr^{\propto} N}{P_s}\right) \exp\left[-\lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}} r^d\ \Gamma\left(1 - \right.\right.$$

$$\left.\left.\frac{d}{\propto}\right)\right]\ \exp\left[-\lambda_p b_d P_{ip,pt}\left(Tr^{\propto} P_p G_p P_s{}^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1 - \frac{d}{\propto}\right)\right]\ r dr$$

$$\Rightarrow A_a{}^{iv} = 2\pi \int_0^{\infty} \exp\left(-\frac{Tr^{\propto} N}{P_s}\right) \exp\left[-\left(\lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}} \Gamma\left(1 - \frac{d}{\propto}\right) + \right.\right.$$

$$\left.\left.\lambda_p b_d P_{ip,pt}\left(Tr^{\propto} P_p G_p P_s{}^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1 - \frac{d}{\propto}\right)\right) r^d\right]\ r dr$$

Using this formula,

$$\int_0^{\infty} \exp\left(-\frac{x^2}{4\beta} - \gamma x\right) dx = \sqrt{\pi\beta}\ \exp(\beta\gamma^2)\left[1 - \phi\left(\gamma\sqrt{\beta}\right)\right]$$

We can get,

$$A_a^{\,iv} = \pi\left[\sqrt{\pi\left(\frac{1}{4\left(\frac{Tr^{\propto}N}{P_s}\right)}\right)}\ \exp\left(\frac{\left(\lambda_s b_d P_{is,st}(TG_p)^{\frac{d}{\propto}}\Gamma\left(1-\frac{d}{\propto}\right)+\lambda_p b_d P_{ip,pt}\left(Tr^{\propto}P_pG_pP_s{}^{-1}\right)^{\frac{d}{\propto}}\Gamma\left(1-\frac{d}{\propto}\right)\right)^2}{4\left(\frac{Tr^{\propto}N}{P_s}\right)}\right)\right]\left[1 - \right.$$

$$\left.\Phi\left(\lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}}\Gamma\left(1-\frac{d}{\propto}\right) + \lambda_p b_d P_{ip,pt}\left(Tr^{\propto}P_pG_pP_s{}^{-1}\right)^{\frac{d}{\propto}}\Gamma\left(1-\frac{d}{\propto}\right)\sqrt{\frac{1}{4\left(\frac{Tr^{\propto}N}{P_s}\right)}}\right)\right]\Bigg] \qquad (4.10)$$

The detailed derivation $A_a^{\,iv}$ is given in Appendix J

Chapter 5

Results and Simulations

Numerical results for the considered CWSN are presented in this chapter. More specifically, DASE performance are compared and find DASE value for maximum transmission power, and DASE for maximum code rate is defined. In this study MATLAB is used for the simulation and the following system parameters are set as follows: Is =20dBm, Ip =30dBm, N=−148dBm, and T=20dBm. Variations of some parameters are given in the figure.

5.1 Impact of transmission power on DASE

Figure 5.1 demonstrates the effect of transmission power (Ps) on DASE. It is investigated that the DASE of original transmission increases as Ps increases upto a certain value and then decreases. At Ps =36dBm, the maximum value of original DASE is given which is 3.716×10^{-2}. Simultaneously, DASE of optimal transmission shows a constant value which is 3.716×10^{-2} .

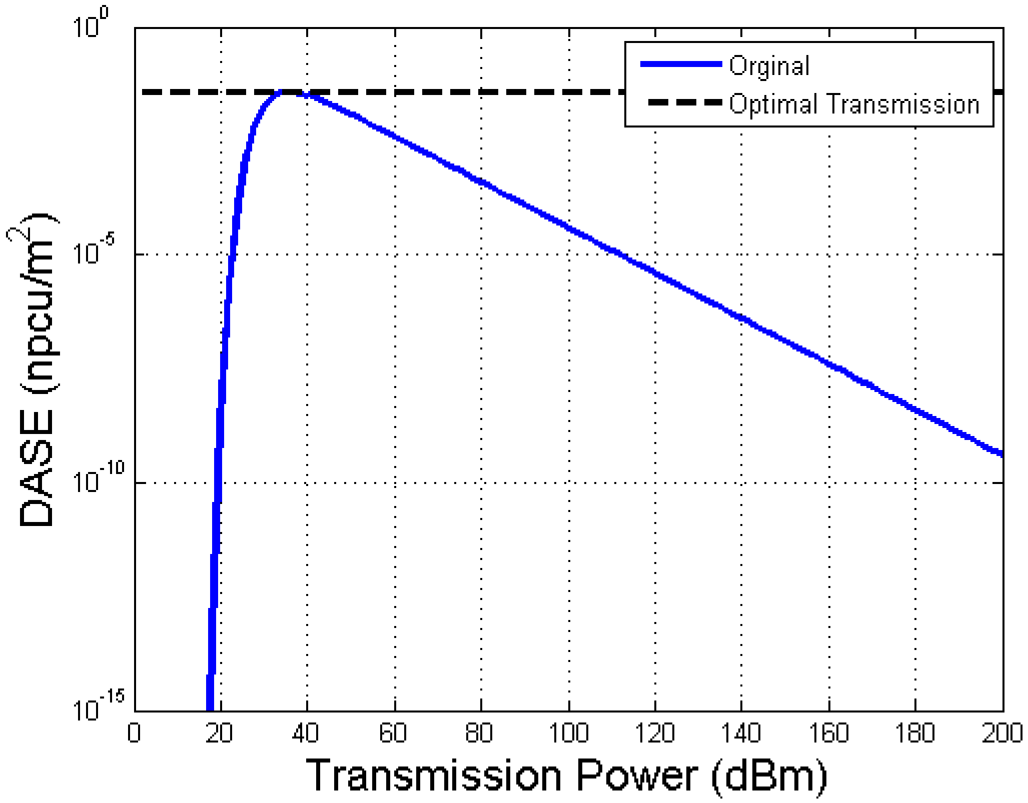

Figure 5.1: DASE vs Transmission Power for optimal transmission

In addition, in fig 5.2 , DASE shows its highest value 4.093×10^{-2} at P_s =38dBm for both of original and optimal transmission. So, the investigation suggests that there is a maximum DASE point at an optimal value of P_s .

