SPECIFIC QUALITY OF SERVICE CONSTRAINED OPTIMAL ALLOCATION OF TRANSMIT POWER IN COGNITIVE OFDMA SYSTEMS

A thesis submitted to the Department of Electrical and Electronic Engineering of Bangladesh University of Engineering and Technology in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

By

NORMIN NAHAR
B.SC. IN EECE, MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY, 2013

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
JANUARY' 2019

The thesis entitled "**SPECIFIC QUALITY OF SERVICE CONSTRAINED OPTIMAL ALLOCATION OF TRANSMIT POWER IN COGNITIVE OFDMA SYSTEMS**" submitted by NORMIN NAHAR, Student No.: 0413062235, Session: April, 2013, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on 16 January, 2019.

BOARD OF EXAMINERS

Lutfa Akter

Chairman(Supervisor)

Dr. Lutfa Akter
Professor
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh.

Member(Ex-Officio)

Dr. Md. Shafiqul Islam
Professor and Head
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh.

Uddin 16.01.19

Member

Dr. Md. Forkan Uddin
Professor
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh.

Member(External)

Dr. Md. Rubaiyat Hossain Mondal
Associate Professor
Institute of Information and Communication Technology
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh.

CANDIDATE'S DECLARATION

I, do hereby declare that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Normin

NORMIN NAHAR

To My Son “Nazif”

Table of Contents

List of Tables

List of Figures

List of Abbreviation

ACI: Adjacent Channel Interference

ADC: Analog to Digital Converter

AP: Access Point

BER: Bit Error Rate

BS: Base Station

BWRC: Berkeley Wireless Research Center

CCI: Co-channel Interference

CDMA: Code Division Multiple Access

CP: Cyclic Prefix

CR: Cognitive Radio

CRNs: Cognitive Radio Networks

CSI: Channel State Information

DAC: Digital to Analog Converter

DSA: Dynamic Spectrum Access

EE: Energy Efficiency

FFT: Fast Fourier Transform

ICI: Inter Channel Interference

IFFT: Inverse Fast Fourier Transform

ISI: Inter symbol Interference

IT: Interference Temperature

MAC: Medium Access Control

MCM: Multi Carrier Modulation

M-QAM: M-ary Quadrature Amplitude Modulation

OFDM: Orthogonal Frequency Division Multiplexing

OFDMA: Orthogonal Frequency Division Multiple Access

PA: Power Amplifiers

PM: Power Minimization

PU: Primary User

QoS: Quality of Service

RCC: Radio Control Channel

RF: Radio Frequency

SDR: Software Defined Radio

SE: Spectral Efficiency

SINR: Signal to Noise Plus Interference Ratio

SNR: Signal to Noise Ratio

SU: Secondary User

Acknowledgements

Foremost, I am very much grateful to Almighty Allah for helping me to fulfill my dreams and make it possible for me to complete my thesis work successfully.

I would like to express my sincere gratitude to my supervisor Dr. Lutfa Akter, for the continuous support, for her patience, motivation, enthusiasm, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. It was a real privilege and honor for me to share her knowledge and also her extraordinary human qualities.

I would like to thank all my teachers for their constant support, availability and constructive suggestions, which were determinants for the accomplishment of the work presented in the thesis.

I would like to thank my parents for being a constant source of encouragement and inspiration to me throughout my life. Their optimism and unconditional support have allowed me to overcome all the obstacle that I faced.

Special mention goes to my husband and my son for almost unbelievable support. They are the most important people in my world and I dedicate this thesis to them. Finally, but by no means least, I would like to thank rest of my friends and family members for their kind support and help.

Abstract

Cognitive radio (CR) is considered to enhance spectrum utilization efficiency by dynamically sharing the spectrum between licensed/ primary users (PUs) and unlicensed/secondary users (SUs). This is achieved by permitting SUs opportunistic access to the white spaces within PUs spectrum while controlling the interference to PUs. This optimizes the use of available radio-frequency (RF) spectrum while minimizing interference to other users. Orthogonal Frequency Division Multiple Access (OFDMA) is widely recognized as an ideal air interface for the CR system due to its flexibility in allocating radio resource among the SUs, which is the prerequisite for the CR system to acquire high throughput. Which means, the technology is recognized as an attractive modulation technique for CR due to its spectrum shaping flexibility, adaptivity in allocating vacant radio resources, and capability of analyzing the spectral activities of PUs. In cognitive OFDMA systems, multiple cognitive radios are considered to compete for multiple subcarriers/subchannels. Most of the prior research efforts on cognitive OFDMA systems are on sensing subchannel, channel allocation, subchannel and transmit power allocation, transmit power allocation etc. Most of the approaches on subchannel and transmit power allocation are for downlink systems and based on maximizing capacity criterion which results on full utilization of power budget and hence, incur huge energy consumption. Recently, resource allocation optimization frameworks based on minimizing energy efficiency (unit joule/bits) or maximizing energy efficiency (unit bits/joule) have got attention. However, energy efficiency based approaches are nonconvex and hence, solutions are near optimal. In this thesis, unlike to prior works, Specific Quality of Service (QoS) constrained power minimization criterion based resource allocation convex optimization framework with transmit power as decision variable for cognitive OFDMA systems is proposed and studied in details.

At first, an uplink cognitive OFDMA system of multiple secondary users and multiple free channels is considered where, users employ orthogonal multiple access scheme. Two resource allocation optimization frameworks namely framework-I and II are proposed. Framework-I aims at designing a resource allocation convex optimization framework to determine the optimal transmit power with a goal of minimizing total transmit power and constrained by signal to noise ratio (SNR) thresholds as a measure of QoS. Whereas, framework-II aims at designing a resource allocation convex optimization framework to determine the optimal transmit power with a goal of minimizing total transmit power and constrained by minimum rate requirements as a measure of QoS. Later a downlink cognitive OFDMA system is considered. Similar frameworks (framework-I and II) are developed to determine optimal allocation of transmit power. Numerical results of both uplink and downlink cognitive OFDMA systems reveal that, both of the proposed frameworks are very much successful in terms of utilization of power budget of users and Energy Efficiency compared to conventional capacity maximization based resource allocation approaches.

Chapter 1

Introduction

1.1 Cognitive OFDMA System

In the era of globalization, wireless communication has become an essential part in every corner of the world whose positive impact can not be denied in our day to day life. This form of communication has reached even some of the more remote regions of the planet. Wireless communication has impacted the world in many important ways (i.e., health care, environmental protection, business communication, news reporting, entertainment etc.). This results in an explosion in the demand for wireless internet access through various smart devices (i.e., smart phones, tablets and laptops). Hence, radio spectrum becomes more and more crowded with the ever increasing demand for mobile and wireless applications which needs to be solved to ensure better communication.

According to existing spectrum policy across globe, the spectrum assignment among communication systems and frequency band allocation inside many wireless systems are fixed. Hence, such policies directly result in idle spectrum in certain location and particular time. Moreover, available spectrum is divided into blocks. In this scenario, the concept of primary users (PU) emerges. This is the term which refers to users with licences and having exclusive access for a given geographical region to some of the blocks which are actually licensed bands. Moreover, some of the blocks can also be operated by users having no license. These blocks are also being allocated by regulatory authorities. These blocks are known as unlicensed blocks (i.e., 2.4 GHz ISM band, upper 5 GHz U-NII band etc.). Users to these unlicensed blocks are termed as secondary users. Conventionally, PUs get the privilege to access the reserved bandwidth. Whereas, unlicensed bands promote coexistence of dissimilar radio systems in the same spectrum. In this context, investigations show that, large portion of spectrum is highly underutilized due to inefficient regulatory policies. For example, the measured result of spectrum activity in downtown, Berkeley is shown in Figure 1.1. The figure clearly indicates drop of utilization of the spectrum in the 3-5 GHz frequency band in downtown, Berkeley [1]. From the figure it is observed that, most part of the bands are less utilized for most of the time. On the other hand, practical measurements have revealed that, some of the allocated spectrum bands are not utilized efficiently in many geographical locations at a given time [2–4]. The inefficient usage of licensed bands has made the situation even worse.

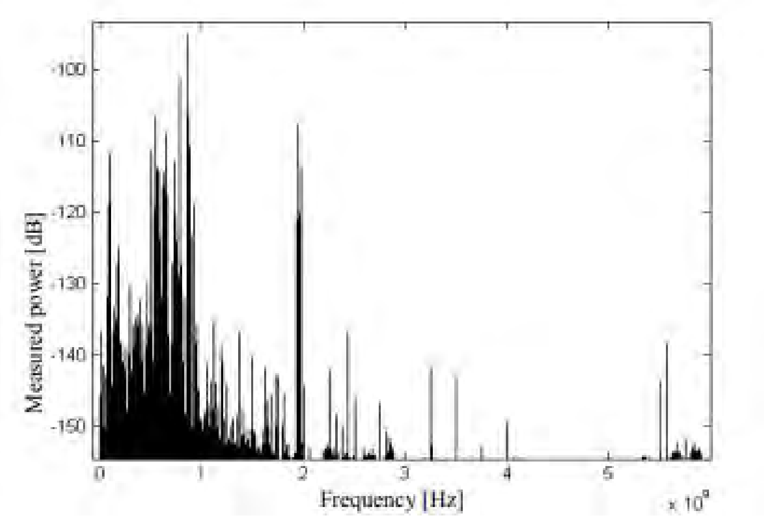


Figure 1.1: Spectrum utilization measurement at Berkeley Wireless Research Center [BWRC] [1]

The utilization of these unused/underutilized bands can be improved significantly by giving dynamic/opportunistic spectrum access to a group of potential users for whom they are not originally assigned. As a promising technique to improve the usage efficiency of spectrum, cognitive radio (CR) has attracted much attention in the past decade. It can be mentioned that, cognitive radio is a term proposed by Joseph Mitola III [5] to represent technologies improving spectrum efficiency by adaptive utilization of idle radio resource.

In wireless communication, orthogonal frequency division multiplexing (OFDM) is widely known as a method of encoding digital data on multiple carriers having multiple frequencies. Conceptually, OFDM is a specialized frequency division multiplexing (FDM) method, with the additional constraint that all subcarrier signals within a communication channel are orthogonal to one another. In OFDM, the subcarrier frequencies are chosen so that, the subcarriers are orthogonal to each other, meaning that, cross talk between the subchannels is eliminated and inter carrier guard bands are not required which is shown in Figure 1.2. This greatly simplifies the design of both the transmitter and the receiver. Unlike conventional FDM, a separate filter for each subchannel is not required. OFDM can effectively avoid frequency selective fading. Besides, inter channel interference (ICI) and inter symbol interference (ISI) can also be avoided by adding cyclic prefix (CP) into the data frame of OFDM symbols. OFDM has more popular usage in applications such as digital television and audio broadcasting, DSL internet access, wireless networks, power line networks, and 4G mobile communications. It can be added that, OFDM is employed in fixed WiMAX system deployed around the world for broadband internet service. In OFDM systems, only a single user can transmit on all of the subcarriers at any given time whereas, Orthogonal frequency division multiple access (OFDMA) is a multiuser version of the popular orthogonal frequency division multiplexing (OFDM) digital modulation scheme. By assigning subsets of subcarriers to individual users multiple access is achieved in OFDMA. This allows simultaneous low data rate transmission from several users.

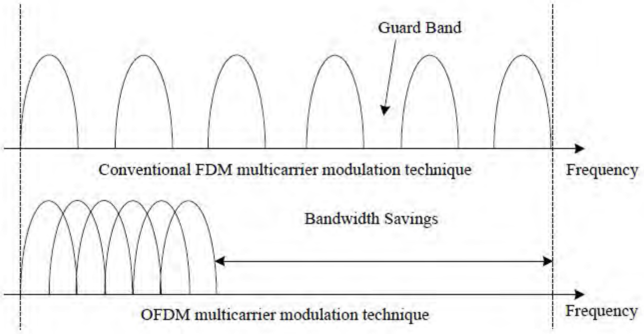


Figure 1.2: Comparing bandwidth utilization between the conventional FDM system and OFDM system

In the past few decades enormous research have been carried out regarding cognitive radio technology, hence technological advancement and multiple forms have been shown up in this regard. OFDMA based cognitive radio system is one of them. It is to be mentioned that, in order to meet the requirements of opportunistic access, the physical layer of the CR system should be very flexible, which necessitates multicarrier methods to operate in the CR scenario. In cognitive OFDMA systems, multiple cognitive radios are considered to compete for multiple subcarriers/subchannels. OFDMA is widely recognized as an ideal air interface for the CR system due to its flexibility in allocating radio resource among the SUs, which is the prerequisite for the CR system to acquire high throughput as discussed earlier [6]. Which means, the technology is recognized as an attractive modulation technique for CR due to its spectrum shaping flexibility, adaptivity in allocating vacant radio resources, and capability of analyzing the spectral activities of PUs.

There are certain challenges in OFDMA based cognitive radio system. Some of them can be broadly listed as:

1. Cognitive radio architecture and implementation issues,
2. Spectrum sensing hardware requirements,
3. Spectrum sensing algorithms,
4. Resource management,
5. Fairness in resource allocation,
6. Policy challenges.

In this thesis, our focus is on finding specific quality of service (QoS) constrained power minimization criterion based resource allocation convex optimization framework with transmit power as decision variable for cognitive OFDMA systems. Hence, we provide a literature review on resource allocation in the following section.

1.2 Literature Review

There has been enormous research on OFDM/OFDMA based cognitive radio system. The authors in [7, 8] study subchannel sensing. Whereas the authors in [9–13] study channel allocation and the authors in [14–20] study subchannel and transmit power allocation. Moreover, the authors in [6, 21–28] study transmit power allocation and the authors in [29] study power minimization criteria in OFDM/OFDMA based cognitive radio system. As our proposed work is on transmit power allocation, hence, we provide a little detailed overview on that only. The author in [14] propose a system model considering a set of available channels which is determined dynamically and total power constraint per individual users. Here, the authors study the problems of power control and channel assignment jointly and develop a near optimal algorithm based on maximizing capacity. However, the limits of the system capacity are quantified given both ideal (no SINR constraints) and conservative (with SINR constraints) designs. In [15], the authors consider a system model of multiple cognitive radios (CRs) and multiple available channels and develop joint channel and power allocation algorithms for both orthogonal transmission and interference transmission to optimize the power allocation across users and channels. They aim at formulating a new metric indicating user satisfaction in both data rate and power consumption. The algorithms are also extended for cognitive radios equipped with multiple antennas. Moreover, the performance gains by allowing interference transmission and by using multiple antennas at transceivers are also demonstrated. In [16], the authors present a system model considering different criteria like capacity in bps and number of links fulfilling in SINR requirements that define the network utility to obtain a game theoretic solution for joint channel allocation and power control in cognitive radio networks (CRNs). The authors aim at finding a distributed solution that maximizes the network utility with limited information. However, the proposed game provides local information that provides similar performance to a potential game that requires global knowledge. The authors in [17] offer a system model considering an uplink OFDMA based cognitive CR and primary user (PU) interference along with the transmit power limits of SUs constraints. To avoid complexity and to maintain good performance, they develop a novel particle swarm optimization (PSO) based joint uplink power and subchannel allocation algorithm based on maximizing uplink throughput of secondary users (SUs) in CR network. Here the authors study the resource allocation problem for such a system. The authors show that, due to the combinatorial nature of the resource allocation problem, the algorithm in which power continuously changes while the subchannel allocation strategy alters in the iteration process can obtain better performance than the existing decomposition based algorithm where, subchannel assignment and power allocation are implemented separately. In [18], the authors propose a system model considering a single primary user (PU) CR system based on OFDMA and minimum transmission rate constraints of

CR users (CRUs) with the specified interference thresholds. Here, the authors study the resource allocation problem in such a system and develop a suboptimal resource allocation algorithm to maximize the sum transmission rate of all CRUs. In an extended version, multiple-PU case is shown and an asymptotically optimal resource allocation algorithm is proposed using dual methods subject to constraints on both interference thresholds of PUs and total transmit power of all CRUs. The authors succeeded to show that, in contrast to classical resource allocation algorithms, the proposed algorithm can achieve higher transmission rate and guarantee each CRU's minimum transmission rate. In [19], the authors develop a system model for OFDM based multi-user cognitive radio systems with Quality of Service (QoS) in terms of signal to interference plus noise ratio (SINR) and proportional rate constraints. They investigate joint power and channel allocation problem for such system and present a formal analysis for a proposed approach and illustrate the approach with numerical results obtained from simulations. The authors show that, the QoS requirement of each cognitive radio user imposed by its minimum SINR and interference introduced by unlicensed secondary users to primary users make power and channel allocation problem more complex. With a view to protect PUs, the authors in [20] consider a system model of varying channel conditions subject to power constraint, minimum QoS requirement for capacity, and collision probability threshold. They determine the optimal channel selection and power distribution for SU transmissions considering mixed integer nonlinear programming (MINLP) based optimization problem, which is generally nondeterministic in polynomial time. The simulation results presented in this paper demonstrate that, adaptive ChA (Channel Assembling) with channel characterization improves performance in terms of channel capacity, outage probability and collision probability. In [27], the authors demonstrate OFDM based cognitive users, considering total power, each subchannel power and PU aggregate interference limits constraints along with SU's coexistence in same as well as adjacent frequency bands by underlay and interweave approaches respectively. A subcarrier power allocation scheme has been proposed by the authors for spectrum sharing with primary users (PU) based on SU sum capacity of reliable communication maximization. They prove that, in terms of SU capacity and PU interference, their proposed algorithm outperforms some of the existing schemes having almost same complexity as the proposed one. In addition it is shown that, the improvement is significant when the adjacent subcarriers channel gains are relatively 'good' or 'bad' compared with the non-adjacent one.

In [21], the authors develop a system model where each SU is allowed to transmit on multiple channels in contrast to existing schemes of cognitive radio networks (CRNs). Moreover, the SUs, who do not have any data to transmit or no channel is assigned to them, transit into the sleep-mode, targeting significant reduction in energy consumption. The authors focus on energy efficiency (EE) and develop a nonlinear integer programming. To address it, a polynomial time heuristic algorithm is presented here. Simulation results indicate that, the proposed algorithm (MCAS) outperforms existing algorithms for CRNs in terms of EE, throughput and energy consumption. It is to be noted that, energy efficiency (EE) is an important issue in wireless networks as with the ever growth of high data rate applications, the energy consumption is also growing at a staggering rate nowadays, which results in a large amount of greenhouse gas and high operation expenditure for wireless service providers. Therefore, OFDMA based CR, which places great emphasis on EE in wireless networks, is becoming increasingly important and prompting new waves of research and standard development activities. Hence, an adequate energy efficient metric is given primary importance in overall energy efficient network design since it is related to the optimized decisions directly. The most popular one is called ‘bits-per-joule’, which is defined as the system throughput (no of bits) to unit energy consumption [25]. Here, both the transmission power and the circuit energy consumption is taken into consideration for energy efficient communication, where the former is used for reliable data transmission and the latter represents average energy consumption of device electronics. However, in some research works, EE is defined as the total energy consumption to deliver one bit in a successful transmission. Which means, it is very much common to call EE metric as ‘joule-per-bits’ [23]. The authors in [22] present a spectrum sharing cognitive radio (CR) system. They develop a power allocation framework based on maximizing the EE. They also solve a nonconvex problem and explicitly derive the optimal power for the proposed average EE under either a peak or an average power constraint. The authors show that, the relation between the EE and the spectral efficiency (SE) is strictly increasing in contrast with the SE-EE tradeoff. In the CR context, they also show that, the interference threshold has a minimal effect on the EE compared to the SE. In [23], the authors propose a OFDM based cognitive radio systems under channel uncertainties, minimum required rate and a specified power budget constraints for the SU while restricting the interference to PUs in a statistical manner. They develop a novel optimization algorithm to optimize the EE of such system. The authors show that, the EE deteriorates as the channel estimation error increases. Comparisons with relevant works show that, the interference thresholds at the PUs receivers can be severely exceeded and the EE is slightly deteriorated if the SU does not account for spectrum sensing errors. The authors in [6] consider CR networks with practical restrictions, including the power budget of system, the interference thresholds of the PUs, the rate requirements of the SUs, and the fairness among them. They investigate the energy consumption issue with a aim to maximize the EE of the CR network. Simulation results show that, the proposed resource allocation schemes perform well in practical scenarios. The energy efficiency obtained by the integer subchannels assignment and the fast power distribution achieves more than 98 percent of the upper bound. On the other hand, the proposed heuristic subchannels assignment with optimal power allocation achieves a good tradeoff between computation complexity and energy efficiency. In [24], authors consider an OFDM-based CR systems and study it under the total power constraint, the interference power constraint and the rate constraint. They intend to improve the system throughput for unit energy consumption for such systems and propose an optimal and energy-efficient power allocation algorithm. Moreover, they propose a novel method named water-filling factors aided search (WFAS) to solve the EE optimization problems with multiple constraints. The authors in [25] propose a system model considering a CR network with practical restrictions, including the power budget of the system, the interference thresholds of the PUs, the rate requirements of the SUs, and the fairness among them and investigate the energy consumption issue in such a system. With a aim to maximize the EE of the CR network, the authors develop an efficient barrier method to work out the (near) optimal solution with a reasonable complexity, significantly better than the standard technique. Numerical results show that, the proposal can maximize the energy efficiency of the CR system, whilst the proposed algorithm performs quickly and stably. In [26], the authors consider an OFDM based CRNs in underlay mode and plot an objective function consisting of the users' performance degradation and the network interference, in the same time to track time varying target of SINR under maximum transmit power for each cognitive user and interference power constraint from primary user. They investigate the energy efficient power allocation for such a system. The authors' scheme is obtained by designing a convex optimisation problem where, the tradeoff between energy consumption and transmission capacity is considered, and a distributed algorithm is developed to solve this problem. The authors in [28] propose a system model with constraint that all primary users are supported with their target-SINRs in a cellular cognitive radio network (CRN). They design an efficient and low-complexity centralized algorithms for joint power and admission control in such a system which coexists with a primary radio network (PRN) in a spectrum underlay fashion. The proposed algorithms aim at removing the minimal number of secondary users (based on the proposed admission metrics). They also show that, in an infeasible system, the proposed algorithms outperform other existing algorithms in terms of complexity and secondary users outage ratio. Here, authors solve the problems of maximizing aggregate throughput and max-min quality-of service (QoS) for secondary users, both subject to the constraint that all primary and secondary users are supported with their minimum target-SINRs.

In [29], the authors aim to design an optimal set of beam-vectors for multi-band multi-antenna cognitive radio networks that jointly allocate power over both space and frequency, so that the sum power of SUs is minimized, subject to rate demands at the SUs, as well as the interference constraints imposed by PUs.

We can conclude from the above that:

1. Most of the approaches on subchannel and transmit power allocation/transmit power allocation are based on maximizing capacity criterion which results on full utilization of power budget and hence, incur huge energy consumption [16–20, 27]. Power minimization as the optimization criterion is especially desirable in the networks with battery-powered nodes [29].
2. Also, energy efficiency (EE) based approaches are nonconvex and hence, solutions are near optimal [6, 21–26, 28].
3. Although there are few works on power minimization approach in CRN [29], however the presented approaches are non-convex and a vigorous study is yet to be explored.

Hence, QoS constrained power minimization based optimal resource allocation schemes for uplink/downlink cognitive OFDMA systems can be explored.

1.3 Motivation

For cognitive OFDMA systems, subchannel and transmit power allocation based on capacity maximization results in full utilization of power budget and hence incur huge energy consumption. On the other hand, resource allocation based energy efficiency maximization approaches are nonconvex and hence, solutions are near optimal. Hence, in our thesis, we tend to a develop specific Quality of Service (QoS) constrained power minimization criterion based resource allocation convex optimization framework with transmit power as decision variable considering both uplink and downlink cognitive OFDMA system and to work accordingly, we consider a cognitive OFDMA system where, multiple cognitive radios are considered to compete for multiple subcarriers/subchannels. It is assumed that each subcarrier/subchannel is assigned to a single user. By considering such system models, our objective is to minimize total transmit power. In this regard, two optimization frameworks for both uplink and downlink cognitive OFDMA systems have been proposed in our thesis. To determine the optimal transmit power, both the frameworks aim at designing resource allocation convex optimization framework where as a measure of QoS, signal to noise ratio (SNR) threshold and minimum rate requirement to attain a specific bit-error-rate (BER) are being considered respectively.

1.4 Contributions

We consider a cognitive OFDMA system having multiple secondary users and multiple free channels. Moreover, subchannel allocation to each of the users is already decided. In our system, it is assumed that, each subcarrier/subchannel is assigned to a single user. An Access Point (AP) is assumed to control the transmission of cognitive radios that lie within its range of coverage and also collects reports about the activities of primary users (PUs) with whom the CR may interfere with. An interference temperature threshold is also imposed to protect the PU transmission on any channel from any harmful interference. For such a system, two resource allocation convex optimization frameworks is developed for both uplink and downlink cognitive OFDMA system. The key contributions of this thesis are summarized below:

1. **Framework-I:** Here, we propose a resource allocation convex optimization framework to determine the optimal transmit power with a goal of minimizing total transmit power and constrained by signal to noise ratio (SNR) thresholds as a measure of QoS. The proposed optimization framework for uplink cognitive OFDMA system is presented in Chapter 3 and for downlink, it is presented in Chapter 5.

2. **Framework-II:** Here, we propose a resource allocation convex optimization framework to determine the optimal transmit power with a goal of minimizing total transmit power and constrained by minimum rate (bits/sec/Hz) requirements as a measure of QoS. The proposed optimization framework for uplink cognitive OFDMA system is also presented in Chapter 3 and for downlink, it is presented in Chapter 5.

3. The proposed optimization frameworks for uplink cognitive OFDMA system are solved and obtained solutions are also compared with the existing resource allocation techniques in Chapter 4.

4. The proposed optimization frameworks for downlink cognitive OFDMA system are solved and obtained solutions are also compared with the existing resource allocation techniques in Chapter 6.

1.5 Thesis Outline

The thesis is organized as follows:

Chapter 1: introduces the topic of the thesis. It also lifts up the earlier reviews of the related literature and motivation behind this thesis. An outline of the specific contributions of this thesis work is also included in this chapter.

Chapter 2: discusses some preliminaries of cognitive OFDMA Systems and resource allocation in cognitive radio networks.

Chapter 3: describes the proposed resource allocation frameworks for uplink cognitive OFDMA system.

Chapter 4: lifts up the solution of the proposed optimization frameworks for uplink cognitive OFDMA system. Graphical representation of the results are analyzed and compared with the existing frameworks. The developed frameworks are also compared between themselves.

Chapter 5: describes the proposed resource allocation frameworks for downlink cognitive OFDMA system.

Chapter 6: shows the similar analysis of obtained results for downlink cognitive OFDMA system.

Chapter 7: briefly summarizes the overall thesis work and suggests the scope of future.

Chapter 2

Some Preliminaries on Cognitive OFDMA system

2.1 Introduction

As discussed in the previous chapter, cognitive radio (CR) has become a smart solution to the spectrum scarcity problem which is a result of the recent development in wireless communication systems. Spectrum availability is assured here by introducing the opportunistic usage of frequency bands that are not heavily occupied by licensed users. The main functions of a cognitive radio network (CRN) are spectrum sensing and exploitation of available spectrum by adjusting the transmission parameters (i.e., bits/channel use, channel allocation, transmit power etc.). With reference to the previous chapter, it can also be added that, in current wireless services, OFDMA is one of the most widely used technologies. It is to be noted that, OFDMA inherits the potential of fulfilling the requirements of cognitive radios inherently or sometimes small changes are required. Moreover, being a multi carrier technique, OFDMA not only supports huge data rates that are robust to channel impairments but also makes the interpretability among the different protocols more easier which is one of the most important requirements in Cognitive radio. Hence, due to it's potential to achieve very high data rates, OFDMA is deployed extensively in many modern communication systems. This modulation technique allows digital data to be transmitted over a radio channel by using a large number of narrow bandwidth subcarriers. Usually, these subcarriers are regularly spaced in frequency, which further forms a contiguous block of spectrum.

OFDMA ensures several advantages over other transmission technologies such as:

1. high spectral efficiency, robustness to fading channel, immunity to impulse interference, and capability of handling very strong multi-path fading and frequency selective fading without having to provide powerful channel equalization.
2. it is possible to turn off subcarriers corresponding to the spectrum occupied by the incumbent users in order to avoid any interference to existing transmissions, thereby enabling secondary utilization of the unused portions of the spectrum to improve the spectrum utilization efficiency as well as mitigate apparent spectrum scarcity problem.

In OFDMA based CRNs, dynamic spectrum access (DSA) is the main concept. OFDMA based transmission is a promising candidate for a flexible spectrum pooling system in DSA environment. Here, the implementation achieves high data rates via collective usage of a large number of subcarrier bands. It is to be noted that, CRs offer versatile, powerful, and portable wireless transceivers enabling DSA. To enhance a cognitive radio performance, this dissertation investigates physical layer techniques. DSA allows a cognitive radio (secondary user) in a network to opportunistically share the spectrum resources which are allocated to primary users. Sharing the licensed spectrum by secondary users improves the overall spectrum utilization. Moreover, the transmission power of secondary user causes interference to primary user. Therefore, it is necessary to design the secondary user network in a way to allocate it's radio resources to satisfy it's own QoS requirements. At the same time, it is necessary to ensure that, the interference caused to the primary users is below the predetermined threshold level.

2.2 Cognitive Wireless Transceiver

In modern communication system, with the development of software defined radio (SDR) technology, wireless transceiver has become more powerful, versatile, and portable. Wireless transceivers perform depending on base band processing, such as modulation/demodulation and equalization, entirely in software and digital logic. It can be mentioned that, SDR technology is a prime candidate for DSA networks. In addition to the agility of the SDR technology, the radio needs to be spectrally aware as well as autonomous in order to dynamically utilize spectrum. A radio transceiver that can adapt its transmitter parameters based on its interaction with the environment in which it operates in order to improve the quality of radio communication is known as a cognitive radio [30].

Research and development of cognitive radios involves experts from various disciplines as given below:

1. Spectrum Sharing Policy.
2. Artificial Intelligence (AI).
3. Spectrum Sharing Policy.
4. Reconfigurable Hardware.
5. Agile Physical Layer Transmission Techniques.

So, it can be said that, cognitive radio research is highly interdisciplinary and various issues need to be addressed to meet the regulatory requirements before becoming a reality. Moreover, cognitive radio transceivers based on multi carrier modulation (MCM) can readily enable DSA networks by employing spectrum pooling, where secondary users may temporarily access and utilize spectral resources during the idle periods of licensed users [31].

2.3 A Basic OFDM System Model

A simplified block diagram of a basic OFDM system is given in Fig. 2.1. Due to the frequency selectivity, each subcarrier can have different attenuation in a multipath fading channel. The power on some subcarriers may be significantly less than the average power because of deep fades. As a result, the overall bit error rate (BER) may be largely dominated by a few subcarriers with the lowest power level. To reduce the degradation of system performance due to this problem, channel coding can be used prior to the modulation of the bits. Channel coding can reduce the BER significantly depending on the code rate, decoder complexity, SNR level among other factors. Interleaving is also applied to randomize the occurrence of bit errors and introduce system immunity to burst errors. Coded and interleaved data bits are then mapped to the constellation points to obtain data symbols.

Next, the serial data symbols are converted to parallel data symbols which are fed to the inverse fast Fourier transform (IFFT) block to obtain the time domain OFDM symbols. Time domain signal is cyclically extended to avoid residual inter symbol interference (ISI) from the previous OFDM symbols. A simplified baseband digital signal is converted to analog signal through the digital to analog converter (DAC) block. Then, the signal is fed to the radio frequency (RF) front end. The RF front end up converts the signal to the RF frequencies using mixers, amplifies it using power amplifiers (PA), and transmits it through antennas.

In the receiver side, the received signal is passed through a band-pass noise rejection filter and down converted to baseband by the RF front end. The analog to digital converter (ADC) digitizes the analog signal and re-samples it. After frequency and time synchronization, cyclic prefix (CP) is removed and the signal is transformed to the frequency domain using the fast Fourier transform (FFT) block. It is to be noted that, OFDM converts the convolution in time domain into multiplication in frequency domain, and hence simple one-tap frequency domain equalizers can be used to recover the transmitted symbols. After FFT, the symbols are demodulated, deinterleaved and decoded to obtain the transmitted information bits.

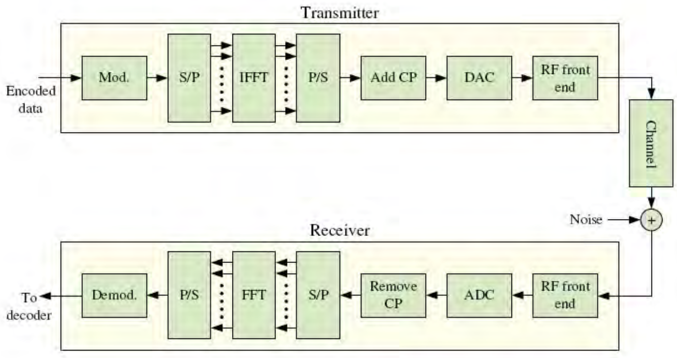


Figure 2.1: Block diagram of a OFDM transceiver.

2.4 OFDM based CR

Let us assume a CR system operating as a SU in a licensed band. The main function of the CR system is to identify available or unused parts of the spectrum and exploit them. The goal is to achieve maximum throughput while keeping interference to PUs to a minimum level.

A block diagram of the OFDM based CR system considered here is shown in Fig. 2.2. The cognitive engine is responsible for making intelligent decisions and configuring the radio and PHY parameters. It is to be noted that, all of the layers can interact with the Cognitive engine. The transmission opportunities are identified by the decision unit based on the information from policy engine as well as local and network spectrum sensing data. As far as the PHY layer is concerned, CR can communicate with various radio access technologies in the environment, or it can improve the communication quality depending on the environmental characteristics, by simply changing the configuration parameters of the OFDM system and the RF interface. However, coding type, coding rate, interleaver pattern, and other medium access control (MAC) and higher layer functionalities, etc., should also be changed accordingly. In Fig. 2.2, FEC stands for forward error correction.

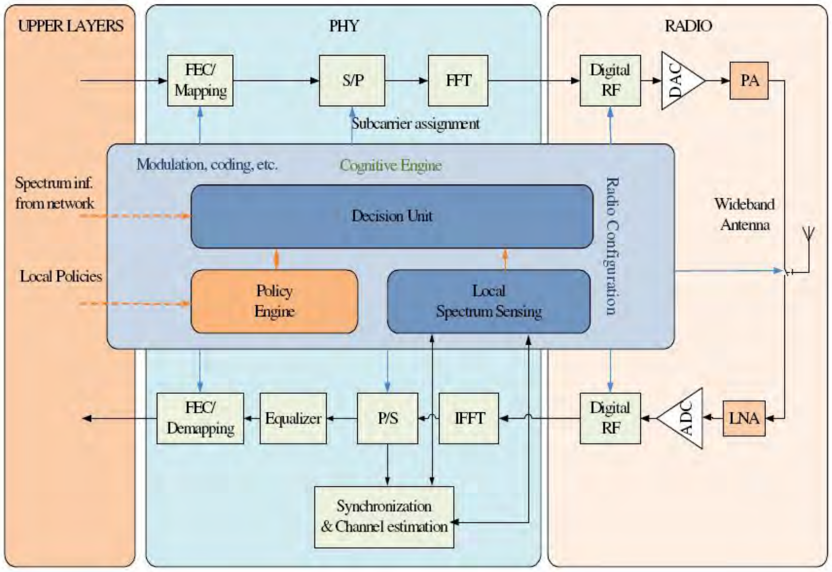


Figure 2.2: OFDM-based CR system block diagram.

2.5 Dynamic Spectrum Access Techniques

With a view to mitigating apparent spectrum scarcity problem and improve spectrum efficiency, Spectrum sharing concept is introduced. Several spectrum sharing strategies have been proposed, which can be broadly categorized based on:

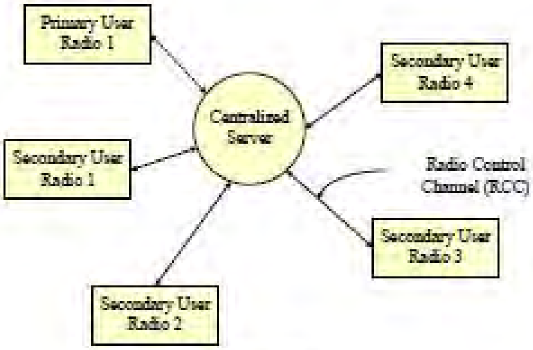
1. Network Architecture.
    (a) Centralized Approach.
    (b) Distributed Approach.

2. Spectrum Allocation Behavior.
    (a) Cooperative Approach.
    (b) Non-Cooperative Approach.
3. Spectrum Access Technique.
    (a) Underlay Approach.
    (b) Overlay Approach.

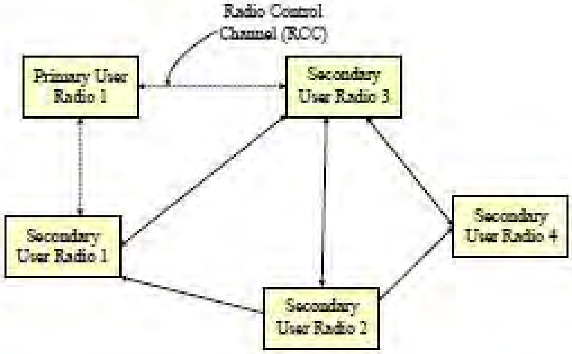
2.5.1 Centralized and Distributed Spectrum Sharing Techniques

In a centralized spectrum sharing approach, a centralized entity coordinates with arbitrary wireless technologies and manages access to arbitrary radio spectra by issuing clients temporary leases for parts of the radio spectrum [32]. In this model, a centralized server is considered whose main function is to collect information from a collaborating group of secondary users. This technique needs to learn about the primary user transmission characteristics, along with primary user cooperation. Moreover, a database for the spectrum access and availability information is being managed by this technique. The users communicate with the centralized server using a pre assigned dedicated radio control channel (RCC). A basic framework for a centralized spectrum sharing model is shown in Fig. 2.3. In the figure, the dashed RCC link between the primary user and the centralized server implies that the primary user may or may not choose to cooperate, whereas the solid RCC link between the secondary user and the centralized server implies that they must cooperate with each other. This form of spectrum management offers simpler and coordinated spectrum access, which enables efficient spectrum sharing and utilization in wireless environments.

Even though a centralized server can optimize across network wide information, there are two serious limitations:



(a) Centralized.



(b) Distributed.

Figure 2.3: Centralized and Distributed Spectrum Sharing.

1. The spectrum server and all secondary users need to communicate using a pre-assigned dedicated RCC. As the network grows in density, a pre-defined control channel can limit the bandwidth available for data communication.

2. As the number of users grows, the server processing complexity will scale at least polynomially. Therefore, any central spectrum server can quickly become a computational bottleneck in the system.

Each node is responsible for its own spectrum allocation and access based on primary user transmissions in its vicinity and policies in a distributed spectrum sharing approach [33], [34]. In this model, primary user contributions need not be enforced since secondary users can sense and share the local spectrum access information among themselves. Since there would be no overhead involved with the incumbent users, this model poses an advantage for the primary license holders.

Since individual nodes are responsible for maintaining the correct information about current spectrum usage, distributed spectrum sharing results in increased overhead communications among the secondary users. However, cooperative distributed algorithm can produce effects similar to global optimization through cooperative local actions distributed throughout the system. One of the serious drawbacks of the distributed spectrum sharing approach is the hidden node problem, where the secondary users fail to detect incumbent users and as a result inadvertently interfere with the incumbent user transmissions [35]. For example, in Fig. 2.4, the secondary user SU2 can sense both primary user PU1 and secondary user SU1, however, the PU1 is hidden to SU1 . Moreover, large amounts of measurement information gathered by the secondary user terminals during the detection cycle need to be transmitted to the other users, which can be a significant overhead in the system.

2.5.2 Cooperative and Non-Cooperative Spectrum Sharing Approaches

Based on the spectrum allocation behavior, spectrum sharing techniques can be classied into cooperative and non-cooperative spectrum sharing. In cooperative spectrum sharing, the primary and secondary users can cooperate and share spectrum occupancy information with each other to improve the spectral usage. The model can either use centralized server sharing [36], where a centralized entity maintains the database of the spectrum usage and coordinates the spectrum access information among the users, or distributed sharing [33], [34], where each user maintains

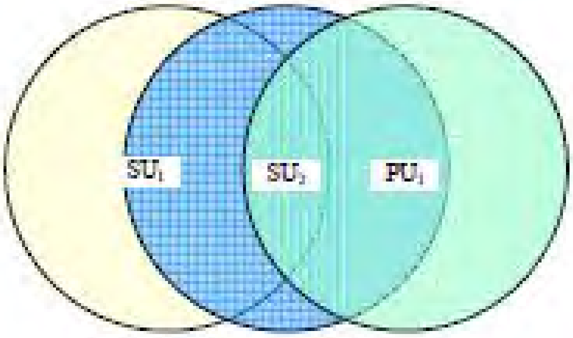


Figure 2.4: An example illustrating a hidden node problem, where the primary user PU1 is hidden from the secondary user SU1.

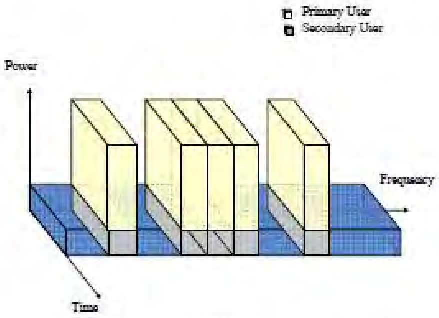
the information about the local spectrum usage and share its knowledge with other nearby users to improve spectrum utilization efficiency. Even though the cooperative approach seems to be the most straightforward method, the primary user must be involved for efficient sharing of spectrum access information among the secondary users, which is often an unwanted burden on the part of the primary users. On the other hand, secondary users may cooperate with each other without any involvement of primary users and share information to detect the presence of a primary user to achieve significant performance enhancements on spectrum utilization and interference avoidance [37]. Cooperative approaches may lead to results that closely approximate the optimal spectrum allocation among the users. However, a cooperative approach model may heavily depend on the communication resources of the DSA networks. As a result, this communication overhead might limit the available spectrum for data communications. Since the ultimate goal of the cooperative approach is to achieve acceptable overall spectrum utilization, the users must be somewhat selfless, occasionally sacrificing local performance to improve overall system utility [38]. In a non-cooperative spectrum sharing approach, information exchange among the users is kept to a minimum, such that the secondary users independently interpret the spectrum usage and availability, while not interacting with the primary users [39], [40]. The non-cooperative approaches result in minimal communication requirements among the nodes at the expense of poor spectrum utilization efficiency. The non-cooperative approaches may act in a selfish, greedy, or rational way [41].

2.5.3 Underlay and Overlay Spectrum Sharing Approaches

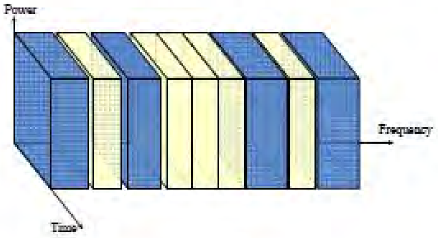
Spectrum sharing techniques can be classified into underlay and overlay spectrum sharing based on the spectrum access techniques. Underlay systems use ultrawide band (UWB) [42] or spread spectrum techniques, such as code division multiple access (CDMA) [43], to transmit the signal below the noise floor of the spectrum [44]. An example of the time and frequency domain information of an underlay spectrum sharing system is shown in Figure 2.7(a). In this figure, we see that, the underlay systems use wide band low power signals for transmissions. However, this technique can increase the overall noise temperature and thereby worsen error robustness of the primary users as compared to the case without underlay systems. To avoid any interference to the primary users, underlay system can use interference avoidance techniques, such as notching [45] and waveform adaptation [46].

To improve the spectral efficiency, overlay systems utilize the unused portions of the spectrum. The spectrum holes filled in by secondary transmissions in an overlay system is shown in Fig. 2.5. As shown in this figure, the overlay systems use the unoccupied portions of the spectrum with a reasonable amount of guard intervals for secondary transmissions keeping the interference to the primary users to a minimum. Since the licensed system has privileged access to the spectrum, it must not be disturbed by any secondary transmissions. This results in two main design goals for an overlay system [47]:

1. Minimum interference to licensed transmissions.



(a) Underlay.



(b) Overlay.

Figure 2.5: Overlay and underlay spectrum sharing.

2. Maximum exploitation of the gaps in the time-frequency domain.

In order to achieve these goals, the overlay system needs information about the spectrum allocation of the licensed systems by regularly performing spectrum measurements. When interference among the users is high, it has been shown that frequency division multiplexing is an optimal technique [41]. To enhance spectral efficiency, an approach called spectrum pooling is proposed [48], which enables secondary access to licensed frequency bands by filling in the spectrum holes with secondary user transmissions without requiring any changes to the primary licensed systems. Spectral pooling represents the idea of merging spectral ranges from different spectrum owners (military, trunked radio, etc.) into a common pool, where users may temporarily rent spectral resources during idle periods of licensed users, thereby enabling the secondary utilization of already licensed frequency bands [48]. In spectrum pooling system, a centralized entity can collect measurement information gathered by the secondary user terminals during the detection cycle, and maintain the spectrum usage information. The centralized entity is responsible for making decisions on granting portions of the spectrum to the secondary users. With the use of a centralized entity, the information management of a spectrum access network would be relatively simple. However, this same entity can also easily be a bottleneck for the network, as already explained. Since the overlay systems can readily exploit the unused portions of the spectrum without interfering with the incumbent users and without increasing the noise temperature of the system, we will consider overlay systems from this point forward.

One of the most challenging problems of spectrum sharing systems is their successful co-existence in the same frequency band, i.e. an overlay system should not degrade the performance of systems already working in the target frequency band. For instance, out-of-band radiation has to be reduced in order to enable coexistence. The transmitter spectral mask is a measure of the transmitter spectral prole in order to verify that the device is not transmitting excessive amounts of energy outside its assigned channel bandwidth. Several approaches have been proposed in literature for suppressing the sidelobe levels, such as the deactivation of subcarriers lying at the borders of an OFDM spectrum [49], windowing [49], subcarrier weighting [50], and insertion of cancellation carriers.

2.6 Resource Allocation in OFDMA based CRNs

The resource allocation scheme in a OFDMA based CRN is the entity which is responsible for avoiding harmful interference caused to the PUs while optimally utilizing the available resources (i.e., power, rate and spectrum). For example, allocating more power to the secondary users with higher channel gains is generally preferable from a sum rate/capacity perspective. However, this increased power can create interference to PUs which has to be taken in to account. For this reason, the resource allocation schemes in CRN need to consider the effect of PU activities in different bands. Moreover, it may be impossible to satisfy QoS requirements for all SUs with limited power. In such scenarios, there should be an optimal decision for power allocation for SUs in CRNs. Therefore, the development of appropriate resource allocation schemes is one of the vital factors in improving the system throughput and operational efficiency in OFDMA based CRNs.

It is very important to manage the participating entities in order to enhance the spectrum utilization and optimize the performance of both primary network and secondary network. Resource allocation in CRNs can be defined as the technique which involves strategies and algorithms for controlling transmission parameters. Various resource allocation techniques have been developed for conventional wireless networks so far. However, they cannot be directly applied to a cognitive radio network due to the following two main reasons:

1. Maximizing utilities of cognitive radios.
2. Maintaining interference constraints to protect PUs.

2.6.1 Elements of Resource Allocation

The main elements which need to be optimized in CR resource allocation problems are as follows:

1. **Power allocation:** In the power allocation schemes the interference caused to the primary networks needs to be taken into account. The power allocation algorithms should always maintain the level of interference at the PUs under the acceptable interference limit.
2. **Bits/channel use allocation:** In rate or bis/channel use (modulation order) allocation schemes the main objective is to maximize the overall rate in order

to ensure the efficient data transmission. Furthermore, the individual rate requirement of the SUs is also met in these schemes. It should be noted that rate or bits/channel use measure can be visualized to indicate the modulation order employed by the SU in a channel.

3. **Quality of Service (QoS):** Like other wireless networks, a CRN also needs to satisfy its user's QoS requirements. The QoS requirement for the CRs could be a minimum rate requirement and a maximum bit error rate (BER). The other QoS metrics could be signal to noise ratio (SNR), response time, delay, outage probability and blocking probability.

4. **Channel allocation:** The channel allocation algorithm in CRNs plays a significant role in mitigating harmful interference at PUs. As an example, in the spectrum underlay mode, the channel allocation scheme should allocate channels to the CRs which receive minimum interference from the PUs. Unlike traditional wireless channel allocation, the channel allocation algorithms in CRNs depend on the PU activities in the considered channels.

5. **User scheduling:** The CR scheduling decision should be made by considering the CR's channel conditions and their QoS requirements in such a way that it does not affect the QoS requirements of the PUs.

6. **Fairness:** A CRN can achieve a higher system throughput or spectral efficiency while not being fair to all the CRs. This is a trade-off between efficiency in resource allocation and fairness. The fairness can be achieved in terms of bandwidth fairness (equal amount of spectrum to all CRs), power fairness (equal portion of power from the total transmit power budget), or rate fairness (allocate resources in such a way that all the CRs can achieve same rate).

2.7 QoS constrained resource Allocation Approaches in OFDMA based CRNs

In general, resource allocation schemes are formulated as constrained optimization problems. A typical constrained optimization problem consists of a utility function used as an objective function, a set of constraints used to confine a feasible solution set, and a set of optimization variables. For example, an optimization problem with arbitrary equality and inequality constraints can always be written in the following standard form:

$$\begin{aligned} \text{To minimize :} \quad & f_0(x) \\ \text{subject to} \quad & \\ & f_i(x) \leq b_i, \;\; i = 1, 2, ...m. \end{aligned} \tag{2.7.1}$$

where, the vector $x = (x_1, ...x_n)$ is the optimization variable of the problem, the function $f_0 : \mathbf{R^n} \rightarrow \mathbf{R}$ is the objective function, and the function $f_i : \mathbf{R^n} \rightarrow \mathbf{R}, i = 1, ..., m$, are the (inequality) constraint functions, and the constants $b_1, ..., b_m$ are the limits, or bounds, for the constraints. For this optimization problem, a vector x^* is called optimal, or a solution of the problem 2.7.1, if it has the smallest objective value among all vectors that satisfy the constraints. If the objective and constraint functions are convex the problem is said to be a convex optimization problem. Convex optimization method is widely used in such scenarios.

2.7.1 Optimization Objectives

The essence of resource allocation in OFDMA based CRNs is to optimal utilization of radio resources while avoiding harmful interference at the PUs and to satisfy the QoS requirements of CRs. The most common types of objective functions used for optimizing resource allocation in CRNs are as follows:

Power Minimization: The objective of power minimization in CRN transmission is to mitigate harmful interference at the PUs while providing the required QoS to the CRs. An optimization problem with a power minimization objective function utilizes as much bandwidth as possible to minimize power allocation to channels while satisfying the cognitive transmission-specific constraints.

Rate Maximization: The optimization problems in CRNs with the objective of sum rate maximization aims to maximize the total system throughput in CRNs under the interference (i.e., interference at the PUs) and total power constraints. It is important to note that the sum rate maximization problems in CRNs may not guarantee the satisfaction of individual CR's minimum rate requirement.

Utility Maximization: Utility maximization based resource allocation can achieve efficiency and fairness in resource optimization. CRNs can exploit the flexibility of defining utility functions in such a way that the unique requirements in CRNs can be satisfied.

2.7.2 Optimization Constraints

In general, the QoS requirements are represented in an optimization problem by a set of constraints that are defined according to the physical limitations of the system. For example, there is always a maximum limit on how much power is available for SUs or users' power budget for the purpose of transmission. This maximum limit also depends on the interference threshold. On the other hand, in power minimization problems, we generally use a constraint to satisfy the SNR threshold or minimum data rate requirement. These constraints are usually imposed in the problem formulation when there is a trade off between the objective function and the system throughput. Moreover, others QoS metric can also be constrained to enhance the system transmission.

2.8 Summary

In this chapter, some basic concepts of OFDMA based CRNs have been discussed. Moreover, the basics of resource allocation approaches with different objectives and various elements in resource allocation have been illustrated.

Chapter 3

Proposed Resource Allocation Optimization Frameworks for Uplink Cognitive OFDMA System

In this chapter, two resource allocation optimization frameworks with transmit power as decision variable is proposed for uplink cognitive OFDMA (orthogonal frequency division multiple access) system. In both the frameworks optimal transmit power is sought with an objective function of minimizing total transmit power. In the first framework, as a measure of QoS, signal to noise ratio (SNR) threshold has been considered as a constraint. Whereas, in the second framework, as a measure of QoS, minimum rate requirement (total bits/sec/Hz) for a specific bit-error-rate (BER) has been considered as a constraint. The rest of the chapter is organized as follows:
In Section 3.1, along with the system model, all of the assumptions and notations used in the rest of the thesis are stated. Section 3.2 provides the description of the proposed resource allocation frameworks. Finally, Section 3.3 summarizes the chapter.

3.1 System Model

This section describes the considered system model for this research work.

3.1.1 Network Architecture

An uplink cognitive OFDMA system of multiple secondary users and several subchannels is considered. Specifically, an uplink cognitive OFDMA system is considered which comprises of L secondary users and N free subchannels. All users are peers to each other in our consideration. An access point (AP) is assumed to control the transmission of cognitive radios that lie within its range of coverage and also collects reports about the activities of primary users (PUs) with whom the CR may interfere with. We may also assume a common control channel for dialogue between CRs and AP specially given the variable set of available channels. Overlay spectrum sharing is adopted by secondary users. That is, secondary users use the spectrum when it is unused by PUs.

3.1.2 Power Allocation, Channel Selection and Modulation Order Scheme

The objective of this research work is to develop specific Quality of Service (QoS) constrained power minimization criterion based resource allocation optimization framework with transmit power as decision variable. To do that, it is assumed that, subchannel allocation to each of the users is already decided by the AP. It is also assumed that, each subcarrier/subchannel is assigned to a single user. Once the transmit power is obtained, then bit allocation scheme is proposed to determine bits/channel use (i.e., modulation order) which is described in Chapter 4.

The following assumptions have been implored to enable mathematical tractability of the proposed optimization frameworks:

(i) Every active SU radio has an upper bound on total transmit power across channels.

(ii) In the first framework each user has a minimum SNR requirement that needs to be maintained.

(iii) In the second framework each user has a minimum rate requirement (bits per transmission) that needs to be maintained.

(iv) M-ary QAM modulation scheme with an adaptive modulation order M is considered.

3.1.3 Propagation Model

Wireless radio channel is susceptible to noise, interference and other channel constraints. It is very important to model the wireless propagation properly for any wireless network. In order to characterize the propagation model accurately, the following things are considered:

(i) Simple path loss model for channel is assumed,

(ii) Orthogonal multiple access scheme is adopted.

More specifically, channels are assumed to be independent and identically distributed (IID). The strength of each is assumed to be Rayleigh distributed and thus the power of each channel is exponentially distributed.