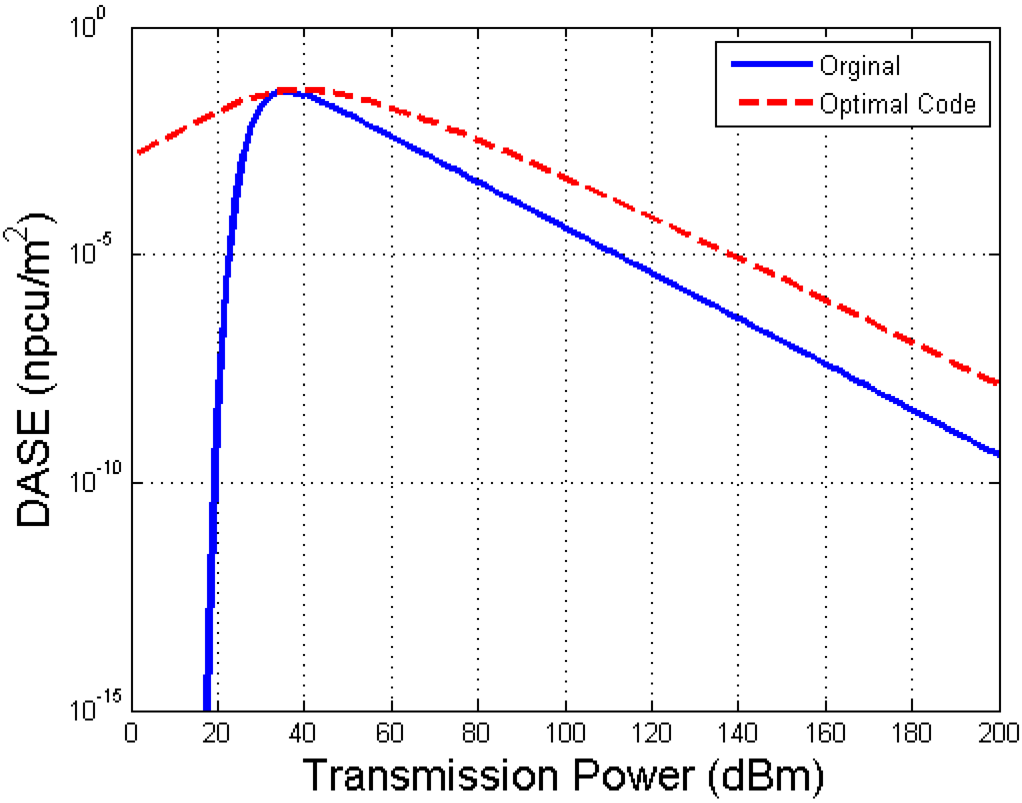

Figure 5.2: DASE vs Transmission Power for optimal code

Now, we observe from fig 5.1 and 5.2 at the value of P_s is 26 dBm. DASE for optimal transmission and optimal code gives 95.59% and 93.01% improvement than original respectively. At the same time, optimal transmission presents 36.92% development than optimal code.

5.2 Impact of distance on DASE

The effect of increasing distance (r) from SN to BS is shown on the DASE in Figure 5.3 and 5.4 It is shown that DASE gradually decreases with r for optimal transmission and sharply decreases for original.

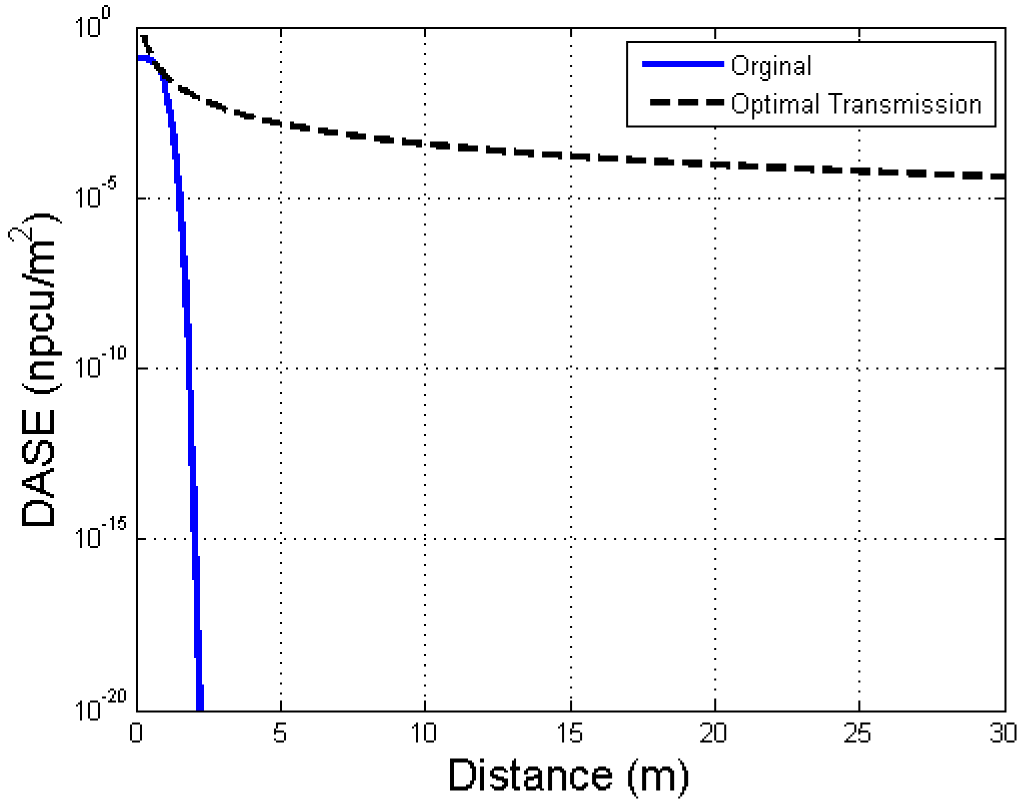

Figure 5.3: DASE vs Distance for optimal transmission

Moreover, DASE increases with the value of r increases upto a certain value and then decreases with r, so it gives an optimal value of r that shows the maximum DASE value which is 3.14×10^{-2} at r =1.