3.1.4 Interference Model

For every user, it is assumed that, a minimum rate (bits/sec/Hz) to attain certain BER or SNR threshold should be maintained. For every user, SNR is computed as:

$$\gamma_{l,n} = \frac{\alpha_{l,n} p_{l,n} h_{l,l}(n)}{\sigma^2(n)}, \quad \forall l, n,$$

where, $p_{l,n}$ is the transmit power of l-th user in n-th subchannel, $h_{l,l}(n)$ is the power gain from l-th transmitter to l-th receiver in n-th subchannel, $\alpha_{l,n}$ is the subchannel assignment index, $\sigma^2(n)$ is the noise power in n-th subchannel. As overlay spectrum sharing and orthogonal multiple access scheme is assumed, hence, any SU experiences only channel noise.

3.1.5 Interference Temperature Model

An interference temperature (IT) threshold is imposed to protect any possible PU transmission on any channel from any harmful interference. Interference temperature

$\sigma^2(n)$	noise power in n-th subchannel
$h_{l,l}(n)$	power gain from l-th transmitter to l-th receiver in n-th subchannel
$h_{l,n}(m)$	power gain from l-th transmitter at location m in n-th subchannel
$p_{l,n}$	transmit power of l-th user in n-th subchannel
$p^{max}{}_{l,n}$	maximum transmit power of l-th user in n-th subchannel
$p_l{}^{max}$	maximum transmit power of l-th user across it's intended subchannels
$I_t(n)$	interference temperature threshold in n-th subchannel
$\gamma_{l,n}$	SNR for l-th user in n-th subchannel
$\gamma_{l,n}^t$	SNR threshold at receiver for l-th user in n-th subchannel
R_l	achievable rate for l-th user in each OFDM subchannel
$r_{l,n}$	achievable rate for l-th user in n-th subchannel
$R_l{}^{min}$	minimum rate for l-th user
$\alpha_{l,n}$	sub channel assignment index
$BER_{l,n}$	bit error rate for l-th user in n-th subchannel
$b_{l,n}$	number of bits per symbol for l-th user in n-th subchannel

Table 3.1: Notations

is defined as the total RF power measured at the primary users' receiver antenna per unit bandwidth. As in [51], IT threshold is set to be 200 times of channel noise power in our research work.

The goal of this research work is to maintain QoS for the secondary users by allocating the resources effectively. As a measure of QoS, minimum rate (bits/sec/Hz) to attain a certain BER and SNR threshold have been considered.

Under the above mentioned system model, two resource allocation optimization frameworks are formulated to compute optimal transmit power in OFDMA based uplink cognitive radio system. In the first framework, each user has a minimum SNR requirement that needs to be maintained whereas, in the second framework, each user has a minimum rate (bits/sec/Hz) requirement that needs to be maintained.

Table 3.1 denotes most of the related terms used throughout the thesis.

3.2 Proposed Resource Allocation Optimization Frameworks

3.2.1 Optimization Framework-I

The mathematical description of the proposed optimization framework corresponds to:

$$\begin{aligned}
\text{Determine} \quad & \mathbf{p} = [p_{1,1}, ..., p_{l,1}, ..., p_{1,n}, ..., p_{l,n}]^T \\
\text{To Minimize} \quad & F = \sum_{n=1}^{N} \sum_{l=1}^{L} p_{l,n} \\
\text{Subject to} \quad & \\
& C_1 : \sum_{n=1}^{N} p_{l,n} \alpha_{l,n} \leq {p_l}^{max}, \quad \forall l \\
& C_2 : p_{l,n} h_{l,n}(m) \alpha_{l,n} \leq I_t(n), \quad \forall l, n \\
& C_3 : \gamma_{l,n} \geq \gamma_{l,n}^{t}, \quad \forall l, n \qquad (3.2.1)
\end{aligned}$$

$$\begin{aligned}
\text{where,} \quad & \\
& \gamma_{l,n} = \frac{\alpha_{l,n} p_{l,n} h_{l,l}(n)}{\sigma^2(n)}, \quad \forall l, n \\
& p_{l,n} \geq 0, \quad \forall l, n \qquad (3.2.2)
\end{aligned}$$

Here, C_1 indicates limit on total transmit power of user l across it's intended channels; C_2 indicates the interference temperature constraint and C_3 indicates the SNR constraint required to guarantee desired QoS. The subchannel assignment index $\alpha_{l,n}$ is given as:

$$\begin{aligned}
\alpha_{l,n} \quad & = 1, \quad \textit{subchannel } n \textit{ is allocated to user } l \\
& = 0, \quad \textit{otherwise} \qquad (3.2.3)
\end{aligned}$$

This is a Convex Optimization Problem. The Convexity of QoS/SNR constraint (C_3)

is discussed in **Theorem 1**. Solution to this optimization problem provides optimal transmit power that every secondary user needs to use in the channel that they are operating in.

Theorem 1. $\gamma_{l,n} \geq \gamma^{t}_{l,n} \;\; \forall l, n,$ *is a convex constraint.*

Proof. From equation (3.2.1) and (3.2.2) we can rewrite the constraint as:

$$\alpha_{l,n} p_{l,n} h_{l,l}(n) \geq {\gamma^{t}}_{l,n}(\sigma^2(n)) \tag{3.2.4}$$

Equation (3.2.4) is equivalent to

$${\gamma^{t}}_{l,n}(\sigma^2(n)) - \alpha_{l,n} p_{l,n} h_{l,l}(n) \leq 0 \tag{3.2.5}$$

This inequality is a linear combination of variables. Hence, the inequality is linear, can be treated as convex.

3.2.2 Optimization Framework-II

In this optimization framework, one of our considerations is to ensure minimum rate requirements as a measure of QoS. In order to model such consideration each user rate R_l needs to be greater than minimum rate ${R_l}^{min}$. In this context QoS is defined in achieving rates no less than ${R_l}^{min}$ with $BER_{l,n} \leq \zeta$ in all sub channels. Assuming a target BER equals to ζ, the mathematical description of the proposed optimization corresponds to:

$$\begin{aligned}
&\text{Determine} \quad && \mathbf{p} = [p_{1,1}, ..., p_{l,1}, ..., p_{1,n}, ..., p_{l,n}]^T \\
&\text{To Minimize} \quad && F = \sum_{n=1}^{N} \sum_{l=1}^{L} p_{l,n} \\
&\text{Subject to} && \\
& && C_1 : \sum_{n=1}^{N} p_{l,n} \alpha_{l,n} \leq {p_l}^{max}, \quad \forall l \\
& && C_2 : p_{l,n} h_{l,n}(m) \alpha_{l,n} \leq I_t(n), \quad \forall l, n \\
& && C_3 : R_l = \sum_{n=1}^{N} r_{l,n} \\
& && = \sum_{n=1}^{N} \alpha_{l,n} log_2 (1 + b_3 \frac{p_{l,n} h_{l,l}(n)}{\sigma^2(n)}) \geq {R_l}^{min}, \quad \forall l \qquad (3.2.6)
\end{aligned}$$

Where,

b_3 is a constant whose computation is given in the description below and

$$p_{l,n} \geq 0, \quad \forall l, n \qquad (3.2.7)$$

Constraints C_1 and C_2 remain same to the constraints as described in Framework-I. Constraint C_3 indicates the achievable rate for l-th user and is the sum of the rates in each OFDM subchannel as mentioned earlier. The subchannel assignment index $\alpha_{l,n}$ is already described in Framework-I. Using the approximate formulation of BER for M-QAM [52], we have:

$$BER_{l,n} \approx b_1 exp[\frac{-b_2 \gamma_{l,n}}{2^{b_{l,n}} - 1}] \qquad (3.2.8)$$

Where, b_1 and b_2 are constants, The approximation is tight within 1 dB for $b_{l,n} \geq 2$ and $BER_{l,n} \leq 10^-3$

We are considering that, our target BER equal to ζ and hence $b_3 = \frac{b_2}{ln \frac{b_1}{\zeta}}$.

Therefore, the requirement for the desired BER to achieve a certain level of QoS is considered in definition of the rate in Equation 3.2.8.

This is a Convex Optimization Problem. The Convexity of QoS/Minimum Rate requirement constraint (C_3) is discussed in **Theorem 2**. Solution to this optimization problem provides optimal transmit power that every secondary user needs to use in the channel that they are operating in.

Theorem 2. $R_l \geq {R_l}^{min}, \ \ \forall l,$ *is a convex constraint.*

Proof. From Equation (3.2.6) we can rewrite the constraint as:

$$\sum_{n=1}^{N} \alpha_{l,n} log_2(1 + b_3 \frac{p_{l,n} h_{l,l}(n)}{\sigma^2(n)}) \geq {R_l}^{min}, \ \ \forall l \tag{3.2.9}$$

Equation (3.2.9) is equivalent to:

$$\begin{aligned} &{R_l}^{min} - \sum_{n=1}^{N} \alpha_{l,n} log_2(1 + b_3 \frac{p_{l,n} h_{l,l}(n)}{\sigma^2(n)}) \leq 0, \ \ \forall l \\ &= {R_l}^{min} - \alpha_{l,1} log_2(1 + b_3 \frac{p_{l,1} h_{l,l}(1)}{\sigma^2(1)}) - ... - \alpha_{l,n} log_2(1 + b_3 \frac{p_{l,n} h_{l,l}(n)}{\sigma^2(n)}) - \\ &... - \alpha_{l,N} log_2(1 + b_3 \frac{p_{l,N} h_{l,l}(N)}{\sigma^2(N)}) \leq 0, \ \ \forall l \end{aligned} \tag{3.2.10}$$

Now, we consider a single term $-\alpha_{l,n} log_2(1 + b_3 \frac{p_{l,n} h_{l,l}(n)}{\sigma^2(n)})$ and denote it as f. The first derivative is obtained as:

$$\frac{df}{dp_{l,n}} = -\alpha_{l,n} \frac{b_3 h_{l,l}(n)}{ln(2)(1 + b_3 p_{l,n} h_{l,l}(n))} \tag{3.2.11}$$

Finally, the second derivative is obtained as

$$\frac{d^2 f}{d{p_{l,n}}^2} = \frac{\alpha_{l,n} (b_3 h_{l,l}(n))^2}{ln(2)(1 + b_3 p_{l,n} h_{l,l}(n))^2} \tag{3.2.12}$$

The constraint described in Equation 3.2.9 represents an inequality. The second term of the inequality is shown as a series in Equation 3.2.10. If we study a single term of the series it is evident that, the term represents a function of Logarithm. If we minutely observe the differentiation of the function, from Equation 3.2.12 we see that, the outcome of the second order derivative of the function is obtained as a positive term. Hence, the function can be treated as convex. As the constraint C_3 described in Equation 3.2.9 is a combination of such convex functions, it can also be treated as convex.

3.3 Summary

In this chapter, our proposed resource allocation optimization frameworks have been stated that provide the optimal transmit power with a goal of minimizing total transmit power and constrained by SNR or minimum rate requirement that each SU needs to employ in maintaining QoS in an uplink OFDMA cognitive network.

Chapter 4

Solution of Proposed Resource Allocation Optimization Frameworks for Uplink Cognitive OFDMA System

In Chapter 3, proposed resource allocation optimization frameworks (Framework-I and II) with transmit power as a decision variable to compute optimal transmit power for uplink cognitive OFDMA system have been described. In this chapter, proposed resource allocation frameworks are solved and results are analyzed. In the first framework, each user has a minimum SNR requirement that needs to be maintained. On the other hand, in the second framework, each user has a minimum rate requirement (bits/sec/Hz) that needs to be maintained.

The rest of the chapter is organized as follows: Section 4.1 describes the simulation setup for both of the proposed frameworks. Numerical result analysis of proposed framework-I and II are presented in Section 4.2 and 4.3, respectively. Comparison between the proposed frameworks are presented in Section 4.4. Section 4.5 describes comparison of proposed frameworks with conventional capacity maximization based resource allocation approach. Finally, Section 4.6 summarizes the chapter.

4.1 Simulation Setup

We assume a Cognitive OFDMA system with $N = 64$ available channels and a total of L =8 SUs. We consider a usage pattern as shown in Table 4.1, where whether the channel is being used by SU or not is represented by ‘1’ and ‘0’, respectively.

Channel	User, 1	User, 2	User, 3	User, 4	user, 5	User, 6	User, 7	User, 8
1	0	0	0	1	0	0	0	0
2	1	0	0	0	0	0	0	0
3	0	0	0	0	0	0	1	0
4	0	0	0	1	0	0	0	0
5	0	0	0	0	1	0	0	0
6	0	1	0	0	0	0	0	0
7	0	1	0	0	0	0	0	0
8	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	1	0
10	0	0	0	0	0	1	0	0
11	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	1	0
13	0	0	0	1	0	0	0	0
14	0	1	0	0	0	0	0	0
15	0	0	0	0	0	0	1	0
16	0	0	0	0	0	0	0	1
17	0	0	0	0	1	0	0	0
18	0	0	0	0	0	0	0	1
19	0	1	0	0	0	0	0	0
20	0	0	1	0	0	0	0	0
21	0	0	0	0	1	0	0	0
22	0	0	0	0	0	1	0	0
23	0	0	1	0	0	0	0	0

Channel	User, 1	User, 2	User, 3	User, 4	user, 5	User, 6	User, 7	User, 8
24	0	0	0	0	0	0	1	0
25	0	0	1	0	0	0	0	0
26	0	1	0	0	0	0	0	0
27	1	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	1
29	0	0	0	0	0	0	0	1
30	0	0	0	0	0	0	1	0
31	0	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	1
33	0	0	1	0	0	0	0	0
34	0	0	0	0	1	0	0	0
35	0	0	0	1	0	0	0	0
36	0	0	0	0	1	0	0	0
37	0	0	0	0	0	0	1	0
38	0	0	0	1	0	0	0	0
39	0	0	0	0	1	0	0	0
40	0	0	0	0	1	0	0	0
41	0	0	0	0	0	1	0	0
42	1	0	0	0	0	0	0	0
43	0	0	0	0	1	0	0	0
44	0	0	0	1	0	0	0	0
45	0	0	0	0	1	0	0	0
46	0	0	0	1	0	0	0	0
47	1	0	0	0	0	0	0	0
48	0	0	0	0	0	1	0	0
49	0	0	1	0	0	0	0	0
50	0	0	0	0	0	0	1	0
51	0	0	0	0	0	1	0	0

Channel	User, 1	User, 2	User, 3	User, 4	user, 5	User, 6	User, 7	User, 8
52	0	0	0	0	0	0	1	0
53	0	0	0	1	0	0	0	0
54	0	1	0	0	0	0	0	0
55	0	0	0	0	1	0	0	0
56	0	0	0	1	0	0	0	0
57	0	0	0	1	0	0	0	0
58	0	0	0	0	0	0	0	1
59	0	0	0	1	0	0	0	0
60	0	0	0	0	0	1	0	0
61	0	0	0	0	0	1	0	0
62	0	0	0	0	0	1	0	0
63	0	0	0	0	1	0	0	0
64	0	0	0	0	0	0	1	0

Table 4.1: Usage pattern across channels.

4.1.1 Simulation Setup for proposed framework-I

Table 4.2 lists the total transmit power upper bound of all SUs for proposed optimization framework-I. Table 4.3 provides all other system parameters that are required for optimization framework-I. It is to be noted, how to obtain channel power gain such as $h_{l,l}(n)$, $h_{l,n}(m)$ in practice. We have mentioned in system model section in assumption-ii that, simple path loss model for channel loss has been considered. In simulation, to simplify the channel realization at some specific time, we use rayleigh distribution to have channel power gain. We also normalize channel power gain properly so that, none of the gains can go above 1. That is, channel power gain may vary with time depending on transmitter and receiver locations.

4.1.2 Simulation Setup for proposed framework-II

Table 4.4 lists the total transmit power upper bound of all SUs for proposed framework-II. Table 4.5 illustrates the minimum rate (bits/sec/Hz) requirement to achieve a

User, l	1	2	3	4	5	6	7	8
$p_{l,n}$(Watt)	4	7	5	11	12	8	10	7

Table 4.2: Total transmit power upper bound of users for framework-I.

$\sigma^2(n)$(Watt)	$1.5(\times 10^{-10})$
$\gamma_{l,n}^t \ \forall\ l, n$(dB)	10
$I_t(n)\ \forall\ l, n$(Watt)	$200 \times \sigma^2(n)$

Table 4.3: System parameters for framework-I.

targeted BER for all users. Table 4.6 provides all other system parameters that are required for proposed optimization framework-II.

4.2 Result Analysis of proposed framework-I

In this section, we investigate the performance of the proposed resource allocation optimization framework-I. Afterwards, a comparison between the performance of proposed framework-I and II is shown. Comparison between the proposed frameworks and conventional resource allocation approach based on capacity maximization is also depicted.

First, we observe the performance of proposed framework-I in terms of the allocated transmit power and obtained SNR across the channels for every SU. Figure 4.1 depicts the allocated transmit power and resulting SNR across channels for user 1. The channel noise power and channel power gain are also shown in the same figure. Here, user 1 is active on channels 2, 27, 42 and 47. From Fig. 4.1, we see the user requires

User, l	1	2	3	4	5	6	7	8
$p_{l,n}$(Watt)	10	10	10	10	10	10	10	10

Table 4.4: Total transmit power upper bound of users for framework-II.

User, l	1	2	3	4	5	6	7	8
${R_l}^{min}$(bits/sec/Hz)	1	1.1	1.4	1.8	0.5	1.7	1.4	1.9

Table 4.5: Minimum rate (bits/sec/Hz) requirement of users for framework-II.

$\sigma^2(n)$(Watt)	$1.5(\times 10^{-10})$
$BER_{l,n}$	10^{-3}
b_3	0.283
$I_t(n)\ \forall\ l, n$(Watt)	$200 \times \sigma^2(n)$

Table 4.6: System parameters for framework-II.

to transmit with more power in a channel with smaller power gain and vice versa. Same SNR is achieved in all channels which is equal to the threshold ($\gamma_{l,n}^t\ \forall\ l, n =$10 dB). So, we can see that, framework-I allocates transmit power just to attain the SNR threshold. This is due to the objective function of the framework. The similar pattern on allocation of transmit power and resulting SNR are also observed for rest of the seven users and shown in Figs. 4.2-4.8.

Figure 4.2 shows the transmit power and obtained SNR across channels for user 2. We can see, user 2 is active on channels 6, 7, 8, 14, 19, 26 and 54. Next, the transmit power and obtained SNR for users 3 and 4 are presented in Figs. 4.3 and 4.4 respectively . It is observed that, user 3 operates on channels 20, 23, 25, 33 and 49. User 4 operates on channels 1, 4, 13, 35, 38, 44, 46, 53, 56, 57 and 59. Then, Figs. 4.5 and 4.6 illustrate the same transmit power and obtained SNR for users 5 and 6, respectively. In Fig. 4.5, we can see user 5 is present on channels 5, 11, 17, 21, 34, 36, 39, 40, 43, 45, 55 and 63, while user 6 is present on channels 10, 22, 41, 48, 51, 60, 61 and 62. Lastly, the transmit power and obtained SNR for users 7 and 8 are depicted in Figs. 4.7 and 4.8 respectively, where user 7 operates on channels 3, 9, 12, 15, 24, 30, 37, 50, 52 and 64 and user 8 operates on channels 16, 18, 28, 29, 31, 32 and 58.

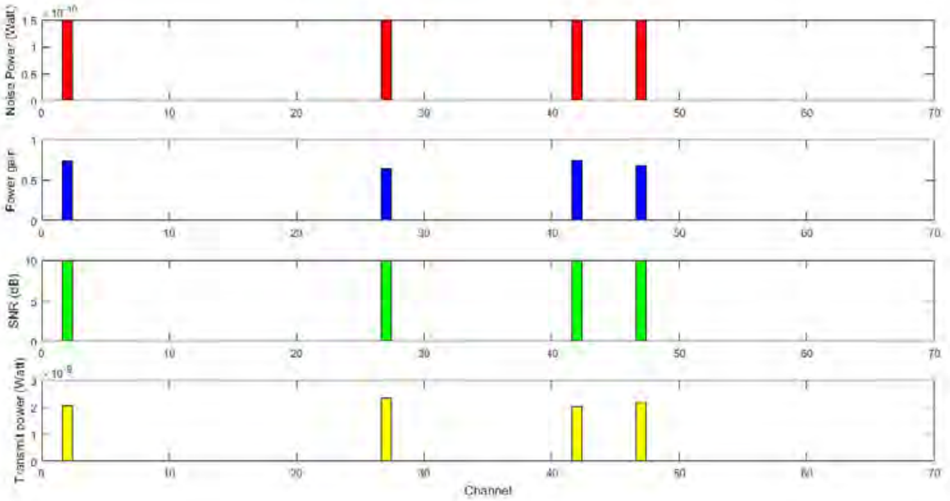


Figure 4.1: Allocation of transmit power and resulting SNR for user 1.

The total allocated transmit power across users obtained by proposed framework-I is shown in Fig. 4.9 as a bar. From Fig. 4.9, it is observed that, the total power spent is with in the users' upper limit. That is, framework-I does not spend all of its power as in existing frameworks, based on capacity maximization.

4.2.1 Effect of SNR threshold

Now, we observe the impact of different SNR thresholds on the performance of the proposed optimization framework-I. We consider the SNR threshold shown in Table 4.3 as example 1. Next we set the SNR threshold to 8 dB and term it as example 2. Whereas, we set the SNR threshold to 12 dB and term it as example 3. The rest of the system parameters are kept same as in Sec. 4.1.1 in all three example cases. Figure 4.10 shows the total transmit power across users for all the three examples as bar plots. Figure 4.10 shows that, with the increase in the value of SNR threshold, total transmit power across users also increases and vice versa. This is because, to achieve higher SNR threshold and to provide users with it, transmit power increases. But in

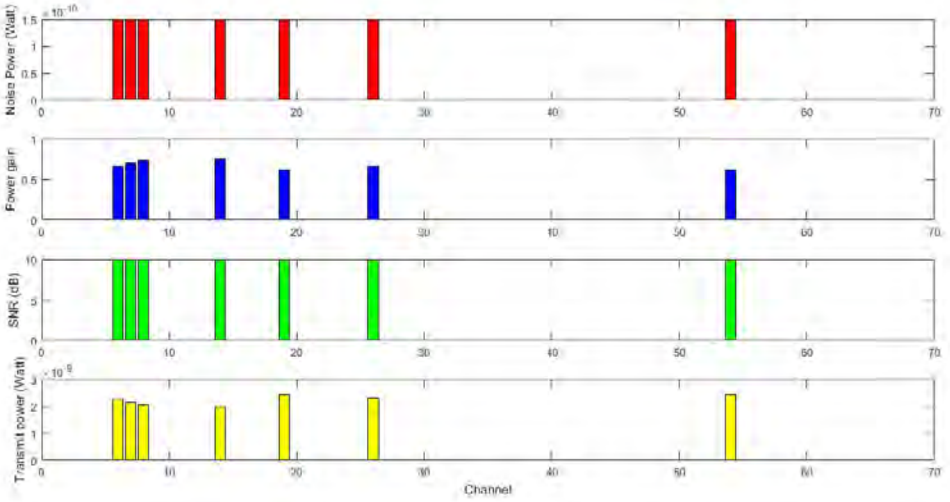


Figure 4.2: Allocation of transmit power and resulting SNR for user 2.

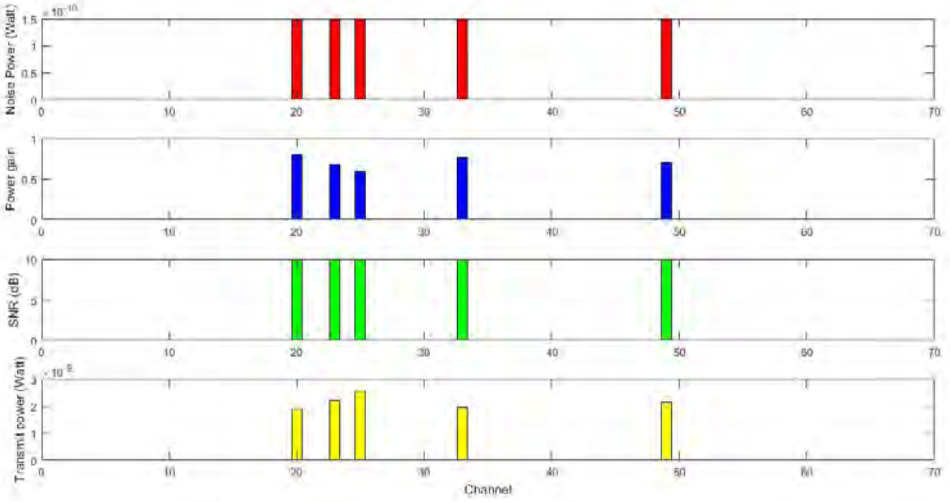


Figure 4.3: Allocation of transmit power and resulting SNR for user 3.

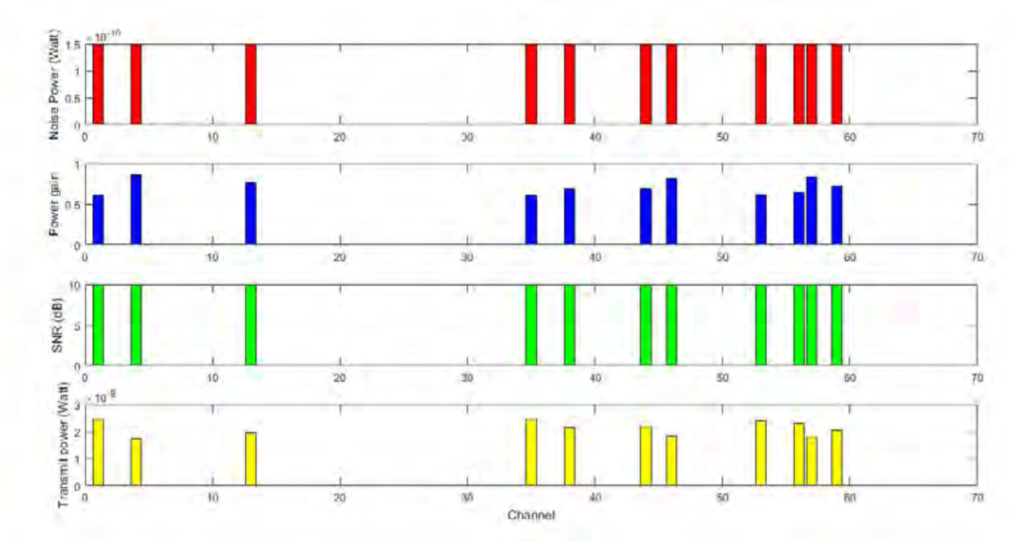


Figure 4.4: Allocation of transmit power and resulting SNR for user 4.

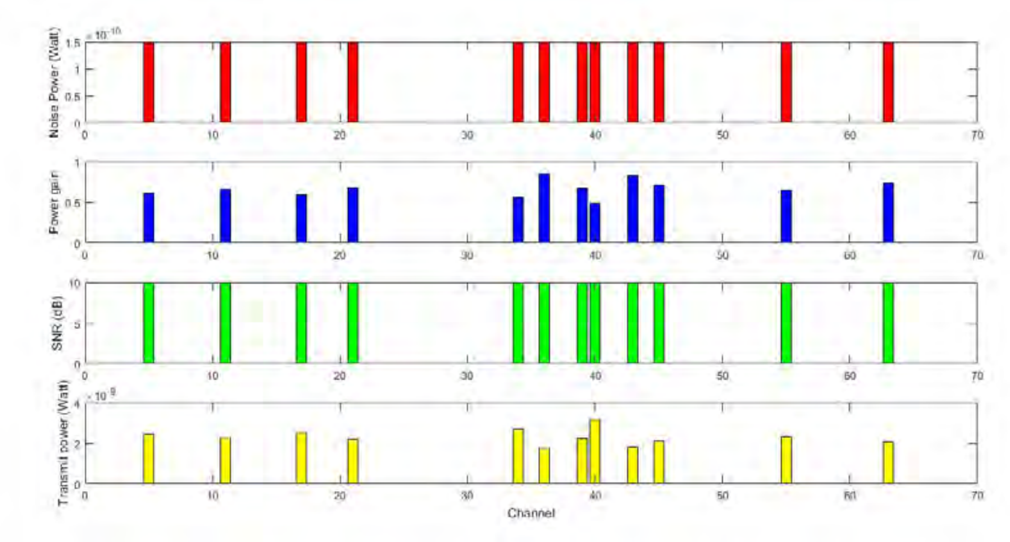


Figure 4.5: Allocation of transmit power and resulting SNR for user 5.

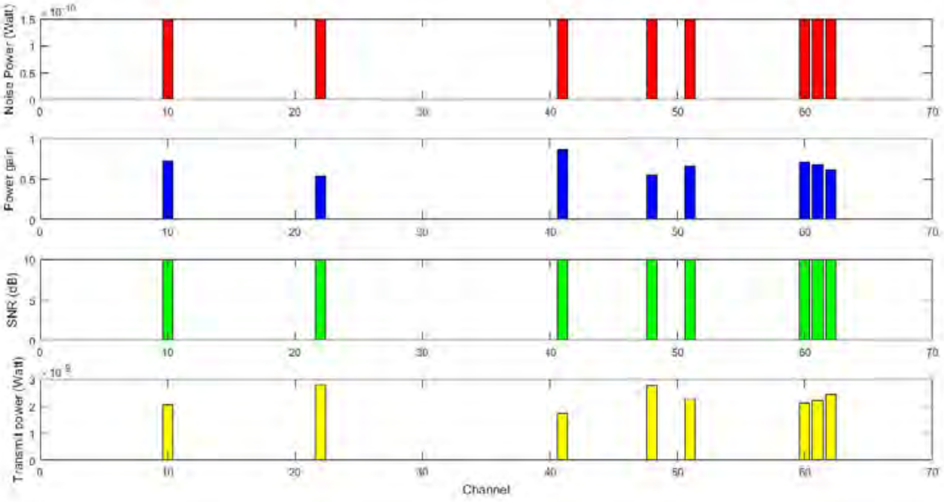


Figure 4.6: Allocation of transmit power and resulting SNR for user 6.

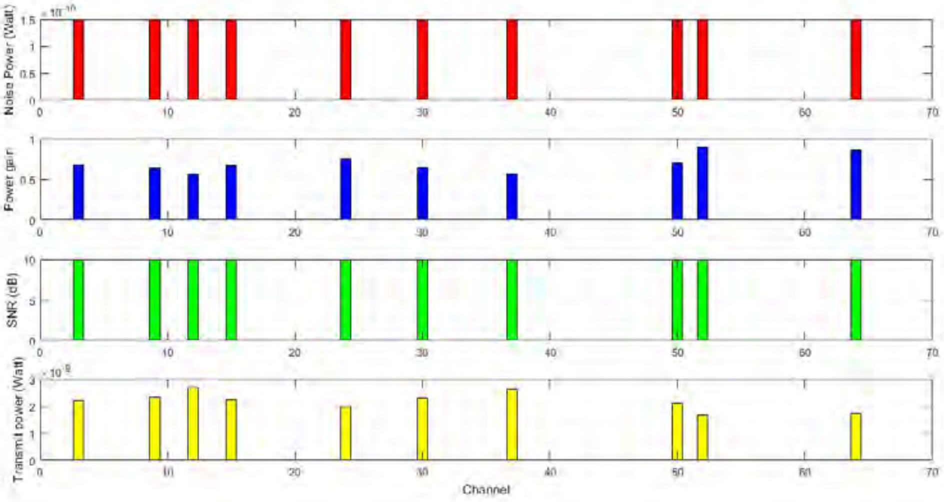


Figure 4.7: Allocation of transmit power and resulting SNR for user 7.

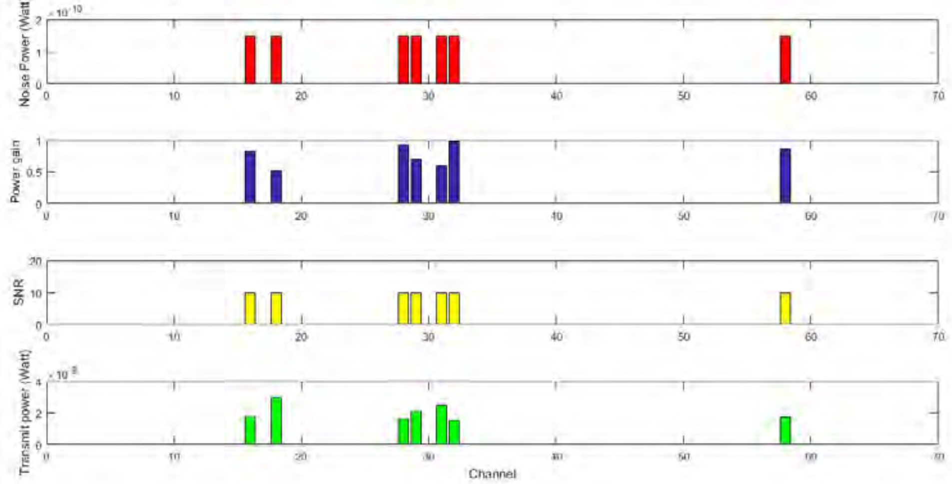


Figure 4.8: Allocation of transmit power and resulting SNR for user 8.

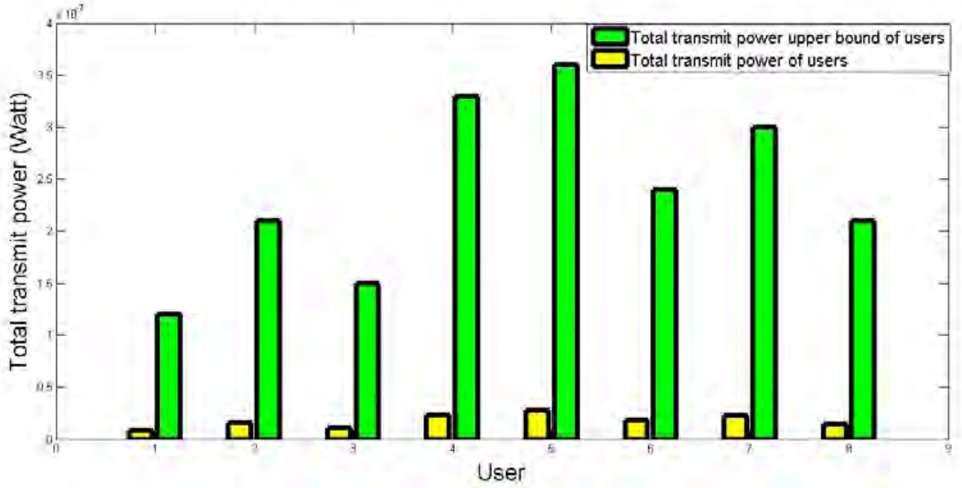


Figure 4.9: Allocation of total transmit power across users.

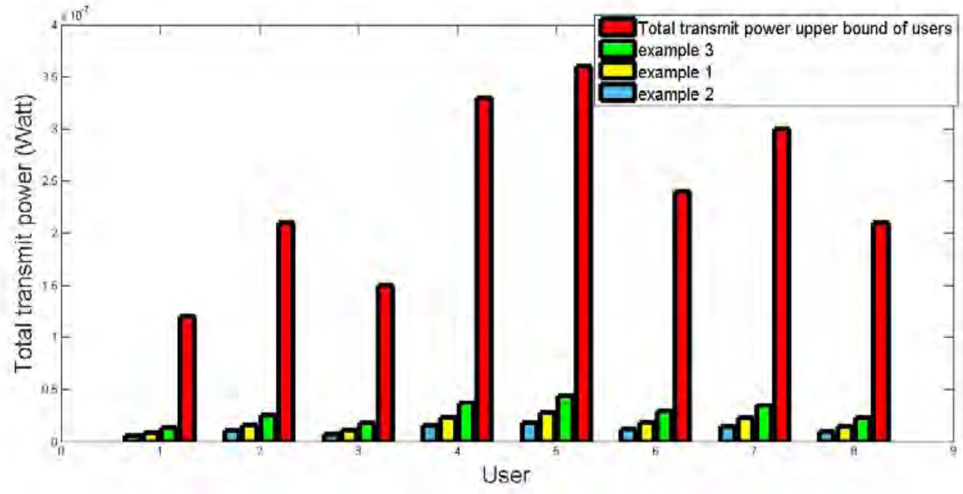


Figure 4.10: Allocation of total transmit power across users for different SNR thresholds.

every cases, it remains with in the limit of total transmit power upper bound of users. Which means, total transmit power across users is proportional to the SNR threshold which is clearly shown in Fig. 4.10. It is to be noted that, proposed optimization framework-I successfully functions within the total transmit power upper bound of users for all three example cases.

Similar pattern on allocation of transmit power and obtained SNR across channels for different SNR thresholds are also observed for all the eight users and shown in the same plot in Figs. 4.11-4.18. Channel noise power and power gain are also shown in the same plot. Once again it is observed that, transmit power is inversely proportional to the power gain. So, it can be implied that, the framework spends more transmit power when the power gain is minimum and vice versa. It is to be noted that, Noise power is constant in our consideration. Hence, we see that, transmit power across channels increases with the increased value of SNR threshold if other parameters remain constant.

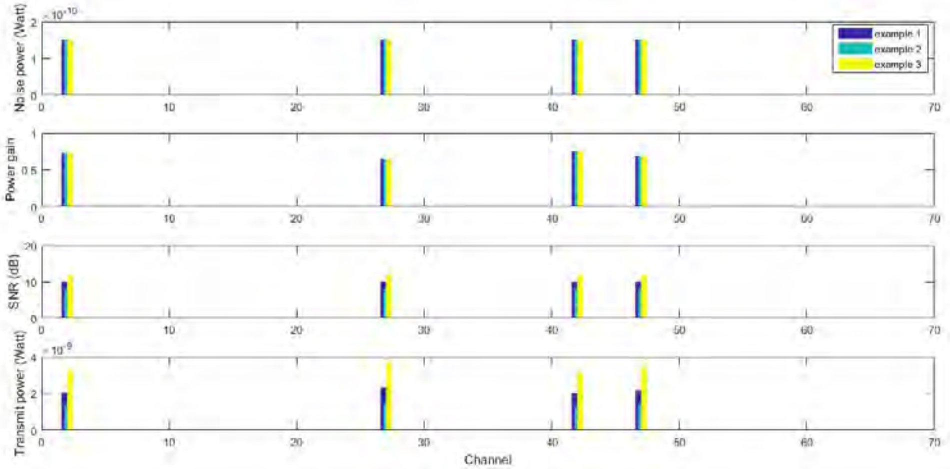


Figure 4.11: Allocation of transmit power and resulting SNR of user 1 for different SNR thresholds.

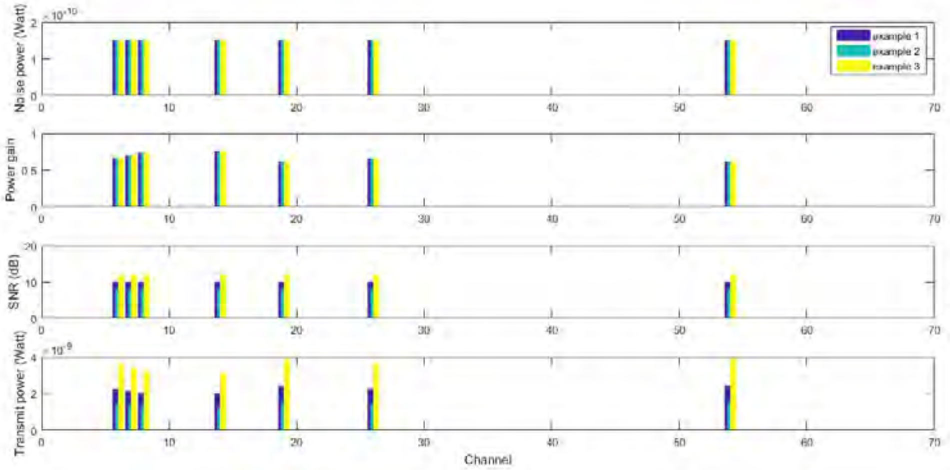


Figure 4.12: Allocation of transmit power and resulting SNR of user 2 for different SNR thresholds.

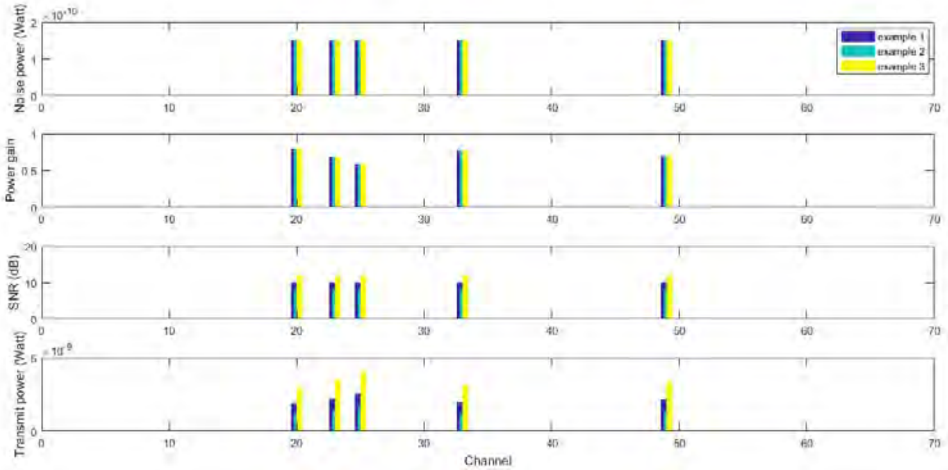


Figure 4.13: Allocation of transmit power and resulting SNR of user 3 for different SNR thresholds.

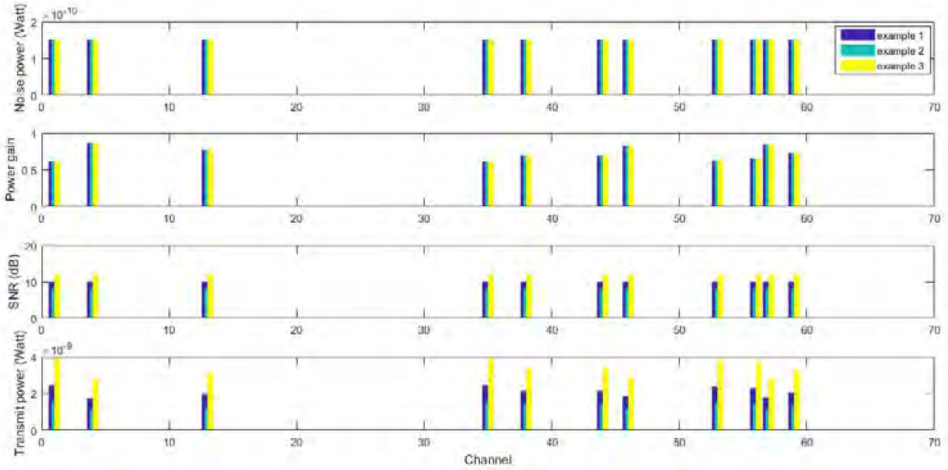


Figure 4.14: Allocation of transmit power and resulting SNR of user 4 for different SNR thresholds.

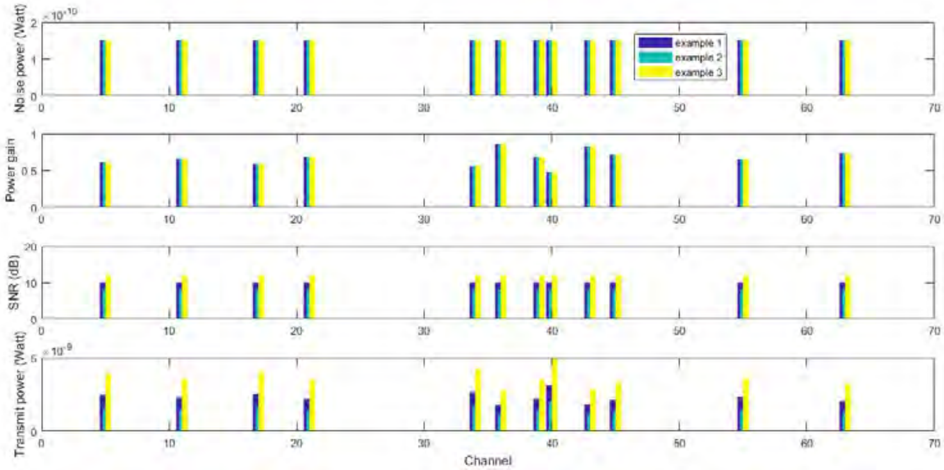


Figure 4.15: Allocation of transmit power and resulting SNR of user 5 for different SNR thresholds.

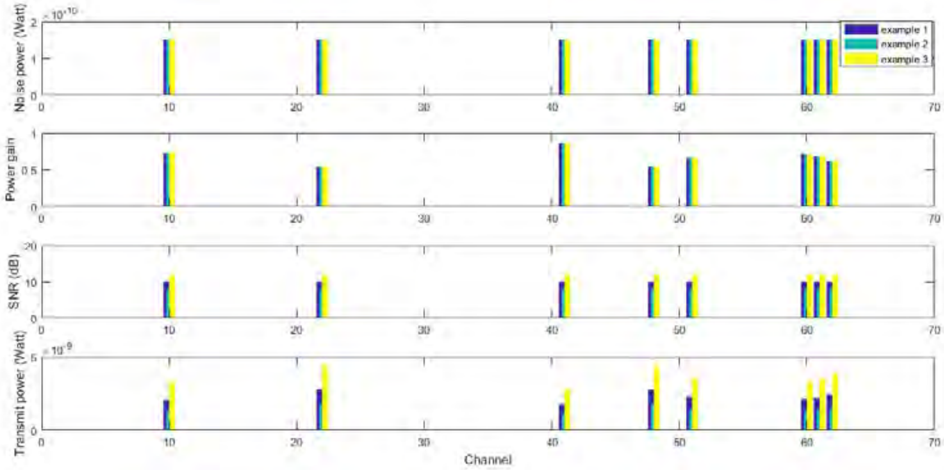


Figure 4.16: Allocation of transmit power and resulting SNR of user 6 for different SNR thresholds.

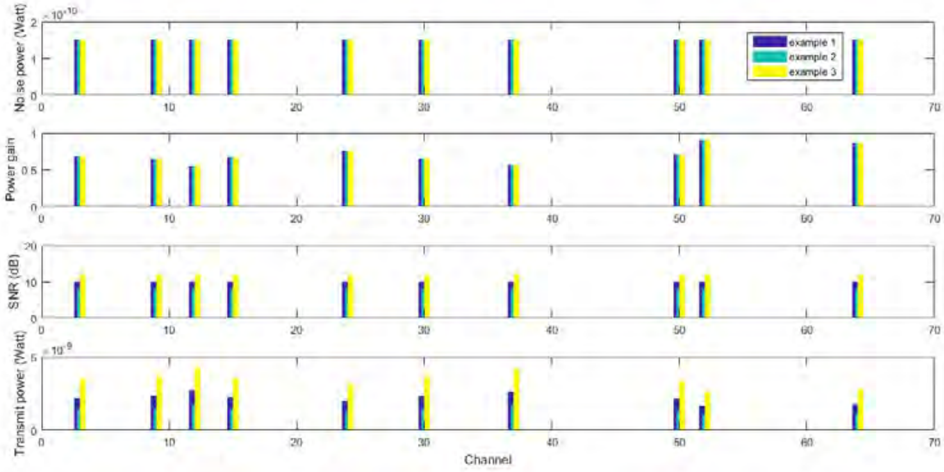


Figure 4.17: Allocation of transmit power and resulting SNR of user 7 for different SNR thresholds.

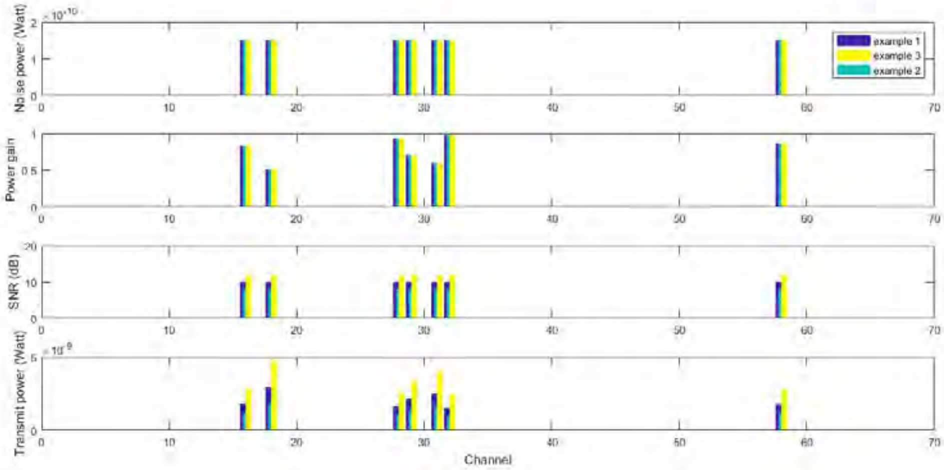


Figure 4.18: Allocation of transmit power and resulting SNR of user 8 for different SNR thresholds.

User, l	1	2	3	4	5	6	7	8
$p_{l,n}$(Watt)	6	10.5	7.5	16.5	18	12	15	10.5

Table 4.7: Total transmit power upper bound of users for example 2.

4.2.2 Effect of Users' Power Budget

Now, we observe the impact of users' power budget on the performance of the proposed optimization framework-I. Here, we consider total transmit power upper bound of users shown in Table 4.2 as example 1 and the total transmit power upper bound of users shown in Table 4.7 and 4.8 as example 2 and example 3, respectively. The rest of the system parameters are kept same as in Section 4.1.1 in all three examples. Figure 4.19 shows the allocation of total transmit power across users for different users' power budget as bar plots. Figure 4.19 shows that, total transmit power for all three examples are identical. Hence, users' power budget does not have any significant impact on the performance on the proposed framework-I in terms of total transmit power of users once the optimal transmit power is achieved. Once again, it is observed that, total transmit power in every case remains within the limit of total transmit power upper bound of users.

Similar pattern on allocation of transmit power and obtained SNR across channels for all three examples are also observed for all the eight users and shown in the same plot in Figs. 4.20-4.27. Channel noise power and power gain are also shown in the same plot. We see that, transmit power is inversely proportional to the power gain. So, it can be implied that, framework-I spends more transmit power when the power gain is minimum and vice versa, considering constant noise level. We also see that, transmit power across channels shows no change with the variation of users' power budget if other parameters remain constant.

User, l	1	2	3	4	5	6	7	8
$p_{l,n}$(Watt)	2	3.5	2.5	5.5	6	4	5	3.5

Table 4.8: Total transmit power upper bound of users for example 3.

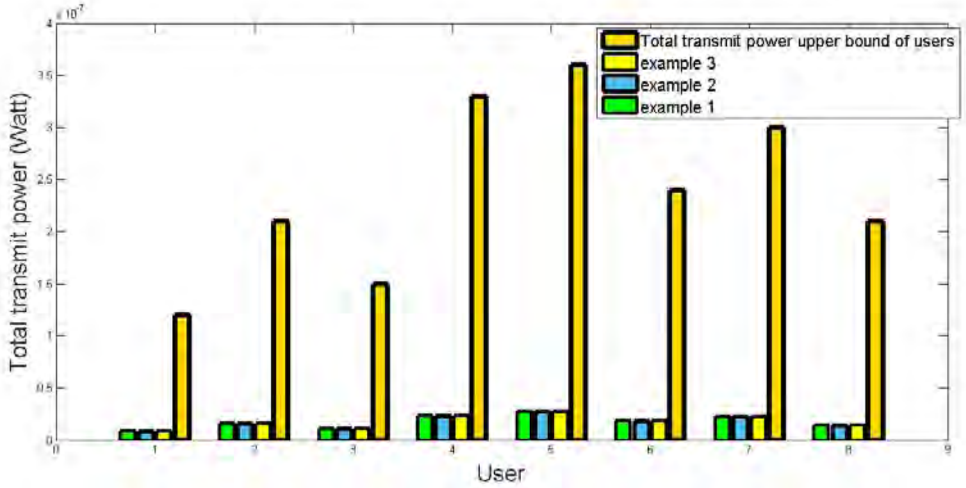


Figure 4.19: Allocation of total transmit power across users for different users' power budget.

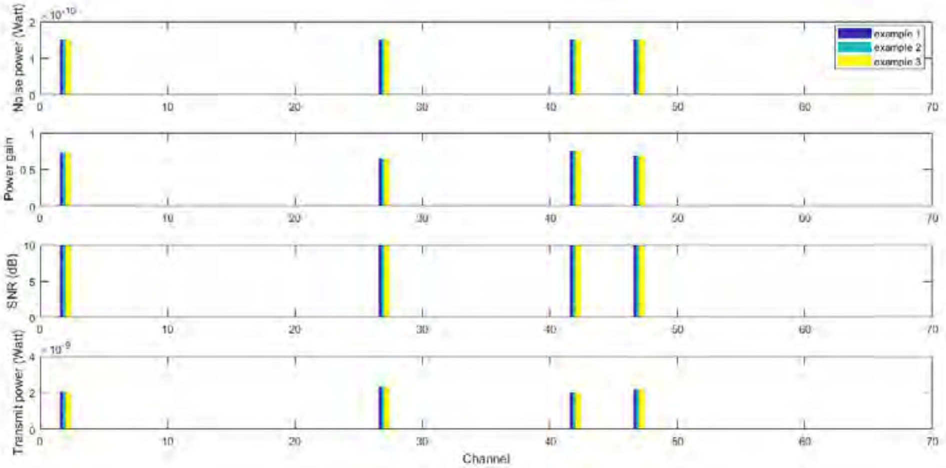


Figure 4.20: Allocation of transmit power and resulting SNR of user 1 for different users' power budget.

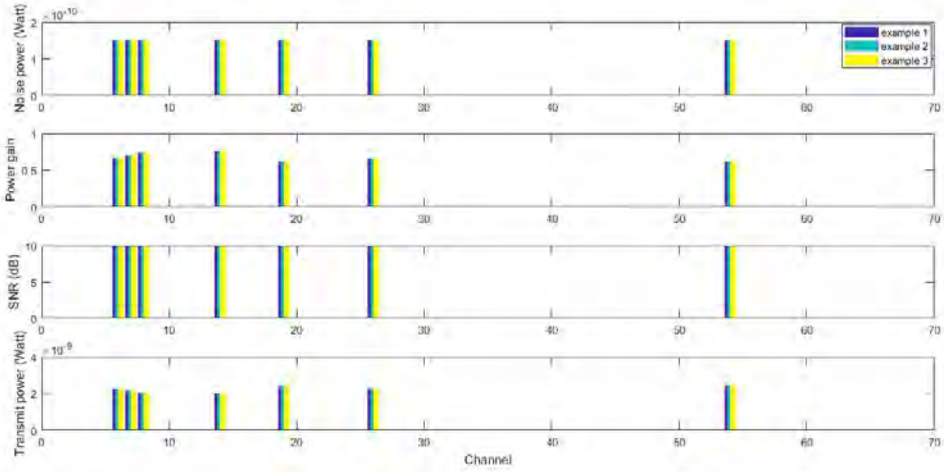


Figure 4.21: Allocation of transmit power and resulting SNR of user 2 for different users' power budget.