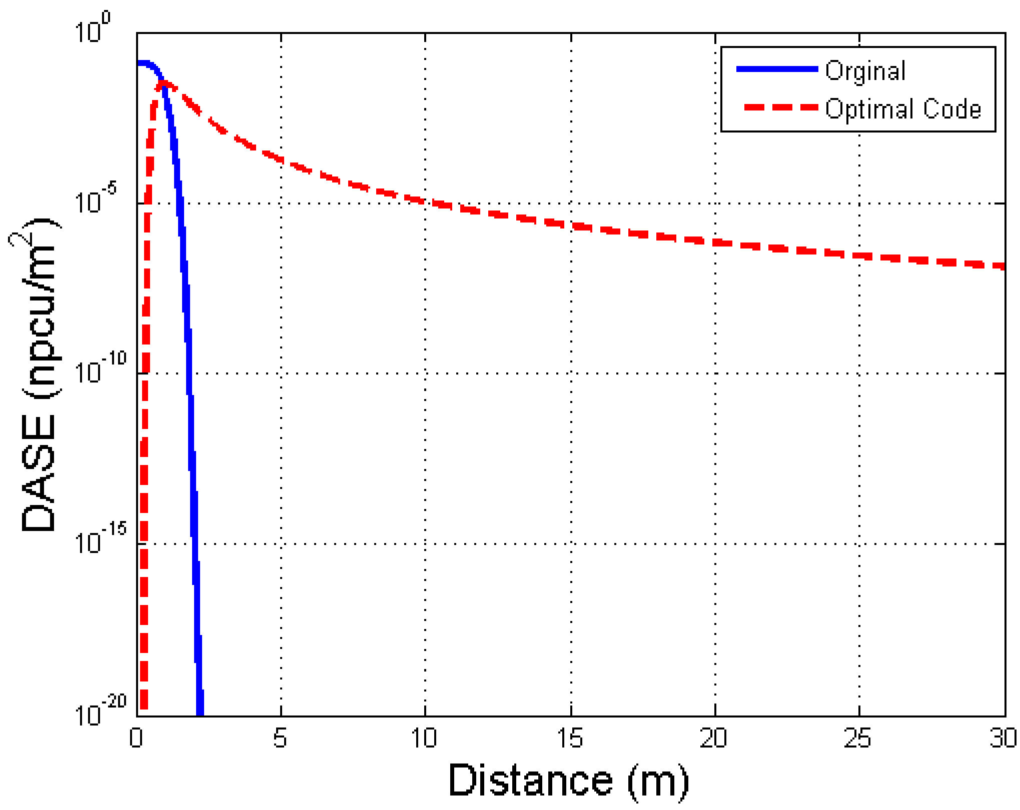

Figure 5.4: DASE vs Distance for optimal code

For the value of r=1.5, the improvement of optimal transmission and optimal code is 99.94% from original and at the same value of r=1.5, optimal transmission shows 5.87% development than optimal code respectively. It can be announced considering their improvement that optimal transmission gives the highest DASE value and for this reason the RF pollution is low.

5.3 Impact of path-loss exponent on DASE

Here, Figure explains the impact of increasing the path loss exponent (α) on the DASE. The DASE of a SN was evaluated using original, optimal transmission and optimal code. As shown in Figure 5.5 and 5.6, the value of DASE increases with the value of α. For α=4, the values of DASE are 1.799×10^{-2}, 3.716×10^{-2} and 3.140×10^{-2} for original, optimal transmission and optimal code respectively.

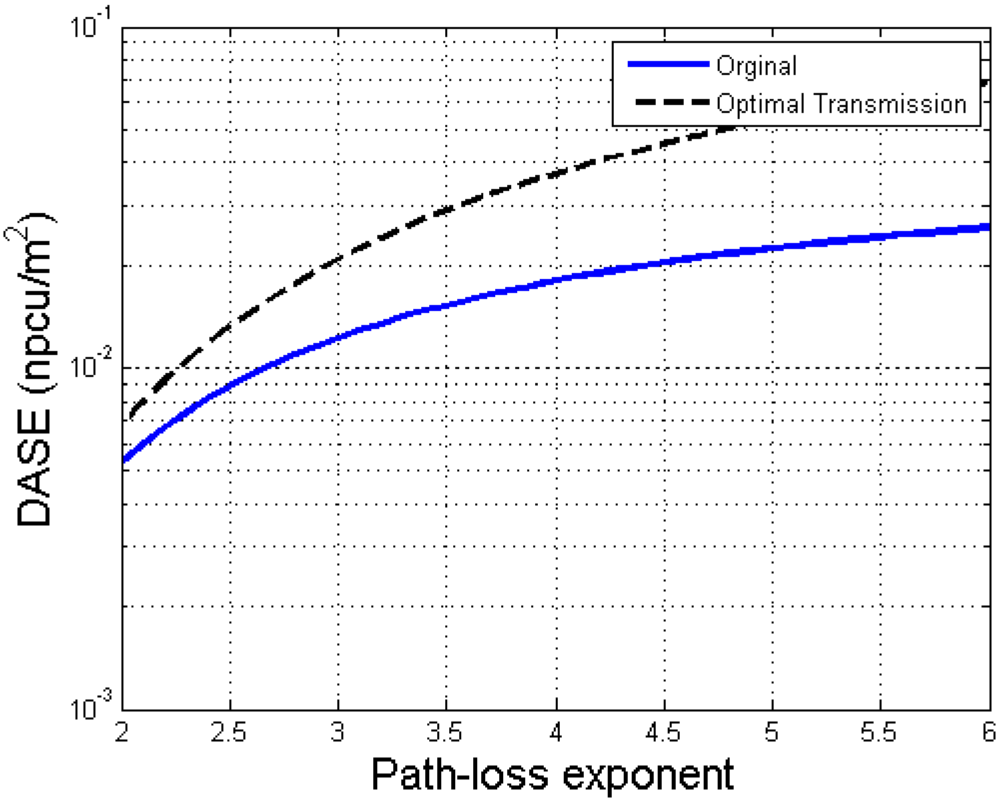

Figure 5.5: DASE vs Path-loss exponent for optimal transmission

Moreover, we calculate that the developments of DASE in optimal transmission and optimal code are 37.05% and 74.54% from that of original . Simultaneously the value of DASE of optimal transmission is 15.50% better than that of optimal code.So, the DASE performance for optimal transmission is the best than others.