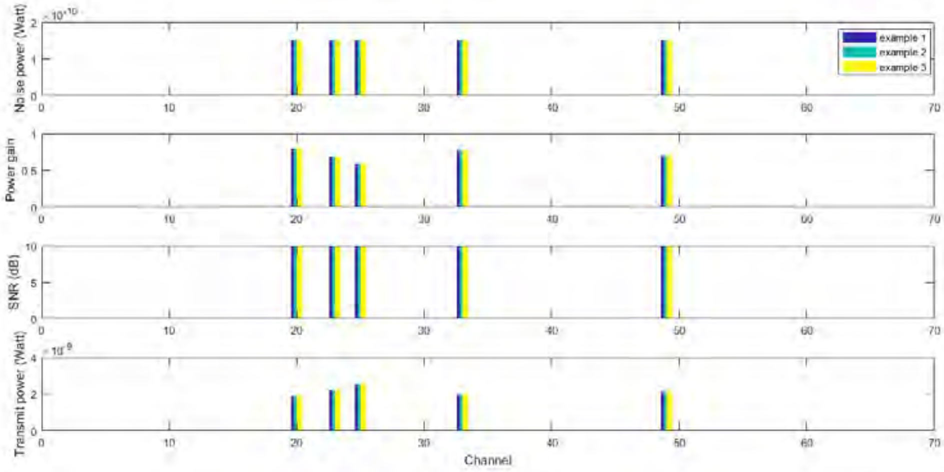


Figure 4.22: Allocation of transmit power and resulting SNR of user 3 for different users' power budget.

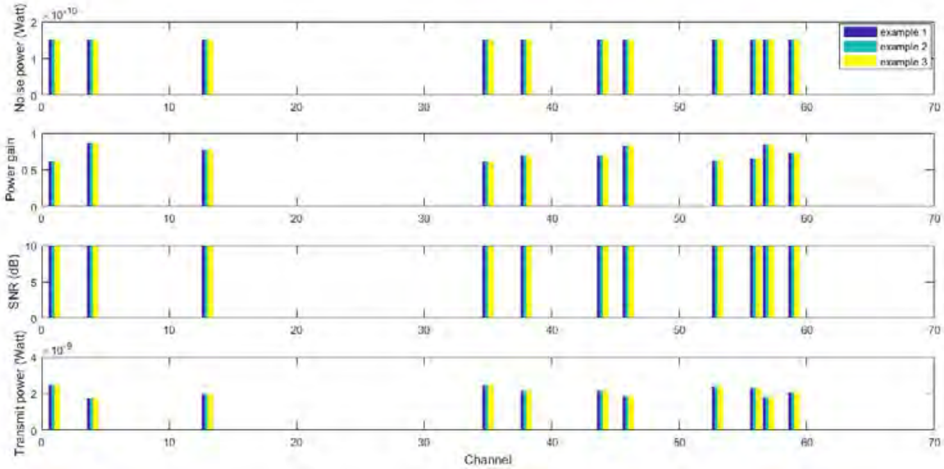


Figure 4.23: Allocation of transmit power and resulting SNR of user 4 for different users' power budget.

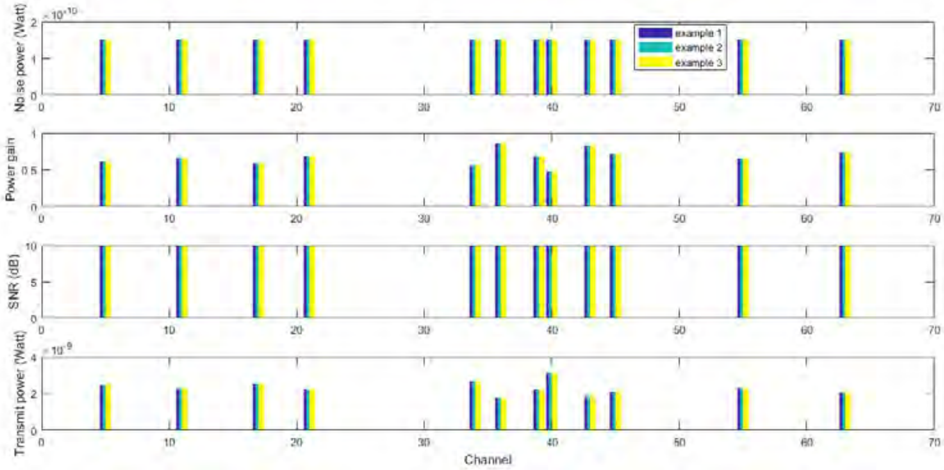


Figure 4.24: Allocation of transmit power and resulting SNR of user 5 for different users' power budget.

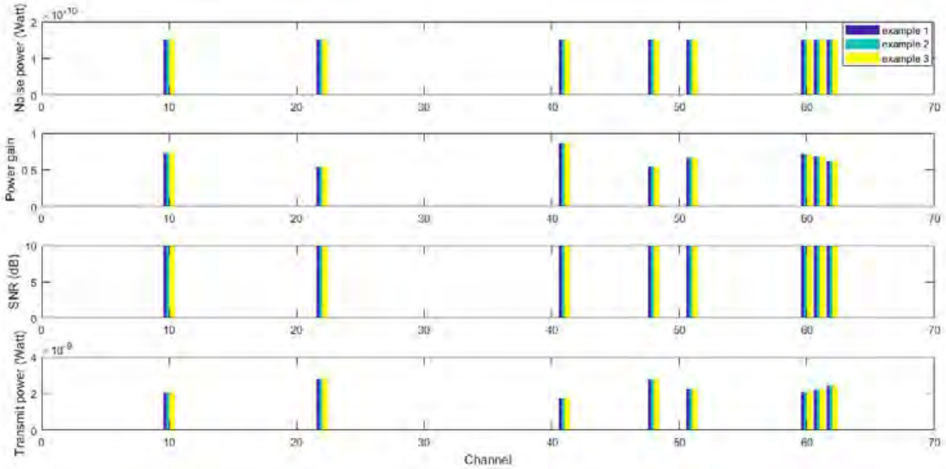


Figure 4.25: Allocation of transmit power and resulting SNR of user 6 for different users' power budget.

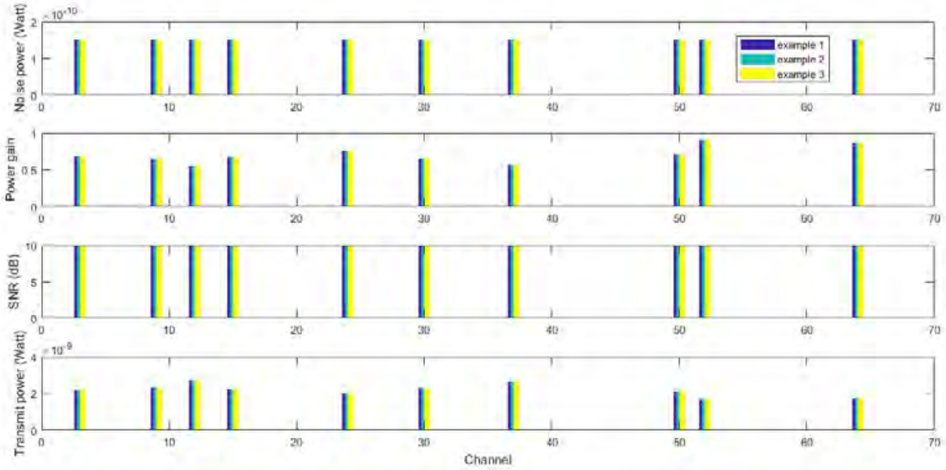


Figure 4.26: Allocation of transmit power and resulting SNR of user 7 for different users' power budget.

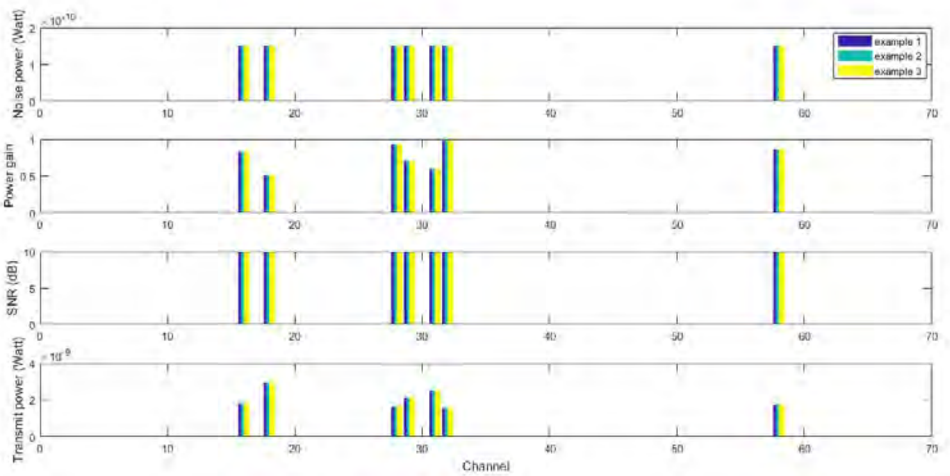


Figure 4.27: Allocation of transmit power and resulting SNR of user 8 for different users' power budget.

4.3 Result Analysis of proposed framework-II

In this section, we investigate the performance of the proposed resource allocation optimization framework-II. First, we observe the performance of proposed framework-II in terms of the allocated transmit power and resulting SNR across the channels for every SU. Figure 4.28 depicts the transmit power and resulting SNR across channels for user 1. The channel noise power and channel power gain are also shown in the same figure. Here user 1 is active on channels 2, 27, 42 and 47. From Fig. 4.28, we see that, transmit power shows no change with the variation of power gain across channel. Here, user 1 is required to transmit with same power across the channels. That means, transmit power across channel have no major relation with channel power gain and hence, remains unchanged for user 1 while keeping noise power constant across channels. But observation reveals that, obtained SNR is proportional to power gain of the channels. That means, resulting SNR in a transmission is more when channel power gain is higher and vice versa. Similar pattern on allocation of transmit power and resulting SNR are also observed for rest of the seven users and shown in Figs.

4.29-4.35.

Figure 4.29 shows the transmit power and resulting SNR across channels for user 2. We can see, user 2 is active on channels 6, 7, 8, 14, 19, 26 and 154. Next, the transmit power and resulting SNR for users 3 and 4 are presented in Figs. 4.30 and 4.31 respectively. It is observed that, user 3 operates on channels 20, 23, 25, 33 and 49. User 4 operates on channels 1, 4, 13, 35, 38 44, 46, 53, 56, 57 and 59. Then, Figs. 4.32 and 4.33 illustrate the same transmit power and resulting SNR for users 5 and 6, respectively. From these figures, we can see, user 5 is present on channels 5, 11, 17, 21, 34, 36, 39, 40, 43, 45, 55 and 63, while user 6 is present on channels 10, 22, 41, 48, 51, 60, 61 and 62. Lastly, the transmit power and resulting SNR for users 7 and 8 are depicted in Figs. 4.34 and 4.35 respectively , where user 7 operates on channels 3, 9, 12, 15, 24, 30, 37, 50, 52 and 64 whereas user 8 operates on channels 16, 18, 28, 29, 31, 32 and 58.

Total allocated transmit power across users obtained by proposed framework-II is shown in Fig. 4.36 as a bar plot. It is observed that, the total power spent is with in the total transmit power upper bound of users. That is, just like framework-I, framework-II also does not spend all of it's power as in existing frameworks, based on capacity maximization. To ensure optimality of solution, as we have used minimum rate (bits/sec/Hz) requirement constraint to obtain a certain BER of our proposed optimization framework. Hence, it is also important to see whether the used bits/sec/Hz constraint is satisfying the minimum requirement of the users. Figure 4.36 also shows the total bits/sec/Hz use across users as a bar plot. Minimum rate (bits/sec/Hz) requirement for all the users is also depicted in the same figure. From this figure it is seen that, proposed optimization framework-II is successful in satisfying both the total transmit power upper bound and minimum bits/sec/Hz use requirement, ${R_l}^{min}$ for all users.

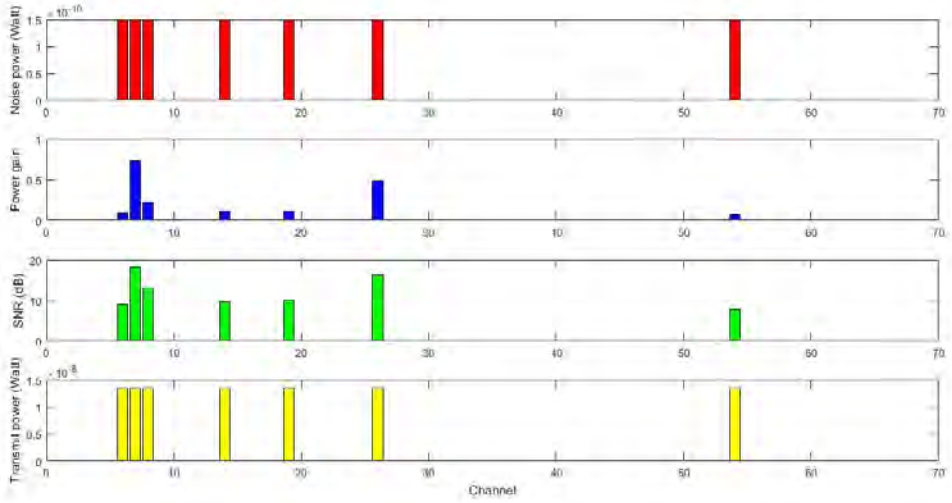


Figure 4.29: Allocation of transmit power and resulting SNR for user 2.

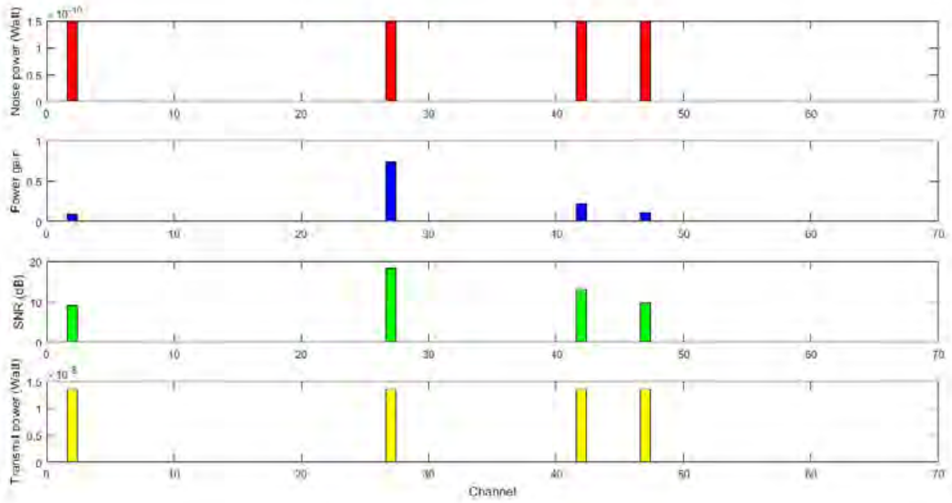


Figure 4.28: Allocation of transmit power and resulting SNR for user 1.

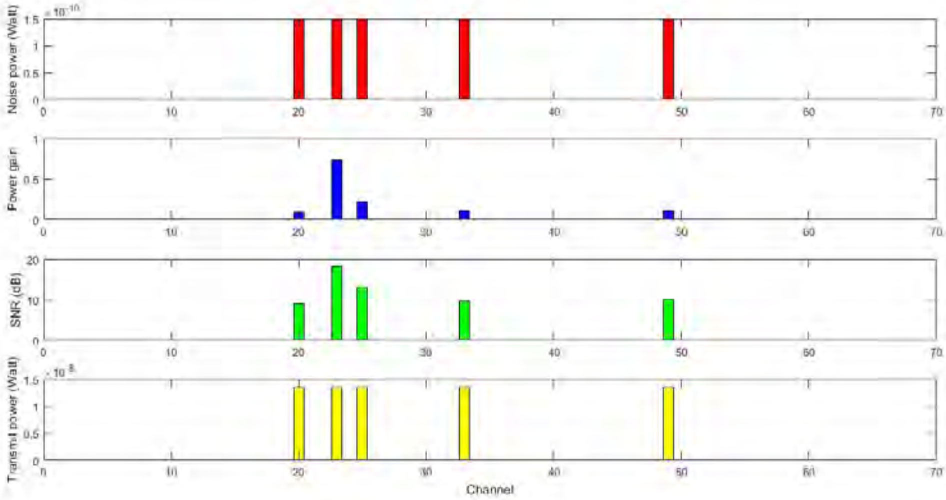


Figure 4.30: Allocation of transmit power and resulting SNR for user 3.

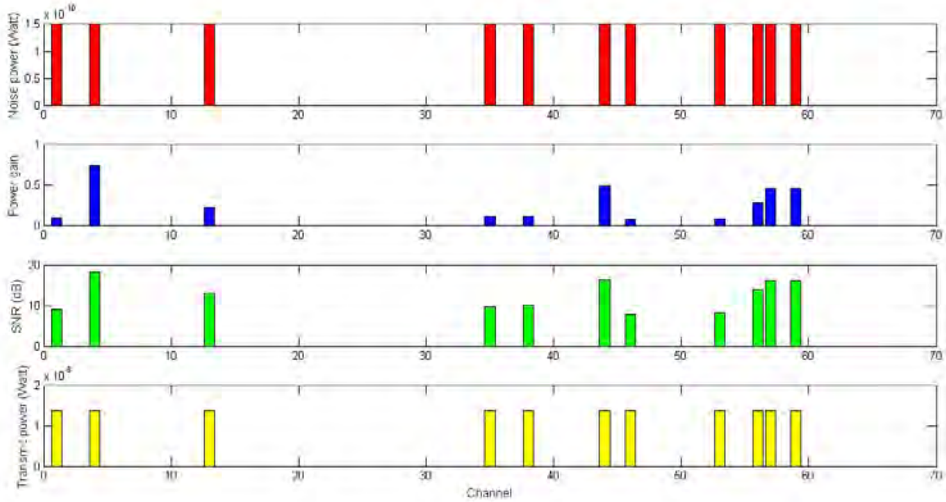


Figure 4.31: Allocation of transmit power and resulting SNR for user 4.

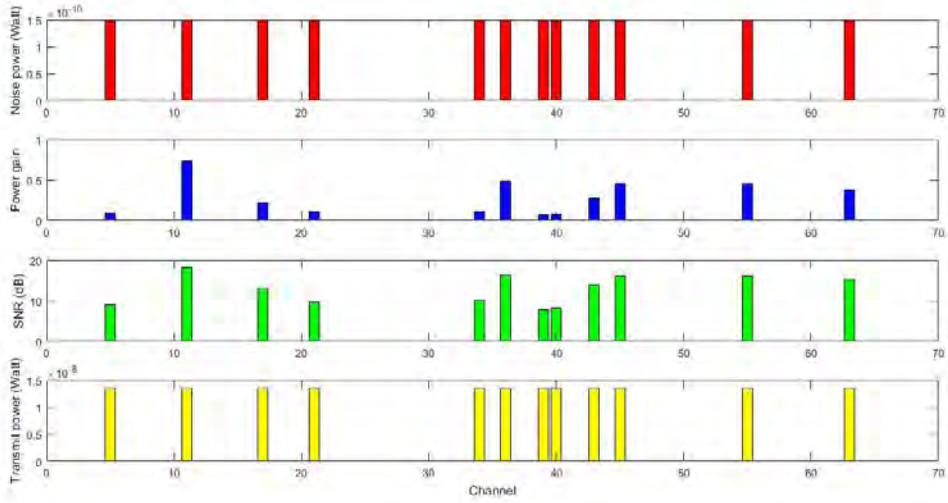


Figure 4.32: Allocation of transmit power and resulting SNR for user 5.

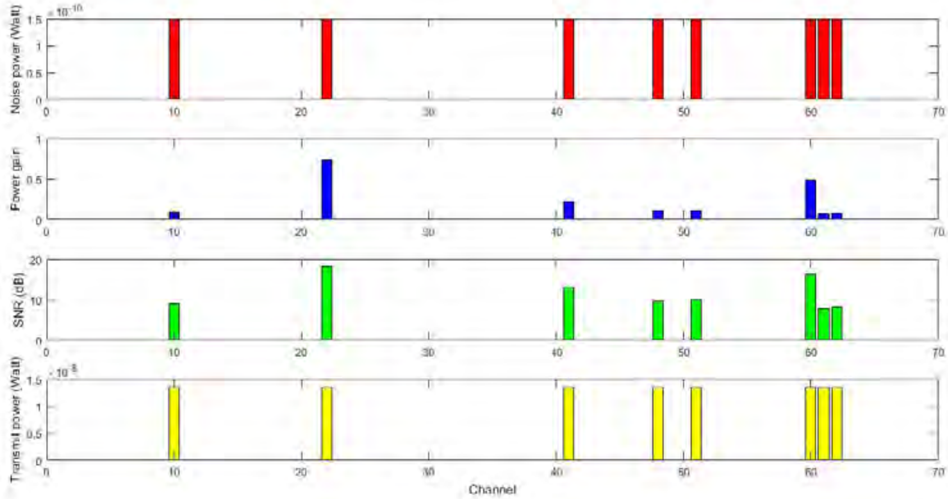


Figure 4.33: Allocation of transmit power and resulting SNR for user 6.

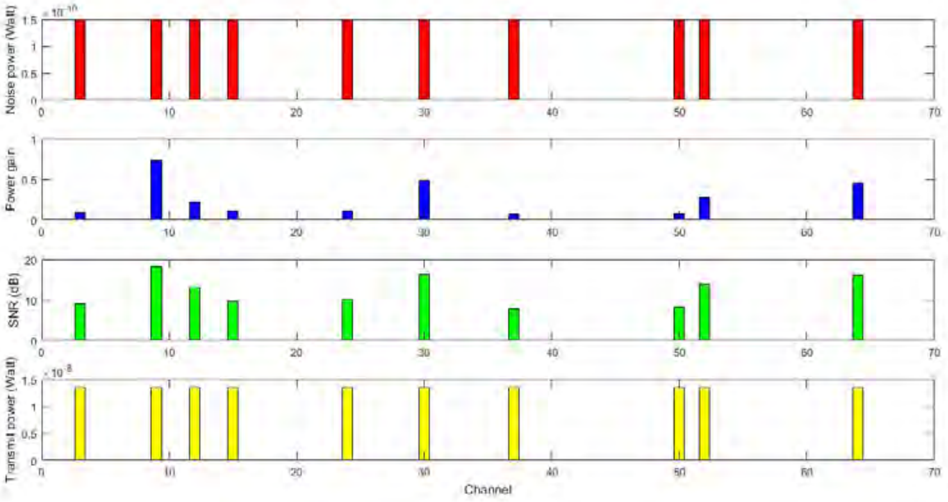


Figure 4.34: Allocation of transmit power and resulting SNR for user 7.

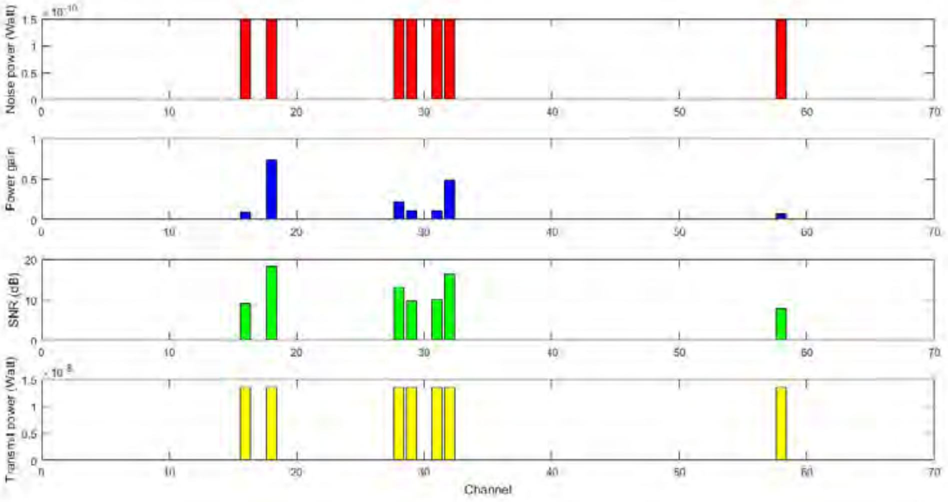


Figure 4.35: Allocation of transmit power and resulting SNR for user 8.

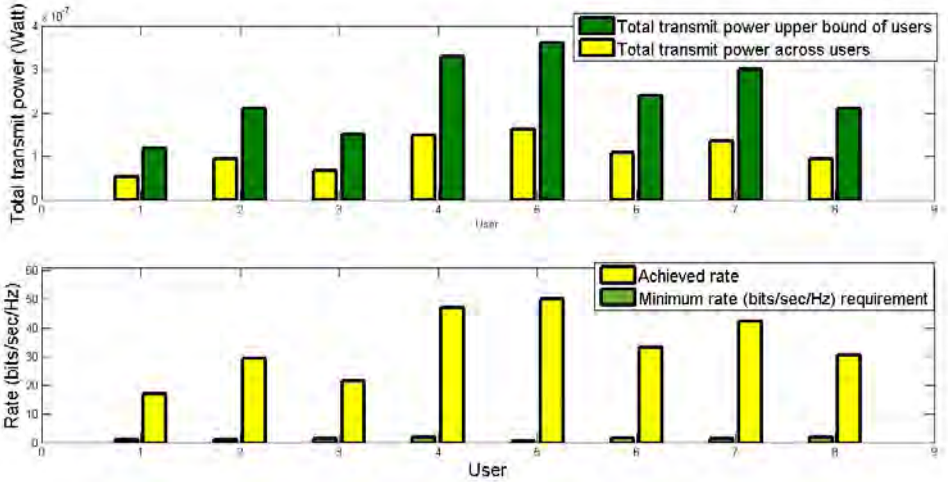


Figure 4.36: Allocation of total transmit power and achieved rate (bits/sec/Hz) across users.

4.3.1 Effect of target BER

As minimum rate requirement (bits/sec/Hz) to obtain a certain BER is a QoS constraint in framework-II, effect of changing the value of BER is another point of interest and can be inspected. Figs 4.37 presents the allocation of total transmit power and achieved rate (bits/sec/Hz) across users for two different BER values ($BER_{l,n}$), which are termed as example 1 and example 2, respectively. Total transmit power upper bound and minimum rate (bits/sec/Hz) requirement for users are also depicted in Fig. 4.37 where, all the plots are shown as bar. Here, $BER_{l,n}$ is set to 10^{-3} and we term it as example 1 while, for example 2, $BER_{l,n}$ is set to 10^{-6}. The rest of the system parameters are kept same as in Sec. 4.1.2. The value of b_3 is computed following the method discussed earlier in Sec 3.2. $b_3 = 0.283$ is considered to guarantee a BER that is less than or equal to 10^{-3} while b_3 is set to 0.1129 to guarantee a BER that is less than or equal to 10^{-6}.

It is observed that, with the variation in target BER, total transmit power across users shows no changes. Which means, total transmit power for example 2 remains identical to the one achieved in example 1. Hence, we see that, target BER does not have any significant impact on the performance of the proposed framework in terms of total transmit power of users. From the figure it is obvious that, the proposed optimization framework-II is successful in satisfying the total transmit power upper bound of users in both examples. Further observation reveals that, with the variation in target BER, achieved rate (bits/sec/Hz) across users shows changes accordingly. That is, achieved rate is higher when target BER is more and vice versa. Although, achieved rate for example 1 is higher compared to example 2, but the proposed optimization framework-II is successful in satisfying the minimum rate requirement for all users in both examples.

Similar pattern on allocation of transmit power and resulting SNR for example 1 and 2 are also observed for all the eight users and shown in Figs 4.38-4.45. Noise power and power gain of channels for both examples are also shown in the figures. It is observed that, the figures of example 2 are identical to example 1. Which means, variation in target BER shows no major effect on framework-II in terms of power allocation and resulting SNR. That is why, example 2 follows the similar pattern of example 1.