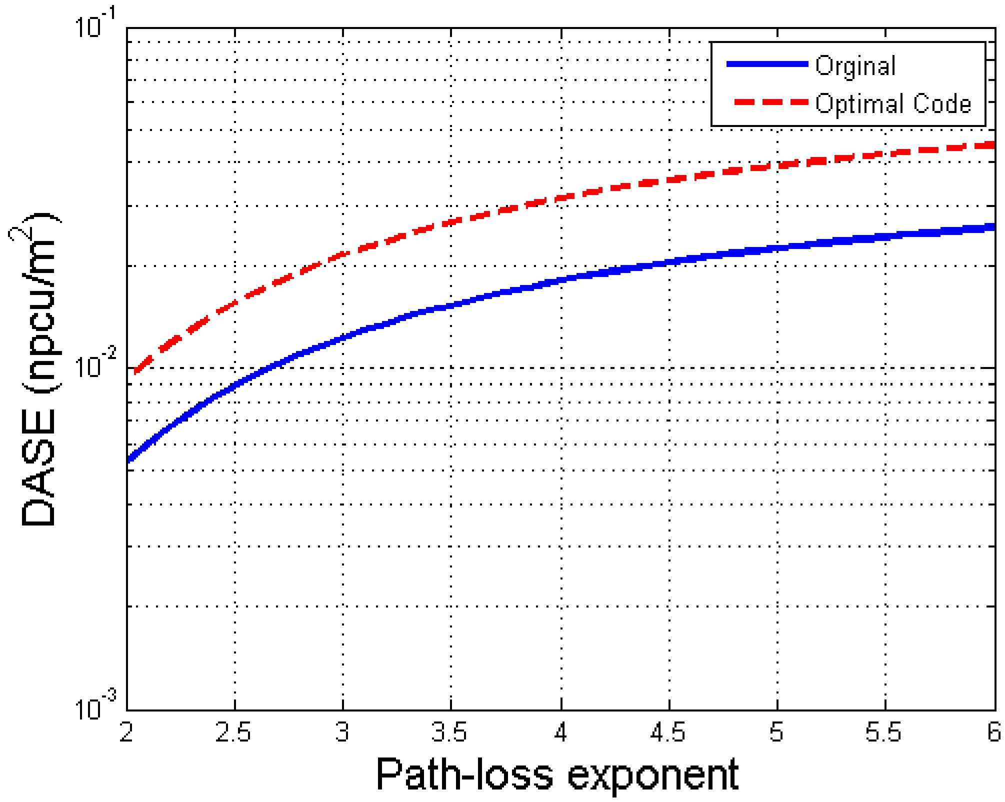

Figure 5.6: DASE vs Path-loss exponent for optimal code

5.4 Impact of code rate on DASE

Figure 5.7 and 5.8 is a comparison of the DASE among original, optimal transmission and optimal code for several value of code rate (R). DASE increases with the increasing value of R upto a certain value, however, orriginal decreases sharply and optimal transmission decreases gradually. Besides in both of them, their maximum DASE values of original and optimal transmission is 3.387×10−2 at R=0.7 and optimal code is 3.916×10^{-2} at R=1.4 .

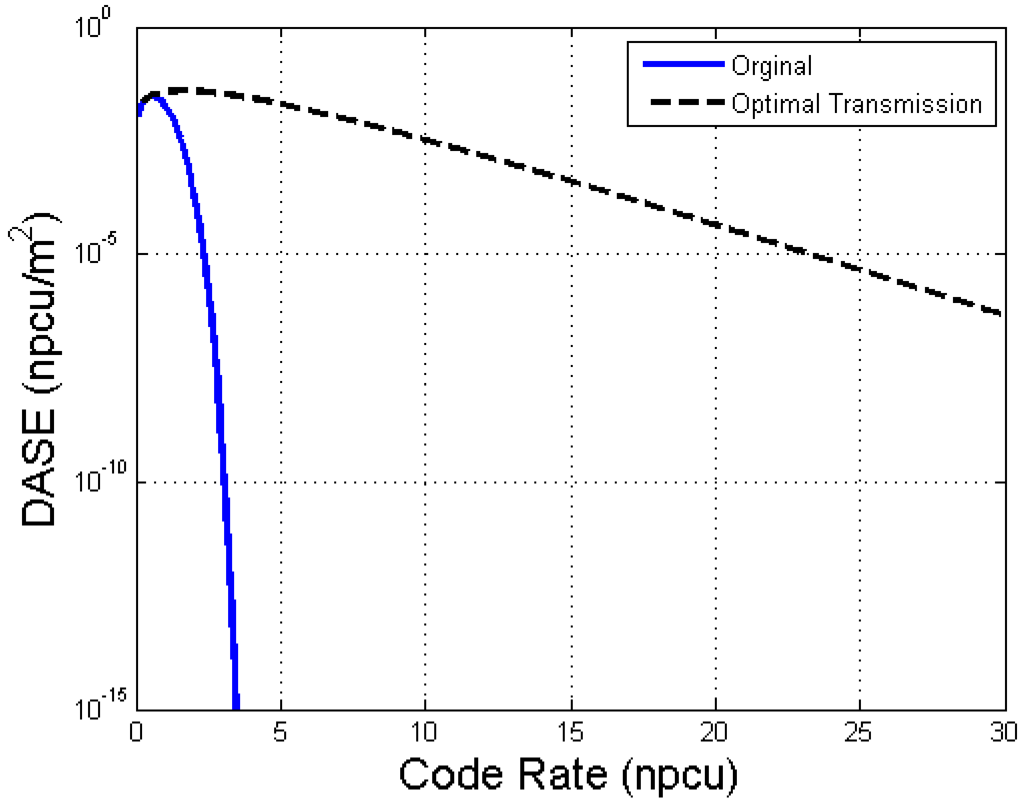

Figure 5.7: DASE vs Code Rate for optimal transmission

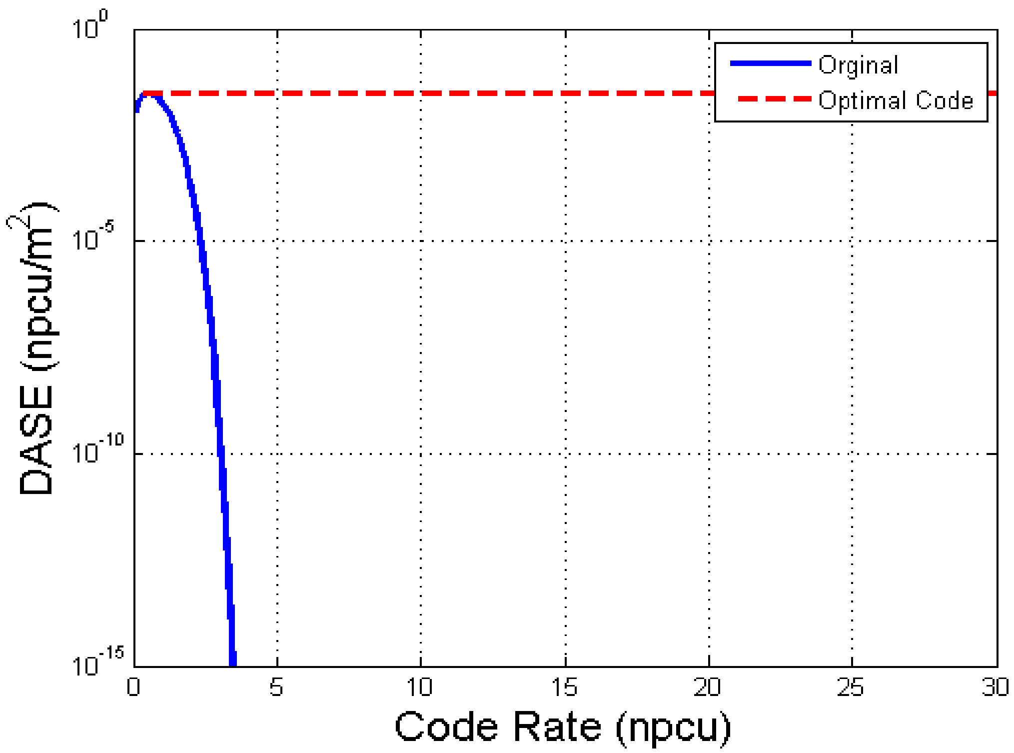

Figure 5.8: DASE vs Code Rate for optimal code

Table 5A: Analysis of Results

Plot (Y vs X)	Figure no	Parameters	X axis	DASE
DASE vs Transmission power	3.1	Original	At P_s=26	1.637×10^{-3}
		Optimal transmission		3.716×10^{-2}
	3.2	Original		1.637×10^{-3}
		Optimal code		2.344×10^{-2}
DASE vs Distance	3.3	Original	At r=1.5	8.325×10^{-6}
		Optimal transmission		1.652×10^{-2}
	3.4	Original		8.325×10^{-6}
		Optimal code		1.553×10^{-2}
DASE vs Code rate	3.5	Original	At R=2	2.113×10^{-4}
		Optimal transmission		3.854×10^{-2}
	3.6	Original		2.113×10^{-4}
		Optimal code		3.145×10^{-2}
DASE vs Path loss	3.7	Original	AT $\propto$= 4	1.799×10^{-2}
		Optimal transmission		3.716×10^{-2}
	3.8	Original		1.799×10^{-2}
		Optimal code		3.140×10^{-2}