4.3.2 Effect Of Users' minimum rate requirement

Now, we observe the impact of users' minimum rate (bits/sec/Hz) requirement on the performance of the proposed optimization framework-II. Here, we consider minimum rate requirement shown in Table 4.5 as example 1 and the minimum rate requirement of users shown in Table 4.9 as example 2. The rest of the system parameters are kept same as in Sec. 4.1.2 in both examples. Figure 4.46 shows the allocation of total transmit power and achieved rate (bits/sec/Hz) across users for examples 1 and 2. Figure 4.46 shows that, total transmit power for example 2 slightly increases compared to example 1 but in both the cases it remains with in the total transmit

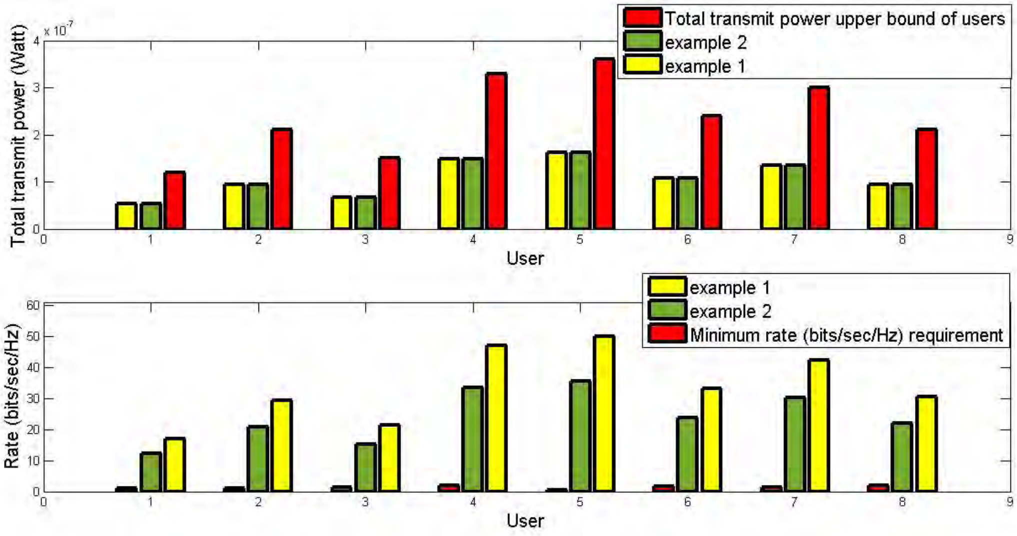


Figure 4.37: Allocation of total transmit power and achieved rate (bits/sec/Hz) across users for different target BER.

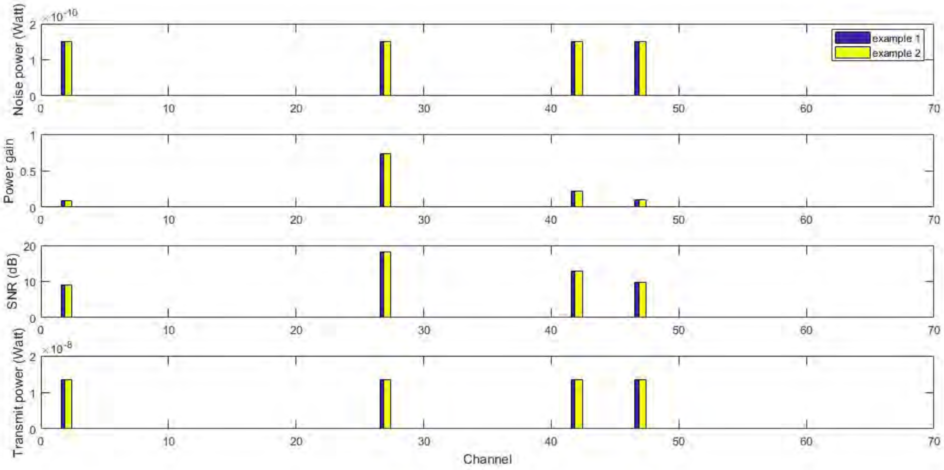


Figure 4.38: Allocation of transmit power and resulting SNR of user 1 for different target BER.

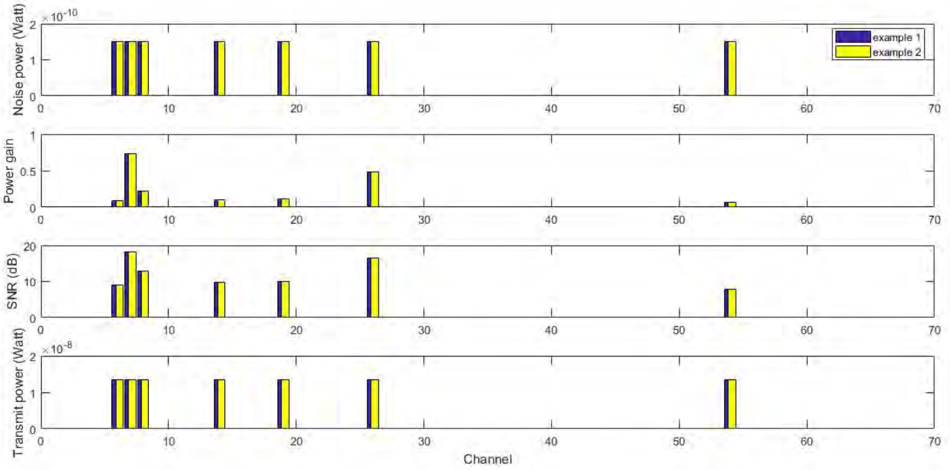


Figure 4.39: Allocation of transmit power and resulting SNR of user 2 for different target BER.

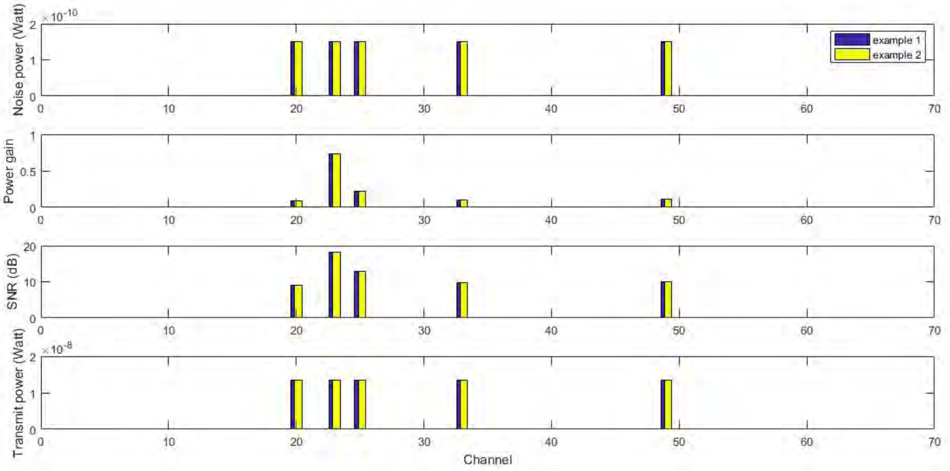


Figure 4.40: Allocation of transmit power and resulting SNR of user 3 for different target BER.

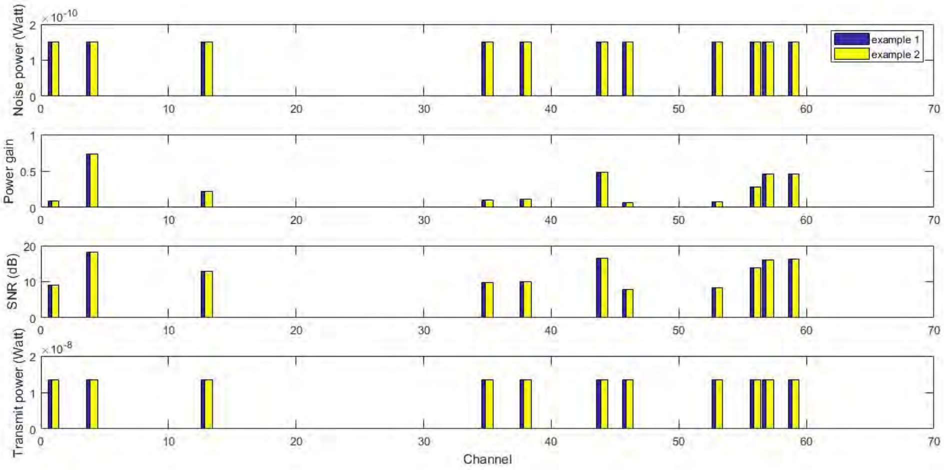


Figure 4.41: Allocation of transmit power and resulting SNR of user 4 for different target BER.

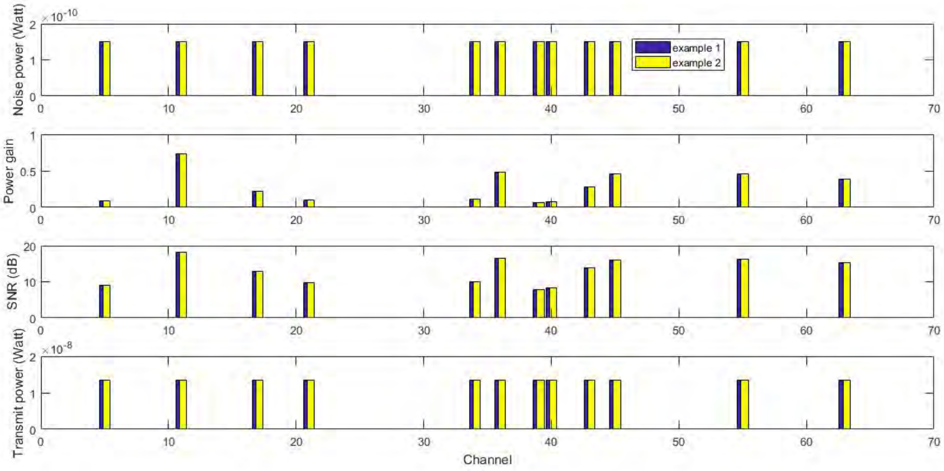


Figure 4.42: Allocation of transmit power and resulting SNR of user 5 for different target BER.

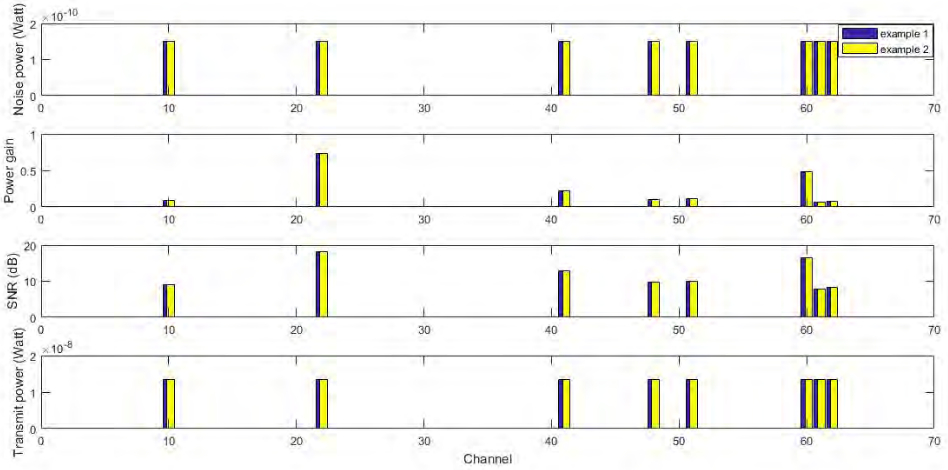


Figure 4.43: Allocation of transmit power and resulting SNR of user 6 for different target BER.

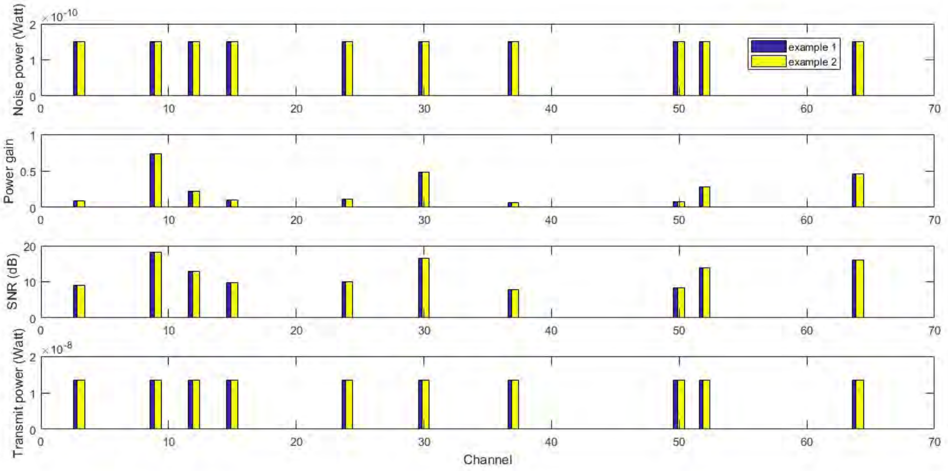


Figure 4.44: Allocation of transmit power and resulting SNR of user 7 for different target BER.

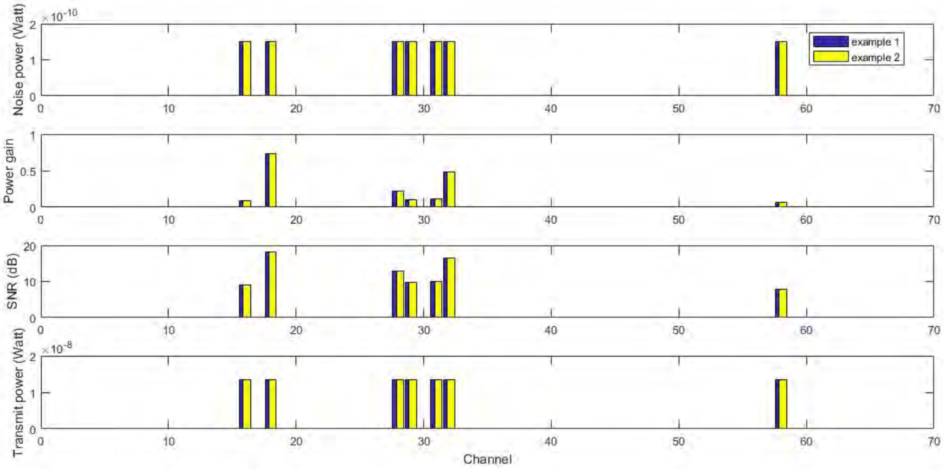


Figure 4.45: Allocation of transmit power and resulting SNR of user 8 for different target BER.

power upper bound of users. Hence, increased value of users' minimum rate requirement has significant impact on the performance on the proposed framework in terms of total transmit power. It is observed that, for both the examples, total transmit power allocation is obtained with in the total transmit power upper bound of users, hence, proposed framework-II performs successfully with in total transmit power upper bound of users. Minimum rate requirement of users for both examples are also depicted in the same figure. From figure 4.46 it is seen that, with the variation of users' minimum rate requirement, achieved rate also shows obvious changes. It is evident that, achieved rate is more when the minimum rate requirement is higher but in every cases, it satisfies minimum rate requirement of users. That means, the proposed optimization framework is successful in satisfying the minimum rate requirement for all users in every case.

Similar pattern on allocation of transmit power and resulting SNR for different minimum rate requirement of users are also observed for all the eight users and shown in Figs 4.47-4.54. These figures also show the power gain and noise power across

User, l	1	2	3	4	5	6	7	8
${R_l}^{min}$(bits/sec/Hz)	3	3.1	4.2	5.4	1.5	5.1	4.2	5.7

Table 4.9: Minimum rate (bits/sec/Hz) requirement of users for example 2.

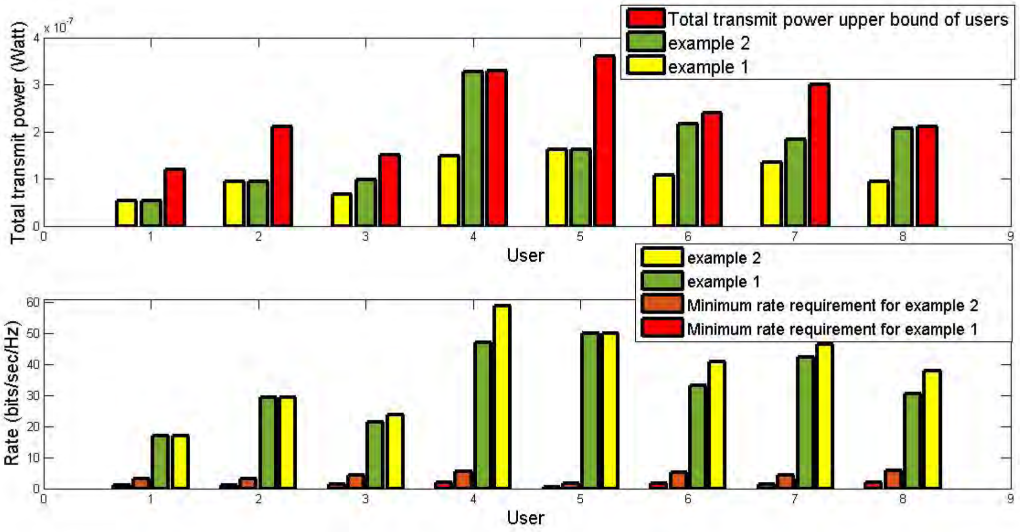


Figure 4.46: Allocation of total transmit power and achieved rate (bits/sec/Hz) across users for different Users' minimum rate requirement.

channels for both the examples. It is observed that, the changes in the figures of example 2 follow almost the same pattern of example 1. Minute observation reveals that, user 3,4,6,7 and 8 obtain higher values of resulting SNR and transmit power in example 2 which further results in higher total transmit power.

4.3.3 Effect Of Users' Power Budget

Now, we observe the impact of users' power budget on the performance of the proposed optimization framework-II. Here, we consider total transmit power upper bound of users shown in Table 4.4 as example 1 and the total transmit power upper bound of users shown in Table 4.10 as example 2. The rest of the system parameters are

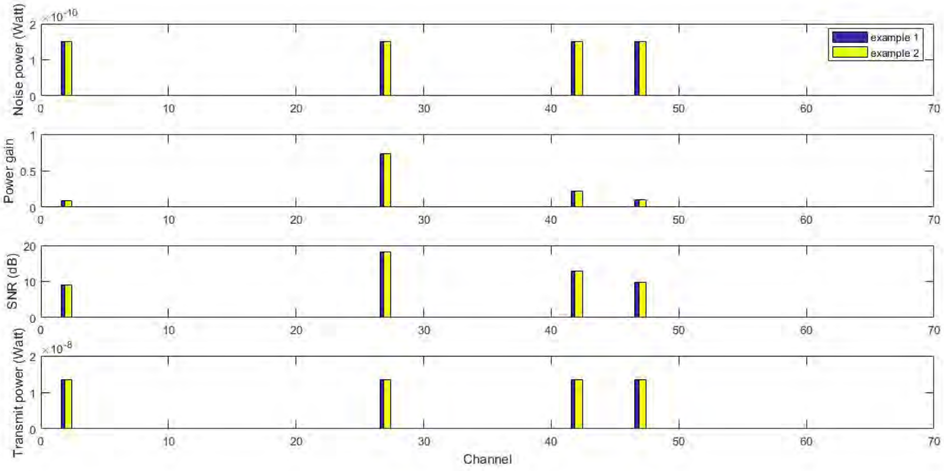


Figure 4.47: Allocation of transmit power and resulting SNR of user 1 for different Users' minimum rate requirement.

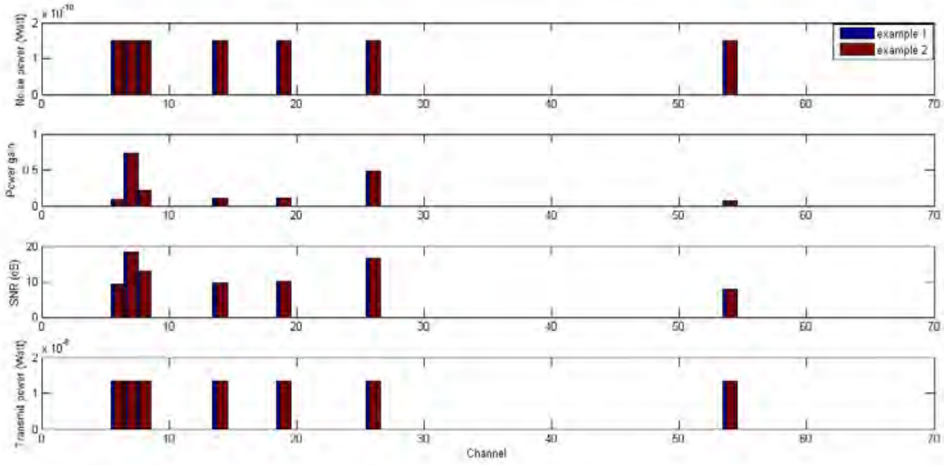


Figure 4.48: Allocation of transmit power and resulting SNR of user 2 for different Users' minimum rate requirement.

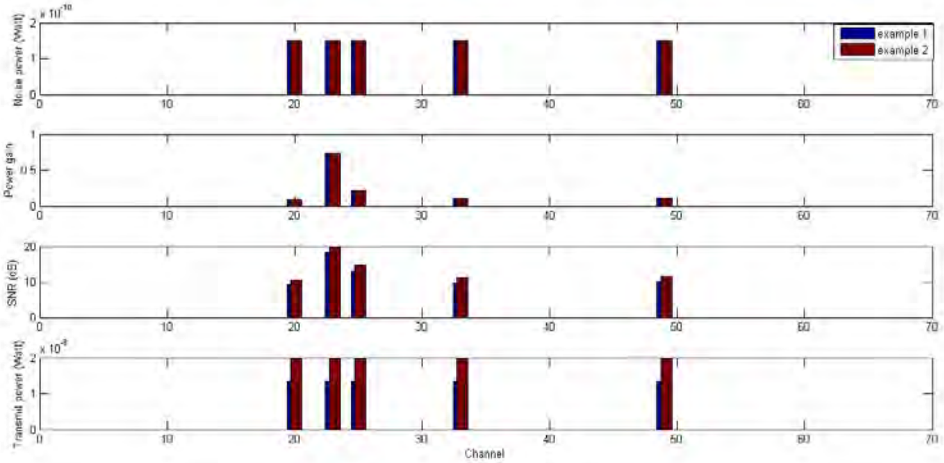


Figure 4.49: Allocation of transmit power and resulting SNR of user 3 for different Users' minimum rate requirement.

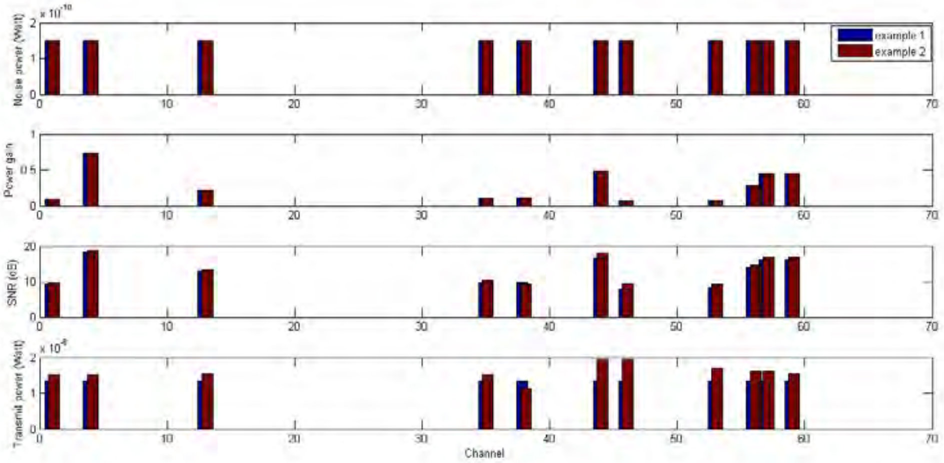


Figure 4.50: Allocation of transmit power and resulting SNR of user 4 for different Users' minimum rate requirement.

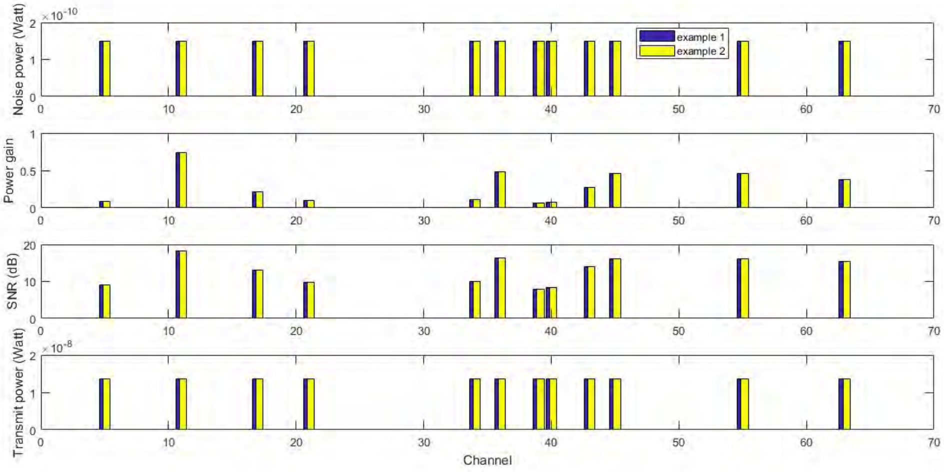


Figure 4.51: Allocation of transmit power and resulting SNR of user 5 for different Users' minimum rate requirement.

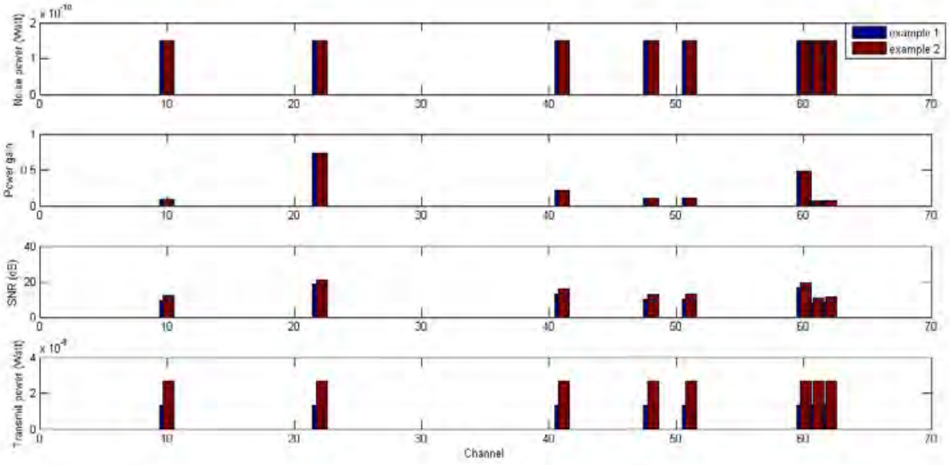


Figure 4.52: Allocation of transmit power and resulting SNR of user 6 for different Users' minimum rate requirement.