From this table it was observed that the maximum value of DASE for original, optimal transmission and optimal code. After observation, it was noted that optimal transmission gives the maximum value of DASE in every plot than all of others. So, optimal transmission is efficient to find the maximum and effective value of DASE.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This chapter provides an analytical approach to the investigation of performance of DASE in CWSN. For this purpose, firstly, we have to derive theoretical expression of outage probability and area spectral efficiency for fixed network. Then by considering the four probability of perfect and imperfect transmission the theoretical expression are derived for the interference limited environment. In this study, numerical analysis considered only for fixed network.

a. In the case of impact of transmission power on DASE that is for optimal transmission and optimal code gives 95.59% and 93.01% improvement than original at a certain value. At the same time, optimal transmission presents 36.92% development than optimal code.
b. In terms of the certain value of r on DASE, the improvement of optimal transmission and optimal code is 99.94% from original and at the same value of r, optimal transmission denotes 5.87% development than optimal code respectively.
c. In this case the observation of increasing the path loss exponent (α) on the DASE and The developments of DASE in optimal transmission and optimal code are 37.05% and 74.54% from that of original are calculated. Simultaneously the value of DASE of optimal transmission is 15.50% better than that of optimal code.
d. A comparison of the DASE among original, optimal transmission and optimal code for several value of code rate (R). The developments of DASE in optimal transmission and optimal code are 37.05% and 74.54% from that of original are

calculated. Simultaneously the value of DASE of optimal transmission is 15.50% better than that of optimal code.

e. Finally, we defined that the maximum value of DASE for original, optimal transmission and optimal code via a table analysis. After observation, we noted that optimal transmission gives the maximum value of DASE in every plot than all of others. So, optimal transmission is efficient to find the maximum and effective value of DASE. It can be announced considering their improvement that optimal transmission gives the highest DASE value and for this reason the RF pollution is low.

6.2 Future Work

The analysis of delay sensitive performance is a promising technique in cognitive wireless sensor network. In this thesis, theoretical expression of DASE for fixed model have been proposed to improve the DASE system performance. There are still many issues for these systems that need to be investigated and some of them are discussed as below.

I. We have analyzed the performance of DASE in CWSN considering uplink model. This technique can also be applied using stochastic geometry.

II. Theoretical expression of Outage probability and DASE for fixed model are investigated in this project and this analysis can be extended by exercising a transmit antenna selection system and stochastic geometry.

III. Maximization technique of DASE can be investigated based Cooperative MIMO-OFDM system over Nakagami Fading Channel and with Implementation of ZF-SIC and MMSE-SIC Signal Detection Schemes [32, 33, 34, 35].

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Appendices

Appendix A.

Integration of A from equation (iv) ,

$$A= 2\pi \int_0^{\infty} r \exp\left(-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right) dr$$

Let, $r^2 = z$ & $r = \sqrt{z}$

- $\Rightarrow$ $2r\,dr = dz$ & $\Rightarrow r^{\propto} = z^{\frac{\propto}{2}}$
- $\Rightarrow$ $rdr = \frac{dz}{2}$
- $\Rightarrow$ $A=2\pi \int_0^{\infty} \exp\left(-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right) \frac{dz}{2}$
- $\Rightarrow$ $A=\pi \int_0^{\infty} \exp\left(-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right) dz$

Let, $t = z^{\frac{\propto}{2}}$ and $z = t^{\frac{2}{\propto}}$

- $\Rightarrow$ $dt = \frac{\propto}{2} z^{(\frac{\propto}{2}-1)} dz$
- $\Rightarrow$ $dz = \frac{2}{\propto} z^{(1-\frac{\propto}{2})} dt$
- $\Rightarrow$ $A = \pi \int_0^{\infty} \frac{2}{\propto} z^{(1-\frac{\propto}{2})} \exp\left(-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right) dt$
- $\Rightarrow$ $A = \frac{2\pi}{\alpha} \int_0^{\infty} (t^{\frac{2}{\propto}})^{(1-\frac{\propto}{2})} \exp\left(-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right) dt$
- $\Rightarrow$ $A = \frac{2\pi}{\alpha} \int_0^{\infty} t^{(\frac{2}{\propto}-1)} \exp\left(-\frac{T(I_s+I_p+N)r^{\propto}}{P_s}\right) dt$

Using this theory, $\Gamma(q) -= \int_0^{\infty} t^{q-1} e^{-t} dt$

- $\Rightarrow$ $A = \frac{2\pi \Gamma(\frac{2}{\propto})}{\propto\{\frac{T}{P_s}(I_s+I_p+N)\}^{\frac{2}{\propto}}}$

Appendix B.

$P_{opt|R} = \arg\{\frac{\partial(DASE)}{\partial P} = 0\}$ and

$$DASE = CP_s^{-\frac{2}{\propto}} \exp\left(-\frac{(\exp(R)-1)I_n r^{\propto}}{P_s}\right)$$

$$\Rightarrow \frac{\partial(DASE)}{\partial P} = C[P_s^{-\frac{2}{\propto}} \frac{\partial\left[\exp\left(-\frac{(\exp(R)-1)I_n r^{\propto}}{P_s}\right)\right]}{\partial P} + \exp\left(-\frac{(\exp(R)-1)I_n r^{\propto}}{P_s}\right) \frac{\partial\ (P_s^{-\frac{2}{\propto}})}{\partial P}]$$

$$\Rightarrow \frac{\partial(DASE)}{\partial P} = C[\exp\left(-\frac{(\exp(R)-1)I_n r^{\propto}}{P_s}\right) \frac{(\exp(R)-1)I_n r^{\propto}}{(P_s{}^2)(P_s)^{\frac{2}{\propto}}} - \frac{2}{\propto} P_s^{-(\frac{2}{\propto}+1)} \exp\left(-\frac{(\exp(R)-1)I_n r^{\propto}}{P_s}\right)]$$

Here, $\frac{\partial(DASE)}{\partial P} = 0$

$$\Rightarrow \frac{(\exp(R)-1)I_n r^{\propto}}{(P_s{}^2)(P_s)^{\frac{2}{\propto}}} = \frac{2}{\propto} P_s^{-(\frac{2}{\propto}+1)}$$

$$\Rightarrow \frac{(\exp(R)-1)I_n r^{\propto}}{P_s} = \frac{2}{\propto}$$

$$\Rightarrow P_s = \frac{\propto(\exp(R)-1)I_n r^{\propto}}{2}$$

$$P_{opt|R} = \frac{\propto(\exp(R)-1)I_n r^{\propto}}{2}$$

Appendix C.

Now, $\frac{\partial(\mathrm{DSE})}{\partial \mathrm{R}} = \frac{\partial}{\partial \mathrm{R}}\left[\mathrm{R}\exp\left(-\frac{(\exp(\mathrm{R})-1)\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\right]$

$\Rightarrow\ \frac{\partial(\mathrm{DSE})}{\partial \mathrm{R}} = \exp\left(\frac{\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\left[\mathrm{R}\exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\right]$

$\Rightarrow\ \frac{\partial(\mathrm{DSE})}{\partial \mathrm{R}} = \left[\mathrm{R}\frac{\partial}{\partial \mathrm{R}}\left(\exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\right) + \exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\right]\exp\left(\frac{\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)$

Here,

Let, $\mathrm{y} = \exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)$ and $\mathrm{z} = \frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}$

$\Rightarrow\ \mathrm{y} = \exp(-\mathrm{z})$ and $\mathrm{dz} = \frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\mathrm{dR}$

$\Rightarrow\ \mathrm{dy} = -\exp(-\mathrm{z})\,\mathrm{dz}$ and $\frac{\mathrm{dz}}{\mathrm{dR}} = \frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}$

$\Rightarrow\ \frac{\mathrm{dy}}{\mathrm{dz}} = -\exp(-\mathrm{z})$

$\Rightarrow\ \left(\frac{\mathrm{dy}}{\mathrm{dz}}\right)\left(\frac{\mathrm{dz}}{\mathrm{dR}}\right) = -\exp(-\mathrm{z})\left(\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)$

$\Rightarrow\ \frac{\mathrm{dy}}{\mathrm{dR}} = -\exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\left(\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)$

Now, $\frac{\partial(\mathrm{DSE})}{\partial \mathrm{R}} = 0$

$\Rightarrow\ -\mathrm{R}\exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right)\left(\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right) + \exp\left(-\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right) = 0$

$\Rightarrow\ -\mathrm{R}\left(\frac{\exp(\mathrm{R})\mathrm{I_n r^{\propto}}}{\mathrm{P_s}}\right) + 1 = 0$

$\Rightarrow\ \frac{\mathrm{P_s}}{\mathrm{I_n r^{\propto}}} = \mathrm{Re^R}$

[according to lambert W function= $\mathrm{xe^x} = \mathrm{y}$; => $\mathrm{x} = \mathrm{W(y)}$]

$\Rightarrow\ \Longrightarrow \mathrm{R} = \mathrm{W}\left(\frac{\mathrm{P_s}}{\mathrm{I_n r^{\propto}}}\right)$

Appendix D.

We derive an expression for the sum of interference at the tagged BS from all SNs, given by

$$I_s = \sum_{i\in\Phi_{st}} P_s G_s \, r_s^{-\propto}$$

where r_s is the distance between the ith interfering SN and the tagged BS. The interference channel gains G_s are considered to be independent and identical distribution for all channels. The Laplace transform of interference received by a BS can be written as

$$\mathcal{L}_{IS}\,(s_s) = \mathbb{E}_{IS}[\exp(-s_s I_s)]$$

$$= \mathbb{E}_{\Phi_{st,G_s}}\left[\exp\left(-s_s \sum_{i\in\Phi_{st}} P_s G_s \, r_s^{-\propto}\right)\right]$$

$$=\mathbb{E}_{\Phi_{st}}\left[\prod_{i\in\Phi_{st}} \mathbb{E}_{G_s}[\exp(-s_s P_s G_s \; r_s^{-\alpha})]\right]$$

(i) $\exp\left[-\mathbb{E}_{G_s}\left[\int_0^{\infty}\left(1-\exp(-s_s P_s G_s \; r_s^{-\alpha})\right)\lambda_{ss}{}'(r_s)\, dr_s\right]\right]$

(ii) $\exp\left[\lambda_s b_d P_{is,st}[(\exp(R)-1) r^{\propto} G_s]^{\frac{d}{\alpha}} \;\Gamma\left(1-\frac{d}{\propto}\right)\right]$

Where $s_s = \frac{(\exp(R)-1)r^{\propto}}{P_s}$ and $\lambda_{ss}{}'(r_s) = \lambda_s b_d P_{is,st} d r_s{}^{d-1}$

Appendix E.

We derive an expression for the sum of interference at the tagged BS from all PTs, given by

$I_p = \sum_{i\in\Phi_{pt}} P_p G_p \, r_p{}^{-\propto}$

where r_p is the distance between the ith interfering PT and the tagged BS. The interference channel gains G_p are considered to be independent and identical distribution for all channels. The Laplace transform of interference received by a BS can be written as

$\mathcal{L}_{IP}(s_s) = \mathbb{E}_{IP}\left[\exp\left(-s_s I_p\right)\right]$

$= \mathbb{E}_{\Phi_{pt,G_p}}\left[\exp\left(-s_s \sum_{i\in\Phi_{pt}} P_p G_p \, r_{pi}{}^{-\propto}\right)\right]$

$=\mathbb{E}_{\Phi_{pt}}\left[\prod_{i\in\Phi_{pt}} \mathbb{E}_{G_p}\left[\exp\left(-s_s P_p G_p \, r_{pi}{}^{-\alpha}\right)\right]\right]$

$$\text{(i)}\ \exp\left[-\mathbb{E}_{G_s}\left[\int_0^\infty \left(1-\exp\left(-s_s P_p G_p \, r_p{}^{-\alpha}\right)\right)\lambda_{sp}{}'(r_p)\, dr_p\right]\right]$$

$$\text{(ii)}\ \exp\left[\lambda_s b_d P_{is,st}\left[(\exp(R)-1) r^{\propto} G_p\right]^{\frac{d}{\alpha}}\ \Gamma\left(1-\frac{d}{\propto}\right)\right]$$

Where $s_s = \frac{(\exp(R)-1)r^{\propto}}{P_s}$and $\lambda_{sp}{}'(r_p) = \lambda_p b_d P_{ip,pt} d r_p{}^{d-1}$. During spectrum sensing, the CUs determine the unoccupied channels of the PUs. After track out the unoccupied channel, the PUs start to transmit signal in their own unoccupied channel.

Appendix F.