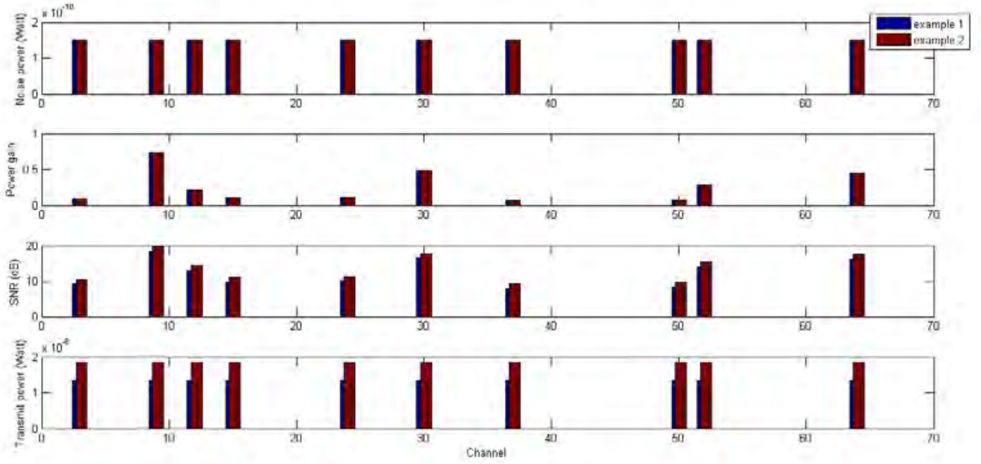


Figure 4.53: Allocation of transmit power and resulting SNR of user 7 for different Users' minimum rate requirement.

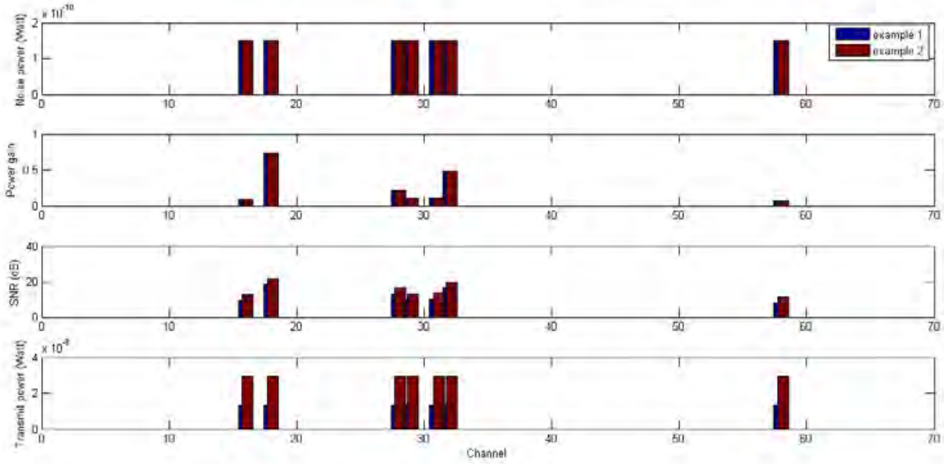


Figure 4.54: Allocation of transmit power and resulting SNR of user 8 for different Users' minimum rate requirement.

User, l	1	2	3	4	5	6	7	8
$p_{l,n}$Watt	15	15	15	15	15	15	15	15

Table 4.10: Total transmit power upper bound of users for example 2.

kept same as in Sec. 4.1.2 in both examples. Figure 4.55 shows the allocation of total transmit power and achieved rate (bits/sec/Hz) across users for both example 1 and 2. Figure 4.55 also shows the total transmit power upper bound and minimum rate requirement of users where, minimum rate requirement is depicted as a bar. Figure 4.55 shows that, total transmit power across users for both the examples are identical. The study points that, as long as QoS constraints of the users are invariable, increasing the total power budget has no effect on the allocation of transmit power and hence, users' power budget does not have any significant impact on the performance on the proposed framework-II. It is also observed that, with the increased value of users' power budget, achieved rate shows no changes. Which means both total transmit power and achieved rate for example 2 is identical to the one achieved in example 1 and hence the proposed optimization framework is successful in satisfying both total transmit power upper bound and minimum rate requirement for all users.
Similar pattern on allocation of transmit power and resulting SNR for different users' power budget are also observed for all the eight users and shown in Figs 4.56-4.63. These figures also show the noise power and power gain across channels. It is observed that, the changes in the figures of example 2 are identical to the changes of example 1.

4.4 Comparison between framework-I and II

In this section, we compare the simulation results of proposed framework-I and II in between. For framework-I, we consider the system parameters as described in section 4.1.1. For framework-II system parameters described in section 4.1.2 will be followed.

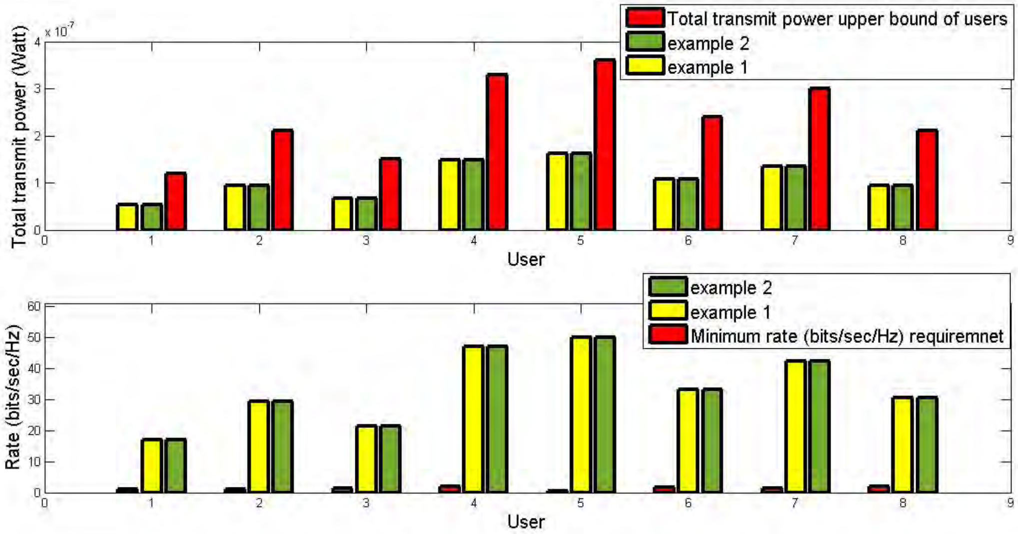


Figure 4.55: Allocation of total transmit power and achieved rate (bits/sec/Hz) across users for different Users' power budget.

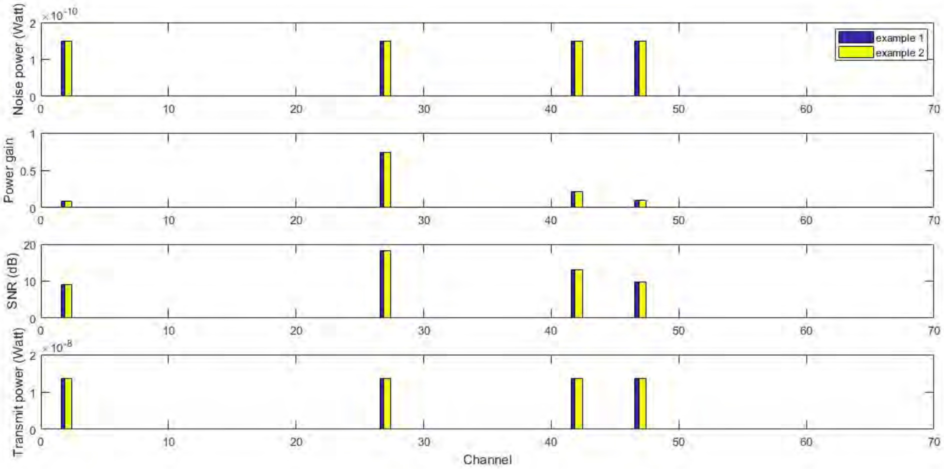


Figure 4.56: Allocation of transmit power and resulting SNR of user 1 for different Users' Power Budget.

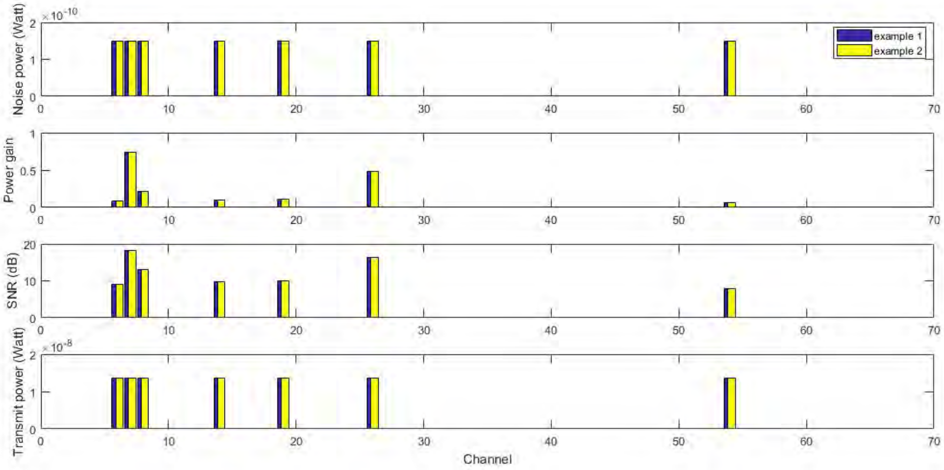


Figure 4.57: Allocation of transmit power and resulting SNR of user 2 for different Users' Power Budget.

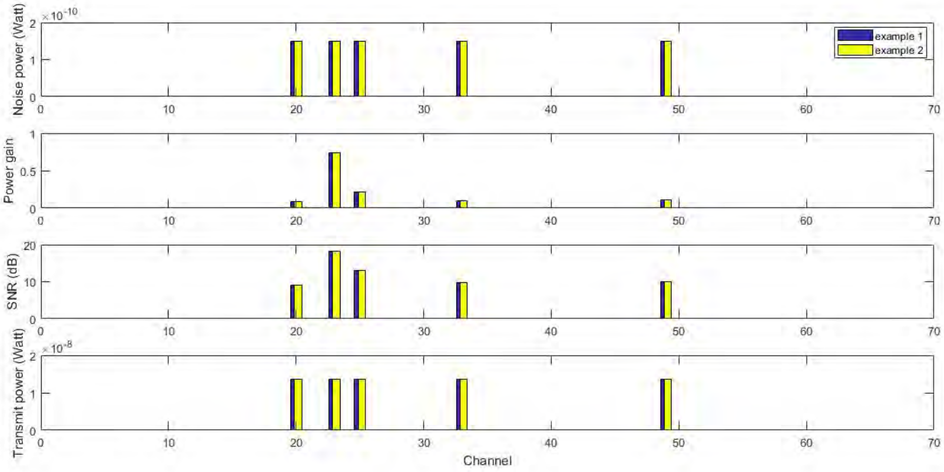


Figure 4.58: Allocation of transmit power and resulting SNR of user 3 for different Users' Power Budget.

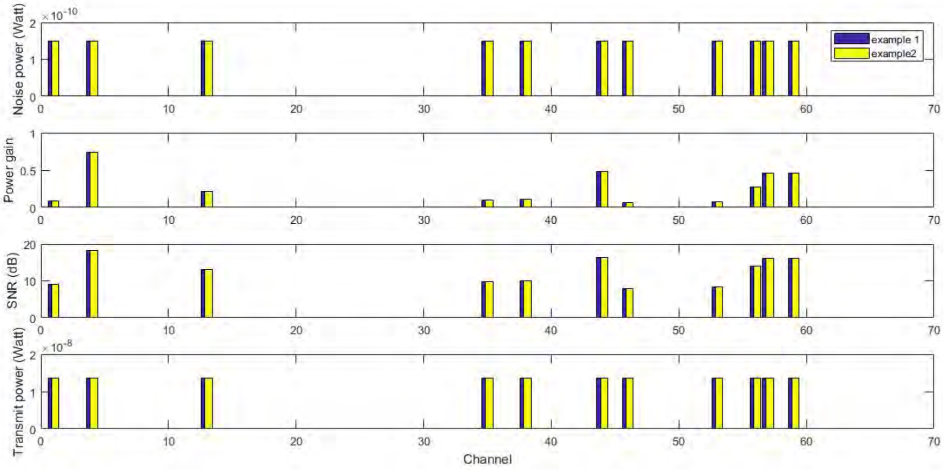


Figure 4.59: Allocation of transmit power and resulting SNR of user 4 for different Users' Power Budget.

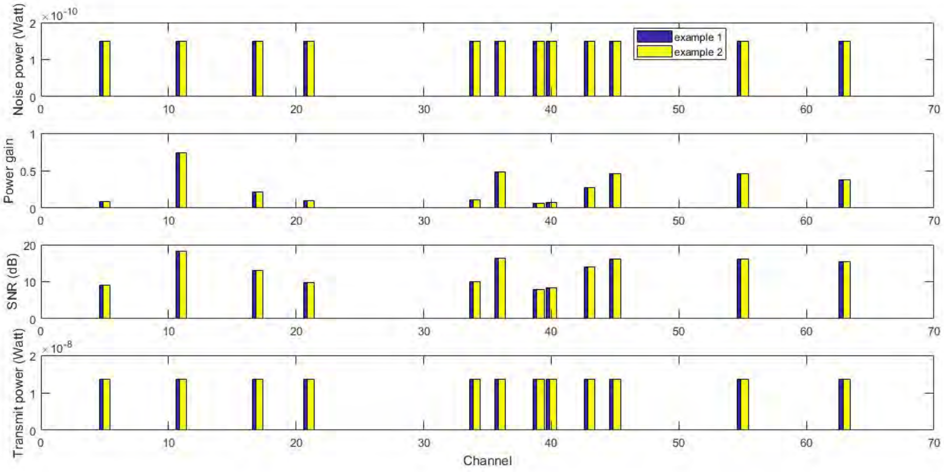


Figure 4.60: Allocation of transmit power and resulting SNR of user 5 for different Users' Power Budget.

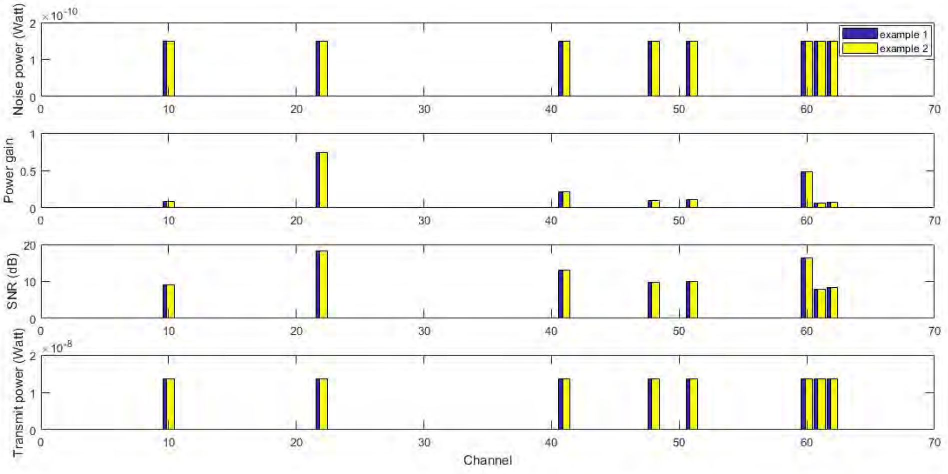


Figure 4.61: Allocation of transmit power and resulting SNR of user 6 for different Users' Power Budget.

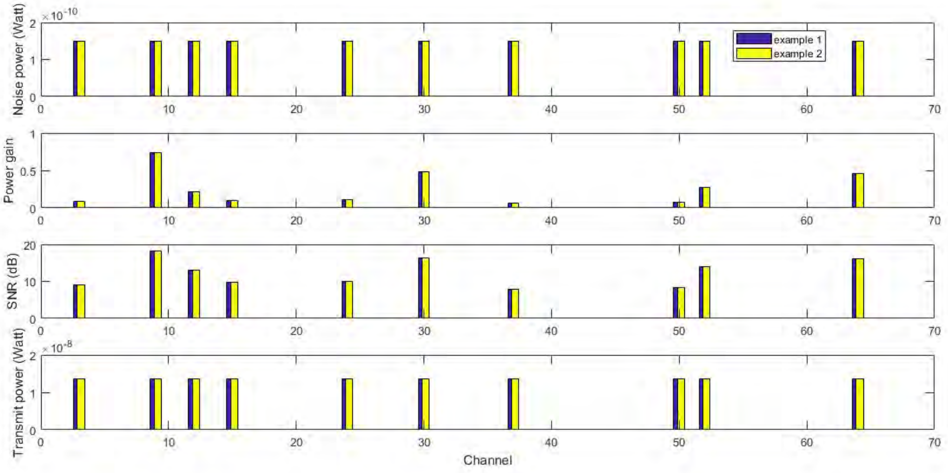


Figure 4.62: Allocation of transmit power and resulting SNR of user 7 for different Users' Power Budget.

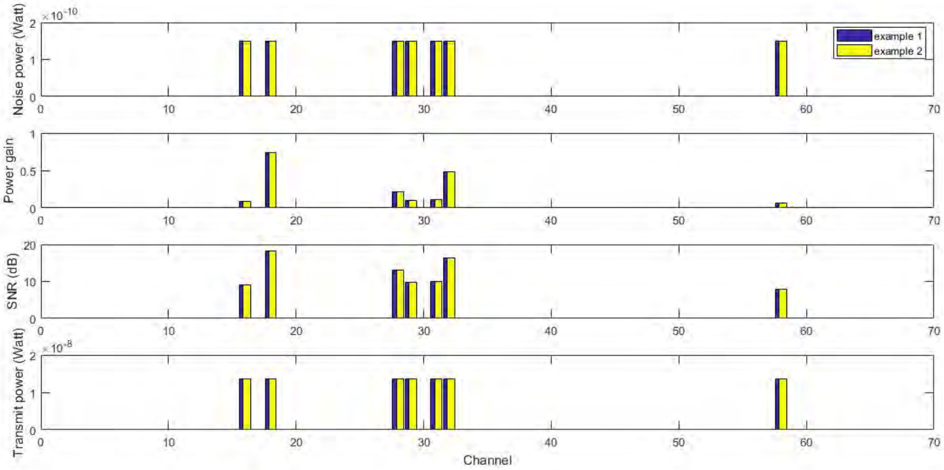


Figure 4.63: Allocation of transmit power and resulting SNR of user 8 for different Users' Power Budget.

First, we observe their performance in terms of total transmit power across users. Figure 4.64 shows total transmit power across users for both framework-I and II. It can be said that, framework-II follows higher values compared to framework-I, which is obvious.

Next, we observe their performance in terms of total bits/channel use across users. To do so, BER threshold is set to 10^{-3} and contellation size is set to 1 to 10 for both framework-I and II. Assuming M-QAM modulation scheme and employing the resulting SNRs from both the frameworks, the following bit allocation optimization framework is proposed:

$$\begin{aligned}
\text{Determine} \quad & \mathbf{b} = [b_{1,1}, ..., b_{l,1}, ..., b_{1,n}, ..., b_{l,n}]^T \\
\text{To Maximize} \quad & F = \sum_{n=1}^{N} \sum_{l=1}^{L} b_{l,n} \\
\text{Subject to} \quad & \\
& C_1 : b_{l,n} \epsilon [1, ..., {b_{l,n}}^{max}], \quad \forall l, n \\
& C_2 : BER \leq BER^t, \quad \forall l, n \qquad (4.4.1)
\end{aligned}$$

where, for M-QAM modulation order:

$$\begin{aligned}
& BER \leq \frac{4}{b_{l,n}} Q(\sqrt{\frac{3 b_{l,n} \gamma_{l,n}}{2^{b_{l,n}} - 1}}), \quad \forall l, n, \ odd \ b_{l,n} \\
& BER = \frac{4}{b_{l,n}} (1 - 2^{-\frac{b_{l,n}}{2}}) Q(\sqrt{\frac{3 b_{l,n} \gamma_{l,n}}{2^{b_{l,n}} - 1}}), \\
& \forall l, n, \ even \ b_{l,n} \qquad (4.4.2)
\end{aligned}$$

Here, $b_{l,n}$ indicates rate of lth user in nth channel. ${b_{l,n}}^{max}$ indicates maximum rate of lth user in nth channel. C_1 indicates limit on rate; C_2 indicates BER requirement for every secondary usesr. It is easy to show that, to achieve a certain BER, constraint C_2 is equivalent to the following constraint:

$$C_3 : \quad -\gamma_{l,n} \leq -C_q (2^{b_{l,n}} - 1), \quad \forall l, n \qquad (4.4.3)$$

Where C_q is a constant. For ease in presentation, we define, $Q_{q(l,n)} = -\frac{\gamma_{l,n}}{(2^{b_{l,n}} - 1)}$. So that, constraint C_3 can be rewritten as:

$$C_4 : \quad Q_{q(l,n)} \leq -C_q \qquad (4.4.4)$$

The rate allocation algorithm can be employed to solve rate allocation problem as follows:

First, we allocate the maximum feasible rate that satisfies equation to all users across channels. Based on this allocation rate, the average $Q_{q(l,n)}$ is calculated for all users and compared with $-C_q$ in the next step. For a specific user, if average $Q_{q(l,n)}$ does not satisfy constraint C_3, the maximum rate allocated to a channel for that specific user is reduced by 1. This process is repeated until constraint C_3 is satisfied or maximum number of iteration are completed. The convexity of constraint C_3 is discussed in **Theorem 3**.

Theorem 3. $-\gamma_{l,n} \leq -C_q(2^{b_{l,n}} - 1), \ \ \forall l, n,$ *is a convex constraint.*

Proof. Equation mentioned above can be rewritten as:

$$\gamma_{l,n} \geq C_q(2^{b_{l,n}} - 1) \tag{4.4.5}$$

As mentioned earlier,

$$\gamma_{l,n} = \frac{\alpha_{l,n} p_{l,n} h_{l,l}(n)}{\sigma^2(n)} \tag{4.4.6}$$

Hence, equation 4.4.5 can be written as:

$$\alpha_{l,n} p_{l,n} \gamma_{l,n} \geq C_q(2^{b_{l,n}} - 1)\sigma^2(n) \tag{4.4.7}$$

Finally, rearranging equation 4.4.7 we get:

$$C_q 2^{b_{l,n}} \sigma^2(n) - C_q \sigma^2(n) - \alpha_{l,n} p_{l,n} \gamma_{l,n} \leq 0 \tag{4.4.8}$$

The first term is convex as it is a function of $2^{b_{l,n}}$ which is a convex function itself. The second term is convex as it is a constant. The third term is a linear function of $p_{l,n}$ which makes it convex too. As a result, the entire inequality becomes convex.

Figure 4.64 shows total bits/channel across users for both the frameworks in same plot. Observation reveals that, just like total transmit power across user, total bits allocated per channel is higher for framework-2, which is obvious as framework-II needs to satisfy minimum rate requirement of it's users. As in framework-II, users are allocated a greater quantity of bits per channel, to provide the users with this, transmit power increases too which can be seen from 4.64. We can conclude that, minimum rate requirement threshold to attain a certain BER as a QoS metric is a better choice.

Finally, we compare the performance of the frameworks in terms of spectral efficiency (SE) and energy efficiency (EE). The energy efficiency of our system is defined as the ratio of total system throughput to total system power and expressed as:

$$EE = \frac{R_s}{\sum_{n=1}^{N}\sum_{l=1}^{L}\alpha_{l,n}p_{l,n}}, \quad \forall l,n \tag{4.4.9}$$

where,

$$R_s = \sum_{n=1}^{N}\sum_{l=1}^{L}\alpha_{l,n}log_2(1+\frac{p_{l,n}h_{l,l}(n)}{\sigma^2(n)}), \quad \forall l,n \tag{4.4.10}$$

Here, R_s is the system throughput. The spectral efficiency (SE) of our system can be expressed as:

$$SE = R_s \tag{4.4.11}$$

Fig. 4.65 depicts both SE and EE of users for framework-I and II. Observation reveals that, framework-II tends to be more spectral efficient whereas, framework-I presents more energy efficient characteristics.

4.5 Comparison with Resource Allocation Approach Based on Capacity Maximization

As discussed earlier, now a days energy efficiency based approaches have got attention. In this, section, we aim at comparing the obtained solutions of our proposed method with the existing resource allocation techniques. We observe the outcomes of conventional capacity maximization based resource allocation technique and compare them with the proposed frameworks (framework-I and II) in terms of total transmit power, energy efficiency and spectral efficiency.

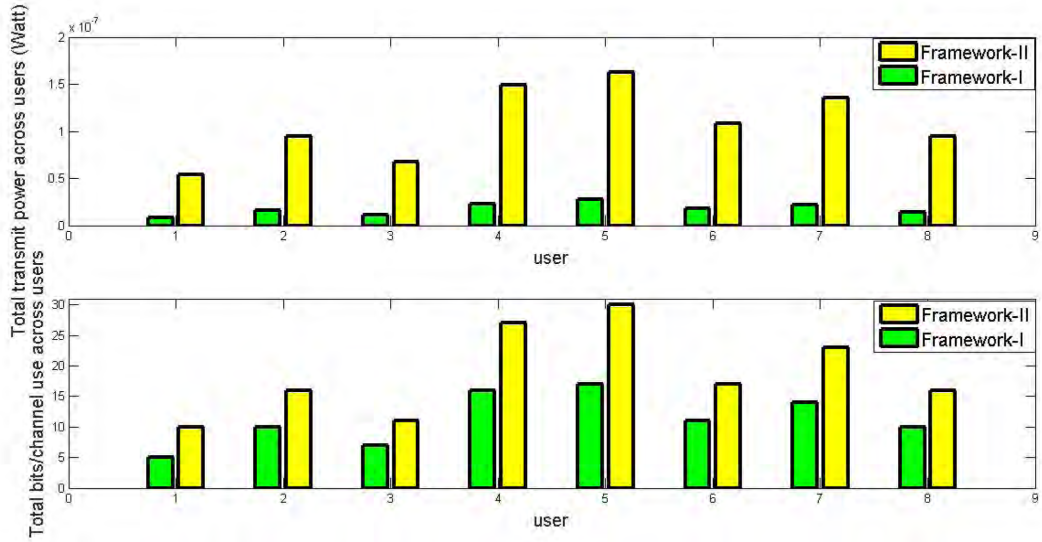


Figure 4.64: Allocation of total transmit power and bits/channel across users.

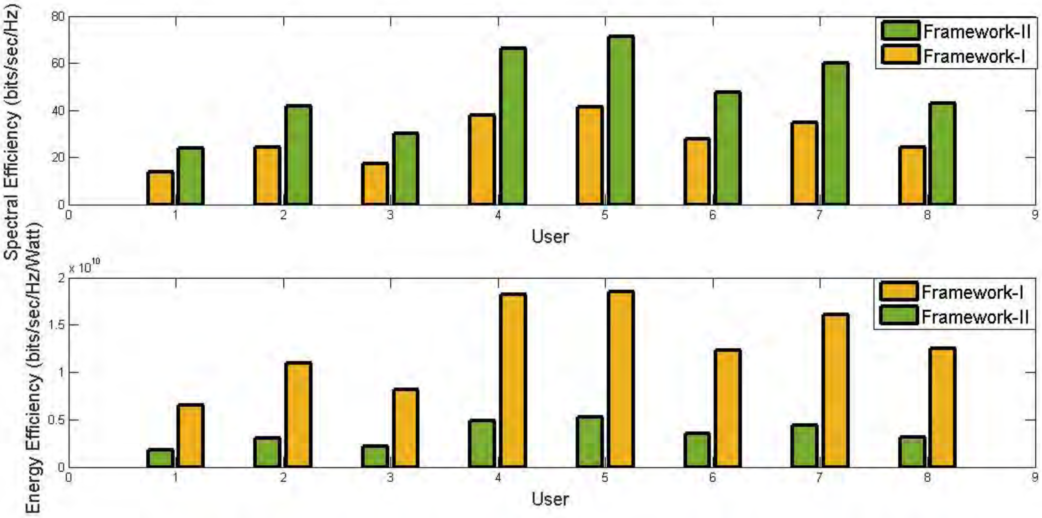


Figure 4.65: Spectral Efficiency and Energy Efficiency versus users.