We derive an expression is given by

$\mathcal{L}_{IS}\,(s_T) = \mathbb{E}_{IS}[\exp(-s_T I_s)]$

$= \mathbb{E}_{\Phi_{st,G_s}}\left[\exp\left(-s_T \sum_{i\in\Phi_{st}} P_s G_s\, r_{si}{}^{-\propto}\right)\right]$

$=\mathbb{E}_{\Phi_{st}}\left[\prod_{i\in\Phi_{st}} \mathbb{E}_{G_s}[\exp(-s_T P_s G_s\ r_{si}{}^{-\alpha})]\right]$

where r_s is the distance between the ith interfering SN and the tagged BS. The interference channel gains G_s

(i) $\exp\left[-\mathbb{E}_{G_s}\left[\int_0^\infty \left(1-\exp(-s_T P_s G_s\ r_s{}^{-\alpha})\right) \lambda_{ss}{}'(r_s)\, dr_s\right]\right]$

(ii) $\exp\left[-\lambda_s b_d P_{is,st}[Tr^{\propto} G_s]^{\frac{d}{\alpha}}\ \Gamma\left(1-\frac{d}{\propto}\right)\right]$

Where $s_T = \frac{Tr^{\propto}}{P_s}$ and $\lambda_{ss}{}'(r_s) = \lambda_s b_d P_{is,st} dr_s{}^{d-1}$

Appendix G.

We derive an expression for the sum of interference at the tagged BS from all PTs, given by

$I_p = \sum_{i\in\Phi_{pt}} P_p G_p \, r_p{}^{-\propto}$

$\mathcal{L}_{Ip}(s_T) = \mathbb{E}_{IP}\left[\exp\left(-s_T I_p\right)\right]$

$= \mathbb{E}_{\Phi_{pt,Gp}}\left[\exp\left(-s_T \sum_{i\in\Phi_{pt}} P_p G_p \, r_{pi}{}^{-\propto}\right)\right]$

$= \mathbb{E}_{\Phi_{pt}}\left[\prod_{i\in\Phi_{pt}} \mathbb{E}_{G_p}\left[\exp\left(-s_T P_p G_p \; r_{pi}{}^{-\alpha}\right)\right]\right]$

where r_p is the distance between the ith interfering PT and the tagged BS. The interference channel gains G_p

(i) $\exp\left[-\mathbb{E}_{G_p}\left[\int_0^\infty \left(1-\exp\left(-s_T P_p G_p \; r_p{}^{-\alpha}\right)\right)\lambda_{pp}{}'(r_p)\, dr_p\right]\right]$

$= \exp\left[-\mathbb{E}_{G_p}\left[\int_0^\infty \left(1-\exp\left(-s_T P_p G_p \; r_p{}^{-\alpha}\right)\right)\lambda_p b_d P_{ip,pt} d r_p{}^{d-1} dr_p\right]\right]$

$= \exp\left[-\lambda_p b_d P_{ip,pt}\left(s_T P_p G_p\right)^{\frac{d}{\alpha}} \; \Gamma\left(1-\frac{d}{\propto}\right)\right]$

$= \exp\left[-\lambda_p b_d P_{ip,pt}\left[\frac{T r^{\propto} P_p G_p}{P_s}\right]^{\frac{d}{\alpha}} \; \Gamma\left(1-\frac{d}{\propto}\right)\right]$

Where $s_T = \frac{T r^{\propto}}{P_s}$ and

$\lambda_{sp}{}'(r_p) = \lambda_p b_d P_{ip,pt} d r_p{}^{d-1}$

Appendix H.

$$A_a{}^{ii} = 2\pi \int_0^{\infty} \exp\left(-\frac{Tr^{\propto}N}{P_s}\right) \exp\left[-\lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}} r^d \,\Gamma\left(1-\frac{d}{\propto}\right)\right] rdr$$

Let,

$A = \frac{TN}{P_s}$ and $B = \lambda_s b_d P_{is,st}\left(TG_p\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)$

Using this equation,

$$\int_0^{\infty} \exp\left(-\frac{x^2}{4\beta} - \gamma x\right) dx = \sqrt{\pi\beta}\ \exp(\beta\gamma^2)\left[1-\phi\left(\gamma\sqrt{\beta}\right)\right]$$

$$A_a{}^{ii} = 2\pi \int_0^{\infty} \exp(-Ar^{\propto}) \exp\left(-Br^d\right) rdr$$

$$\Rightarrow A_a{}^{ii} = 2\pi \int_0^{\infty} \exp\left[-\left(Ar^{\propto} + Br^d\right)\right] \frac{dx}{2}$$

$$\Rightarrow A_a{}^{ii} = \pi \int_0^{\infty} \exp\left[-\left(Ar^{\propto} + Br^d\right)\right] dx$$

Let, $r^2 = x$ and $r = \sqrt{x}$

$$\Rightarrow 2rdr = dx \quad \text{and} \quad \Rightarrow r^{\propto} = x^{\frac{\propto}{2}}$$

$$\Rightarrow rdr = \frac{dx}{2} \quad \text{and} \quad \Rightarrow r^{\propto} = x^{\frac{\propto}{2}}$$

$$\Rightarrow A_a{}^{ii} == \pi \int_0^{\infty} \exp\left[-\left(Ax^{\frac{\propto}{2}} + Bx^{\frac{d}{2}}\right)\right] dx$$

$$\Rightarrow A_a{}^{ii} == \pi \int_0^{\infty} \exp[-(Ax^2 + Bx)] dx \qquad [\propto = 4 \text{ and } d = 2]$$

$$\Rightarrow A_a{}^{ii} == \pi \int_0^{\infty} \exp\left[-\frac{x^2}{4\left(\frac{1}{4A}\right)} - Bx\right] dx$$

$$\Rightarrow A_a{}^{ii} == \pi \left[\sqrt{\pi\left(\frac{1}{4A}\right)}\ \exp\left(\frac{B^2}{4A}\right)\left[1-\Phi\left(B\sqrt{\frac{1}{4A}}\right)\right]\right]$$

Appendix I.

$$A_a^{iii}=2\pi\int_0^\infty \exp\left(-\frac{Tr^\propto N}{P_s}\right)\exp\left[-\lambda_p b_d P_{ip,pt}\left(Tr^\propto P_p G_p P_s^{-1}\right)^{\frac{d}{\propto}}\Gamma\left(1-\frac{d}{\propto}\right)\right] rdr$$

Let, $A=\frac{TN}{P_s}$ and $C=\lambda_s b_d P_{is,st}\left(Tr^\propto P_s P_s^{-1} G_p\right)^{\frac{d}{\propto}}\Gamma\left(1-\frac{d}{\propto}\right)$

$$\Rightarrow A_a^{iii} = 2\pi\int_0^\infty \exp(-Ar^\propto)\exp\left(-Cr^d\right) rdr$$

Using this equation, $\int_0^\infty \exp\left(-\frac{x^2}{4\beta}-\gamma x\right)dx = \sqrt{\pi\beta}\ \exp(\beta\gamma^2)\left[1-\phi\left(\gamma\sqrt{\beta}\right)\right]$

Let,

$r^2 = x$ and $r = \sqrt{x}$

$\Rightarrow 2rdr = dx$ and $\Rightarrow r^\propto = x^{\frac{\propto}{2}}$

$\Rightarrow rdr = \frac{dx}{2}$ and $\Rightarrow r^\propto = x^{\frac{\propto}{2}}$

$$\Rightarrow A_a^{iii}=\pi\int_0^\infty \exp\left[-\left(Ax^{\frac{\propto}{2}}+Cx^{\frac{d}{2}}\right)\right]dx$$

$$\Rightarrow A_a^{iii}= \pi\int_0^\infty \exp[-(Ax^2+Cx)]dx \qquad [\therefore \propto = 4 \text{ and } d = 2]$$

$$\Rightarrow A_a^{iii}= \pi\int_0^\infty \exp\left[-\frac{x^2}{4\left(\frac{1}{4A}\right)}-Cx\right]dx$$

We get, $A_a^{iii} = \pi\left[\sqrt{\pi\left(\frac{1}{4A}\right)}\ \exp\left(\frac{C^2}{4A}\right)\left[1-\Phi\left(C\sqrt{\frac{1}{4A}}\right)\right]\right]$

Appendix J.

$$A_a^{iv} = 2\pi \int_0^\infty \exp\left(-\frac{Tr^\propto N}{P_s}\right) \exp\left[-\lambda_s b_d P_{is,st} (TG_p)^{\frac{d}{\propto}} r^d \,\Gamma\left(1-\frac{d}{\propto}\right)\right]$$

$$\exp\left[-\lambda_p b_d P_{ip,pt} \left(Tr^\propto P_p G_p P_s^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)\right] rdr$$

Let,

$A = \frac{TN}{P_s}$ and $E = \lambda_s b_d P_{is,st} (TG_p)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right) + \lambda_p b_d P_{ip,pt} \left(Tr^\propto P_p G_p P_s^{-1}\right)^{\frac{d}{\propto}} \Gamma\left(1-\frac{d}{\propto}\right)$

$$\Rightarrow A_a^{iv} = 2\pi \int_0^\infty \exp(-Ar^\propto) \exp(-Er^d)\, rdr$$

Using this equation, $\int_0^\infty \exp\left(-\frac{x^2}{4\beta} - \gamma x\right) dx = \sqrt{\pi\beta}\, \exp(\beta\gamma^2)\left[1 - \phi\left(\gamma\sqrt{\beta}\right)\right]$

Let,

$$r^2 = x \quad \text{and} \quad r = \sqrt{x}$$

$$\Rightarrow 2rdr = dx \quad \text{and} \quad \Rightarrow r^\propto = x^{\frac{\propto}{2}}$$

$$\Rightarrow rdr = \frac{dx}{2} \quad \text{and} \quad \Rightarrow r^\propto = x^{\frac{\propto}{2}}$$

$$\Rightarrow A_a^{iv} = \pi \int_0^\infty \exp\left[-\left(Ax^{\frac{\propto}{2}} + Ex^{\frac{d}{2}}\right)\right] dx$$

$$\Rightarrow A_a^{iv} = \pi \int_0^\infty \exp[-(Ax^2 + Ex)]dx \qquad [\therefore \propto = 4 \text{ and } d = 2]$$

$$\Rightarrow A_a^{iv} = \pi \int_0^\infty \exp\left[-\frac{x^2}{4\left(\frac{1}{4A}\right)} - Ex\right] dx$$

We get, $\Rightarrow A_a^{iv} = \pi \left[\sqrt{\pi\left(\frac{1}{4A}\right)}\, \exp\left(\frac{E^2}{4A}\right)\left[1 - \Phi\left(E\sqrt{\frac{1}{4A}}\right)\right]\right]$

Appendix K. Matlab Code

1.

```
clc
clear
close all

%% parameter
al = 4;
eta = 0.1;
K = 100;
d = 1;
R = 1;

Is = 10^-3.*10.^(20./10);  % dBm
Ip = 10^-3.*10.^(30./10);
N = 10^-3.*10.^(-148./10);

%% Code

P_dBm = 0:2:200;
P = 10^-3.*10.^(P_dBm./10);

Pth_dBm = 20;
Pth = 10^-3.*10.^(Pth_dBm./10);


for i = 1:1:length(P_dBm)

DSE1(i) = Delay_SpectralEff(R,al,Pth,P(i),Is,Ip,N,d);

DSE2(i) = Delay_SpectralEff_OT(R,al,Pth,d);

DSE3(i) = Delay_SpectralEff_OR(al,Pth,P(i),Is,Ip,N,d) ;
```

```
end

figure(1)
semilogy(P_dBm,DSE1,'LineWidth',2.5)
hold on
grid on
semilogy(P_dBm,DSE2,'--k','LineWidth',2.5)
xlabel('Transmission Power (dBm)','FontSize', 16);
ylabel('DASE (npcu/m^2)','FontSize', 16);
legend('Orginal','Optimal Transmission')
ylim([10^-15 1])


figure(2)
semilogy(P_dBm,DSE1,'LineWidth',2.5)
hold on
grid on
semilogy(P_dBm,DSE3,'--r','LineWidth',2.5)
xlabel('Transmission Power (dBm)','FontSize', 16);
ylabel('DASE (npcu/m^2)','FontSize', 16);
legend('Orginal','Optimal Code')
ylim([10^-15 1])
```

2.

```
clc
clear
close all

%% parameter
al = 4;
eta = 0.1;
K = 100;
d = 1;
```

```
R = 0.1:0.1:30;

Is = 10^-3.*10.^(20./10);  % dBm
Ip = 10^-3.*10.^(30./10);
N = 10^-3.*10.^(-148./10);

%% Code

P_dBm = 30;
P = 10^-3.*10.^(P_dBm./10);

Pth_dBm = 20;
Pth = 10^-3.*10.^(Pth_dBm./10);


for i = 1:1:length(R)

DSE1(i) = Delay_SpectralEff(R(i),al,Pth,P,Is,Ip,N,d);

DSE2(i) = Delay_SpectralEff_OT(R(i),al,Pth,d);

DSE3(i) = Delay_SpectralEff_OR(al,Pth,P,Is,Ip,N,d) ;

end

figure(1)
semilogy(R,DSE1,'LineWidth',2.5)
hold on
grid on
semilogy(R,DSE2,'--k','LineWidth',2.5)
xlabel('Code Rate (npcu)','FontSize', 16);
ylabel('DASE (npcu/m^2)','FontSize', 16);
legend('Orginal','Optimal Transmission')
ylim([10^-15 1])
```

```
figure(2)
semilogy(R,DSE1,'LineWidth',2.5)
hold on
grid on
semilogy(R,DSE3,'--r','LineWidth',2.5)
xlabel('Code Rate (npcu)','FontSize', 16);
ylabel('DASE (npcu/m^2)','FontSize', 16);
legend('Orginal','Optimal Code')
ylim([10^-15 1])
```