Figure 4.66 illustrates total transmit power across users obtained from framework-I and II. Total transmit power across users obtained form capacity maximization approach is also shown in the same figure. For proposed framework-I and II we see that, total power spent is with in the total transmit power upper bound of users. That is, our proposed frameworks do not spend all of their power. Where as, existing capacity maximization based approach spends all it's power which is very obvious from the figure. Hence, our proposed frameworks are very successful in terms of utilization of power budget.

Next, our field of interest is spectral efficiency of the frameworks. From Fig. 4.67 it is clearly observed that, capacity maximization based approach tends to be more spectral efficient compared to our proposed frameworks. At the same time, framework-II presents more spectral efficient characteristics than framework-I. It is obvious due to the minimum rate requirement constraint. Unlike framework-I, users in framework-II needs to satisfy minimum rate requirement of users which results in higher bits/channel use and further increases spectral efficiency.

Finally, we will observe the frameworks in terms of energy efficiency. Fig. 4.68 illustrates energy efficiency of the frameworks in a single plot. It is observed that, our proposed frameworks are more energy efficient compared to the capacity maximization based approach. Which is obvious due to less power consuming characteristics of the frameworks. Hence, Our proposed frameworks of specific QoS constrained resource allocation are very much successful in terms of satisfying total transmit power upper bound of users and energy efficiency compared to conventional capacity maximization based approaches.

4.6 Summary

In this chapter, the proposed optimization frameworks are solved and results are analyzed.

Simulation results of proposed framework-I illustrate that, more transmit power is

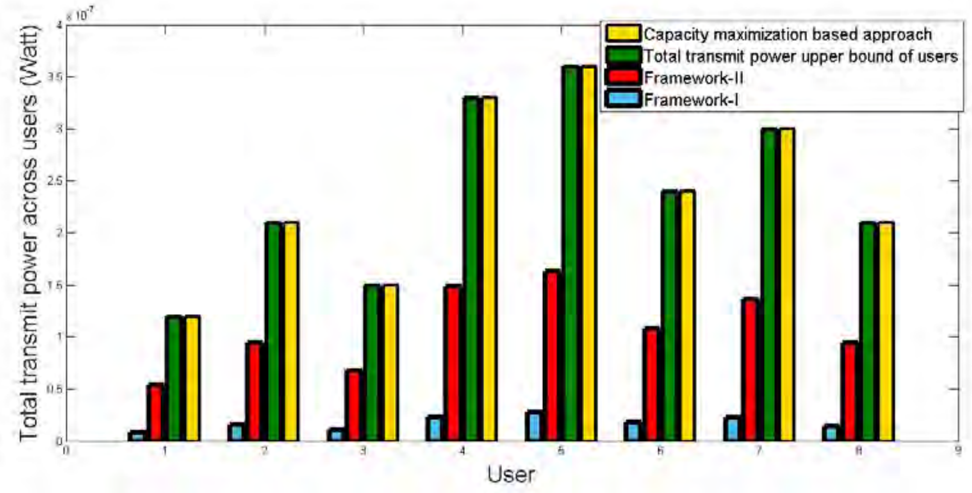


Figure 4.66: Allocation of total transmit power across users.

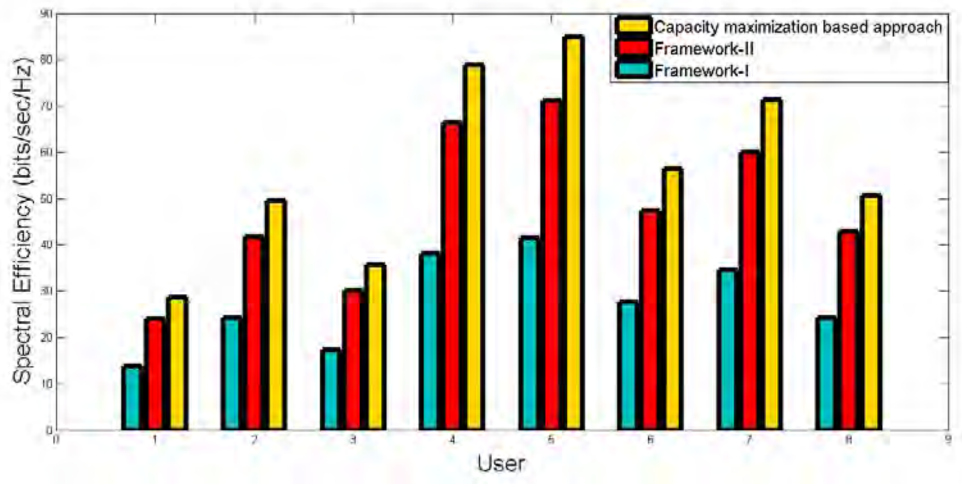


Figure 4.67: Spectral Efficiency versus users.

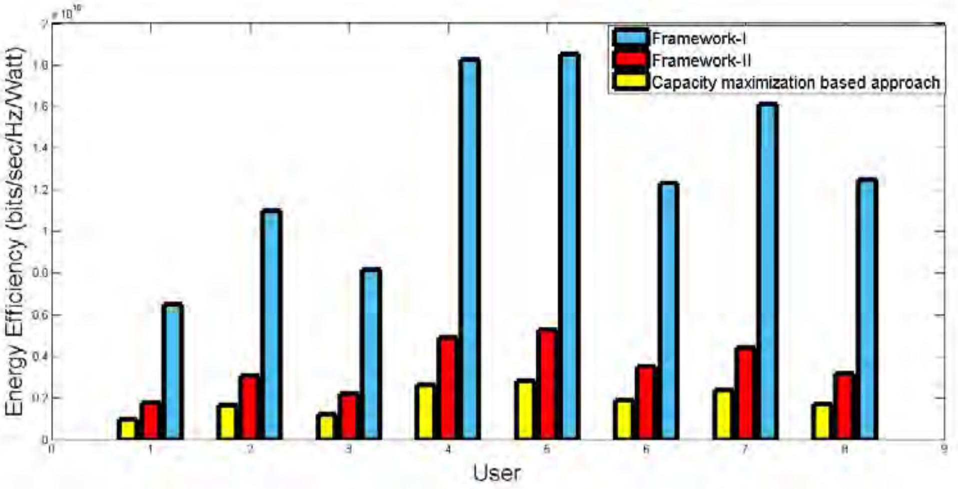


Figure 4.68: Energy Efficiency versus users.

required in a channel with smaller power gain. Same SNR is obtained across channels which is equal to SNR threshold. Higher SNR threshold results in higher total transmit power across users and vice versa. It is seen that, users' power budget has no significant impact on the allocation of transmit power once the optimal transmit power is obtained. In all the cases, proposed framework-I operates successfully with in the total transmit power upper bound of users.

Framework-II shows that, the variation in allocation of transmit power remains almost similar with the change in power gain of the channel whereas, unequal SNR is obtained across channels. Higher SNR is obtained in a channel with higher power gain. It is seen that, different users' power budget and target BER of users have no significant impact on the allocation of total transmit power once the optimal transmit power is obtained. However, higher value of target BER and minimum rate requirement of users has resulted in higher rate (bits/sec/Hz). Moreover, total transmit power is more when minimum rate requirement of users is higher. This is because, to achieve higher rate and to provide users with higher rate transmit power also increases.

Comparison between the two frameworks and existing capacity maximization based resource allocation framework clearly reveals that, framework-II uses higher values of total transmit power and provides higher total bits/channel allocation than framework-I. Moreover, both the frameworks work with in the total transmit power upper bound of users. That is, both of them do not spend all of their power as in existing frameworks based on capacity maximization. Observation reveals that, framework-II is more spectral efficient than framework-I whereas, framework-I is more energy efficient than framework-II. Both the frameworks are more energy efficient compared to conventional capacity maximization based approaches.

We can conclude that, successful satisfaction of the total transmit power upper bound of users through both the frameworks is marked. Achieved rate is observably satisfying the constrained minimum rate requirement of framework-II. Finally, comparison with conventional capacity maximization based resource allocation approach reveals that, both of the proposed frameworks are very much successful in terms of utilization of power budget of users and Energy Efficiency compared to conventional capacity maximization based resource allocation approaches.

Chapter 5

Proposed Resource Allocation Optimization Frameworks for Downlink Cognitive OFDMA System

In Chapter 3, system model along with the description of proposed resource allocation optimization frameworks (Framework-I and II) to compute optimal transmit power for uplink cognitive OFDMA system is presented. In this chapter, proposed resource allocation optimization frameworks are described for downlink cognitive OFDMA system. The prime interest is to optimize the transmission parameter namely transmit power. Just like uplink cognitive OFDMA system, each user has a minimum SNR requirement that needs to be maintained here in framework-I. On the other hand, in framework-II, each user has a minimum rate requirement (bits/sec/Hz) that needs to be maintained. Here, single user can be communicated over multiple subchannels by the BS. The objective is to estimate the best choice of transmit power with a view to minimize total transmit power.

The rest of the chapter is organized as follows: in Section 5.1, the system model is stated. Section 5.2 provides the description of the proposed resource allocation frameworks. Finally Section 5.3 summarizes the chapter.

5.1 System Model

This section describes the considered system model for this research work regarding downlink cognitive OFDMA system.

5.1.1 Network Architecture

An OFDMA based downlink cognitive radio system with a single Base Station (BS), multiple secondary users and several subchannels is considered. Specifically, an OFDMA based downlink cognitive radio system is considered in which a base station (BS) serves L secondary users. The frequency band available for CR transmission is divided in to N orthogonal subchannels. It is assumed that, the BS has a network coverage (cell) of hexagonal shape. As the BS can transmit simultaneously to both primary and secondary users, the primary users' signal can cause unacceptable interference to the secondary users. Therefore, overlay spectrum sharing is adopted by SUs. That is, secondary users use the spectrum when it is unused by PUs. It is also assumed that, BS is informed of the secondary users' subchannel state information and QoS in periodic interval.

5.1.2 Power Allocation, Channel Selection and Modulation Order Scheme

The objective of the work is to optimize transmission parameter namely transmit power of the BS without violating QoS.

To do that, it is assumed that, subchannel allocation to each of the users is already completed. These channels are available for opportunistic use by BS. To access the licensed spectrum, BS continuously sense the spectrum and determine L free subchannels that are available for use in opportunistic way.

It is also assumed that, BS can use several subchannels simultaneously to communicate a single user via an orthogonal access scheme. Once the transmit power is obtained, then the bit allocation scheme is proposed to determine bits/channel use which is also known as the modulation order. The following assumptions are also made in the system model of the proposed frameworks:

(i) A BS is assumed that will perform the resource allocation and has access to all users' channels and interference parameters,

(ii) BS has an upper limit of transmit power,

(iii) BS uses M-ary QAM modulation scheme with an adaptive modulation order M.

5.1.3 Propagation Model

Wireless radio channel is susceptible to noise, interference and other channel constraints. It is very important to model the wireless propagation properly for any wireless network. In order to characterize the propagation model accurately, the following things were considered:

(i) Simple path loss model is being assumed,

(ii) Orthogonal multiple access scheme is assumed.

More specifically, channels are assumed to be independent and identically distributed (IID). The strength of each is assumed to be Rayleigh distributed and thus the power of each channel is exponentially distributed.

5.1.4 Interference Model

In our consideration, SNR threshold or minimum rate (bits/sec/Hz) should be maintained for each user. For every user SNR is computed as:

$$\gamma_{l,n} = \frac{\alpha_{l,n} p_{l,n} h_{l,l}(n)}{\sigma^2(n)}, \quad \forall l, n,$$

where, $p_{l,n}$ is the transmit power of l-th user in n-th subchannel, $h_{l,l}(n)$ is the power gain from l-th transmitter to l-th receiver in n-th subchannel, $\alpha_{l,n}$ is the subchannel assignment index, $\sigma^2(n)$ is the noise power in n-th subchannel. As overlay spectrum sharing and orthogonal multiple access scheme is assumed, hence, any SU experiences only channel noise. Most of the related terms used in this chapter are already described in Chapter 3.

5.1.5 Interference Temperature Model

An interference temperature (IT) threshold is imposed to protect possible primary transmission in any channel. Interference temperature is defined as the total RF power measured at the primary users' receiver antenna per unit bandwidth. As described in chapter 3, IT threshold is set to be 200 times of channel noise power in our research work.

The goal of this work is to maintain QoS for these cognitive users by allocating resource effectively. Users' minimum rate requirement and SNR threshold are considered as a measurement of QoS.

Under this system model, two optimization frameworks are proposed for resource allocation of SUs in a OFDMA based downlink CRN in order to determine optimal allocation of power. In the first framework, each user has a minimum SNR requirement that needs to be maintained whereas, in the second framework, each user has a minimum rate (bits/sec/Hz) requirement that needs to be maintained.

5.2 Proposed Resource Allocation Optimization Frameworks

5.2.1 Optimization Framework-I

The optimization problem is formulated as:

$$
\begin{aligned}
\text{Determine} \quad & \mathbf{p} = [p_{1,1}, ..., p_{l,1}, ..., p_{1,n}, ..., p_{l,n}]^T \\
\text{To Minimize} \quad & F = \sum_{n=1}^{N} \sum_{l=1}^{L} p_{l,n} \\
\text{where,} \quad & \\
& p_{l,n} \geq 0, \quad \forall l, n \\
\text{Subject to} \quad & \\
& C_1 : \sum_{n=1}^{N} \sum_{l=1}^{L} p_{l,n} \alpha_{l,n} \leq p_{bs} \\
& C_2 : \sum_{l=1}^{L} p_{l,n} h_{l,n}(m) \alpha_{l,n} \leq I_t(n), \quad \forall n \\
& C_3 : \gamma_{l,n} \geq \gamma_{l,n}^{t}, \quad \forall l, n \qquad (5.2.1)
\end{aligned}
$$

where

$$\gamma_{l,n} = \frac{\alpha_{l,n} p_{l,n} h_{l,l}(n)}{\sigma^2(n)}, \quad \forall l, n \qquad (5.2.2)$$

Here, p_{bs} is the power budget at base station. Since power budget is finite, total transmit power of all SUs across their intended subchannels is restrained to be smaller than the maximum limit p_{bs} and the constraint takes the form of C_1; C_2 indicates the interference temperature threshold constraint so that when a PU enters a subchannel used by a secondary user, interference is constringed to a certain limit and C_3 indicates the SNR threshold constraint required to guarantee desired QoS. The subchannel assignment index $\alpha_{l,n}$ and convexity of constraint C_3 are already described in Chapter 3.

5.2.2 Optimization Framework-II

The mathematical description of the proposed optimization framework corresponds to:

$$\begin{aligned}
\text{Determine} \quad & \mathbf{p} = [p_{1,1}, ..., p_{l,1}, ..., p_{1,n}, ..., p_{l,n}]^T \\
\text{To Minimize} \quad & F = \sum_{n=1}^{N} \sum_{l=1}^{L} p_{l,n} \\
\text{Where,} \quad & \\
& p_{l,n} \geq o, \quad \forall l, n \\
\text{Subject to} \quad & \\
& C_1 : \sum_{n=1}^{N} \sum_{l=1}^{L} p_{l,n} \alpha_{l,n} \leq p_{bs} \\
& C_2 : \sum_{l=1}^{L} p_{l,n} h_{l,n}(m) \alpha_{l,n} \leq I_t(n), \quad \forall n \\
& C_3 : R_l = \sum_{n=1}^{N} r_{l,n} \\
& = \sum_{n=1}^{N} \alpha_{l,n} log_2(1 + b_3 \frac{p_{l,n} h_{l,l}(n)}{\sigma^2(n)}) \geq {R_l}^{min}, \quad \forall l \qquad (5.2.3) \\
\text{Where,} \quad & \\
& b_3 \text{ is a constant whose computation is already} \\
& \text{given in chapter 3}
\end{aligned}$$

Constraints C_1 and C_2 remain same to the constraints as described in Framework-I. Constraint C_3 indicates the achievable rate for l-th user and is the sum of the rates in each OFDM subchannel as mentioned earlier. The convexity of constraint C_3 is already described in chapter 3.

5.3 Summary

In this chapter, proposed resource allocation optimization frameworks have been stated that provide the optimal transmit power with a goal of minimizing total transmit power and constrained by SNR or minimum rate requirement that BS needs to employ in maintaining QoS in a downlink OFDMA cognitive network.

Chapter 6

Solution of Proposed Resource Allocation Optimization Frameworks for Downlink Cognitive OFDMA System

In Chapter 5, proposed resource allocation optimization frameworks (Framework-I and II) to compute optimal transmit power for downlink cognitive OFDMA system have been shown. In this chapter, proposed resource allocation optimization frameworks for downlink cognitive OFDMA system are solved and results are analyzed.

The rest of the chapter is organized as follows: Section 6.1 describes the simulation setup for both of the proposed frameworks. Numerical result analysis of proposed framework-I and II are presented in Section 6.2 and 6.3, respectively. Comparison between the proposed frameworks are presented in Section 6.4. Section 6.5 describes comparison of proposed frameworks with conventional capacity maximization based resource allocation approach. Finally, Section 6.7 summarizes the chapter.

$\sigma^2(n)$(Watt)	$1.5(\times 10^{-10})$
$\gamma^t_{l,n}\ \forall\ l,n$(dB)	10
$I_t(n)\ \forall\ l,n$(Watt)	$200 \times \sigma^2(n)$
p_{bs} (Watt)	64

Table 6.1: System parameters for framework-I.

User, l	1	2	3	4	5	6	7	8
${R_l}^{min}$(bits/sec/Hz)	1	1.1	1.4	1.8	0.5	1.7	1.4	1.9

Table 6.2: Minimum rate (bits/sec/Hz) requirement of users for framework-II.

6.1 Simulation Setup

We assume a Cognitive OFDMA system with $N = 64$ available channels and a total of L =8 SUs. We consider the similar usage pattern as shown in Chapter 4, section 4.1.

6.1.1 Simulation Setup for proposed framework-I

Table 6.1 provides the system parameters that are required for optimization framework-I. It is to be noted, how to obtain channel power gain such as $h_{l,l}(n)$, $h_{l,n}(m)$ is already described in the previous chapter.

6.1.2 Simulation Setup for proposed framework-II

Table 6.2 illustrates the minimum rate (bits/sec/Hz) requirement to achieve a targeted BER of all users for proposed framework-II. Table 6.3 provides all other system parameters that are required for proposed optimization framework-II.

$\sigma^2(n)$(Watt)	$1.5(\times 10^{-10})$
$BER_{l,n}$	10^{-3}
b_3	0.283
$I_t(n)\ \forall\ l, n$(Watt)	$200 \times \sigma^2(n)$
p_{bs} (Watt)	80

Table 6.3: System parameters for framework-II.

6.2 Result Analysis of proposed framework-I

In this section, we investigate the performance of the proposed resource allocation optimization framework-I for downlink cognitive OFDMA system.

Just like Section 4.2, at first, we observe the performance of proposed framework-I in terms of the allocated transmit power and obtained SNR across the channels for every SU. Figure 6.1 depicts the allocated transmit power and resulting SNR across channels for user 1. The channel noise power and channel power gain are also shown in the same figure. From Fig. 6.1, we see the BS requires to transmit with more power in a channel with smaller power gain and vice versa. Same SNR is achieved in all channels which is equal to the threshold value. So, we see that, framework-I allocates transmit power just to attain the SNR threshold. This is due to the objective function of the framework. The similar pattern on allocation of transmit power and resulting SNR are also observed for rest of the seven users and shown in Figs. 6.2-6.8.

Total allocated transmit power by the BS obtained by proposed framework-I is shown in Fig as a bar plot. 6.9. From Fig. 6.9, it is observed that, the total power spent is with in upper limit of the channels. Moreover, allocation of total transmit power by the BS across users is computed to be 1.4×10^{-7} Watt which is smaller than the total power budget at BS. That is, framework-I does not spend all of its power as in existing frameworks based on capacity maximization.

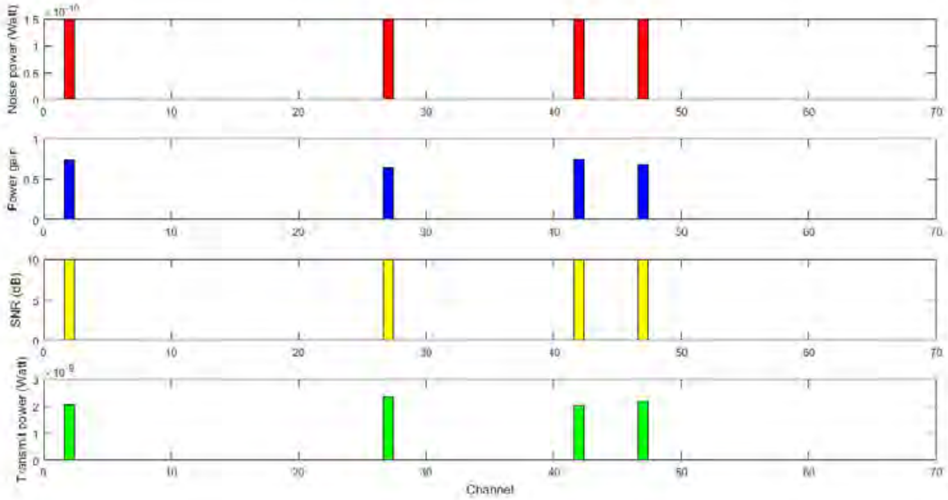


Figure 6.1: Allocation of BS's transmit power and resulting SNR for user 1.

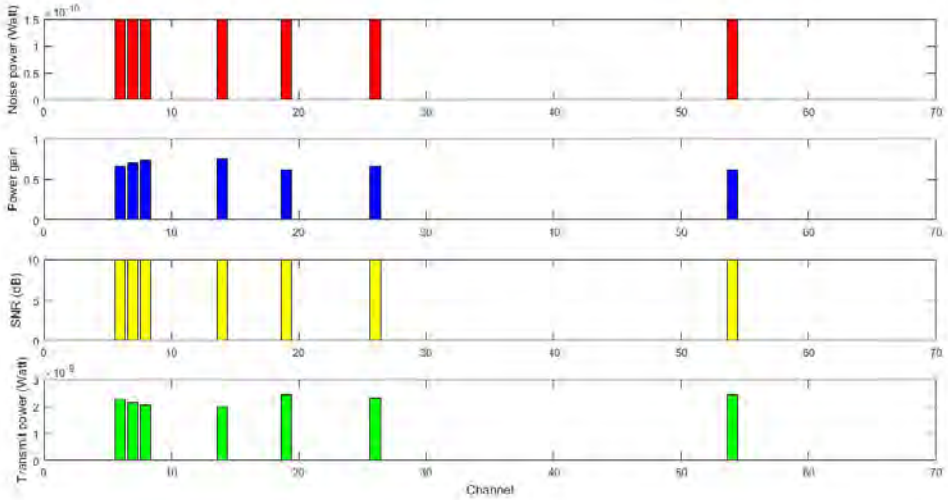


Figure 6.2: Allocation of BS's transmit power and resulting SNR for user 2.

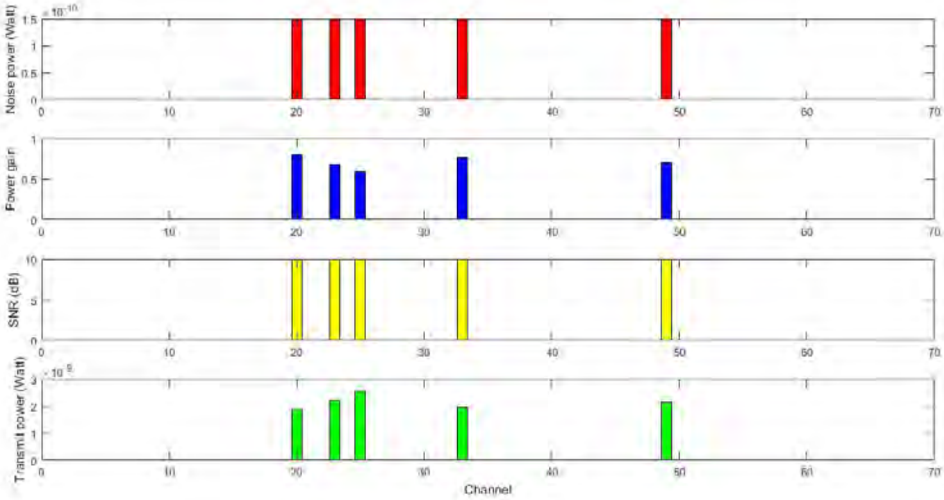


Figure 6.3: Allocation of BS's transmit power and resulting SNR for user 3.

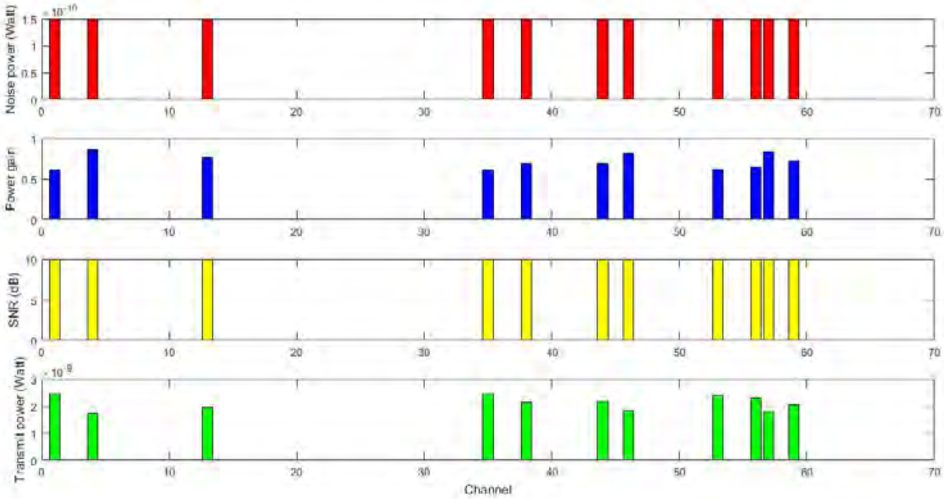


Figure 6.4: Allocation of BS's transmit power and resulting SNR for user 4.

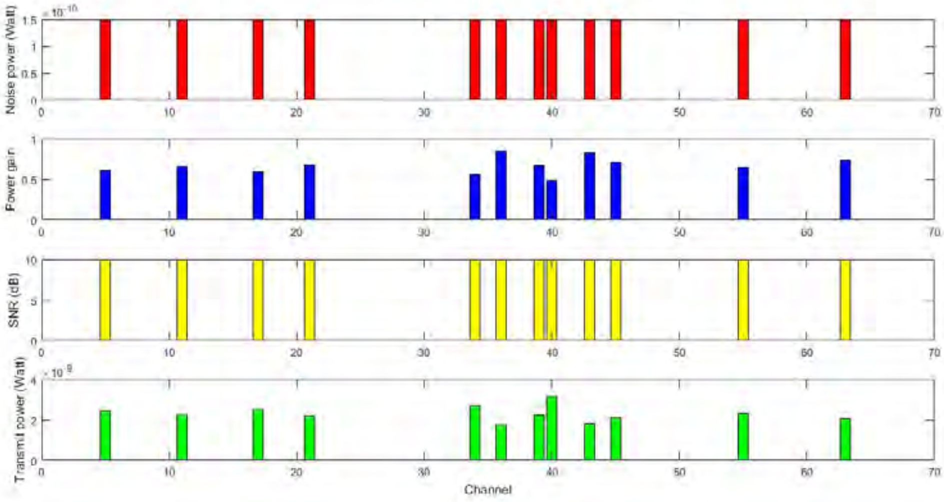


Figure 6.5: Allocation of BS's transmit power and resulting SNR for user 5.

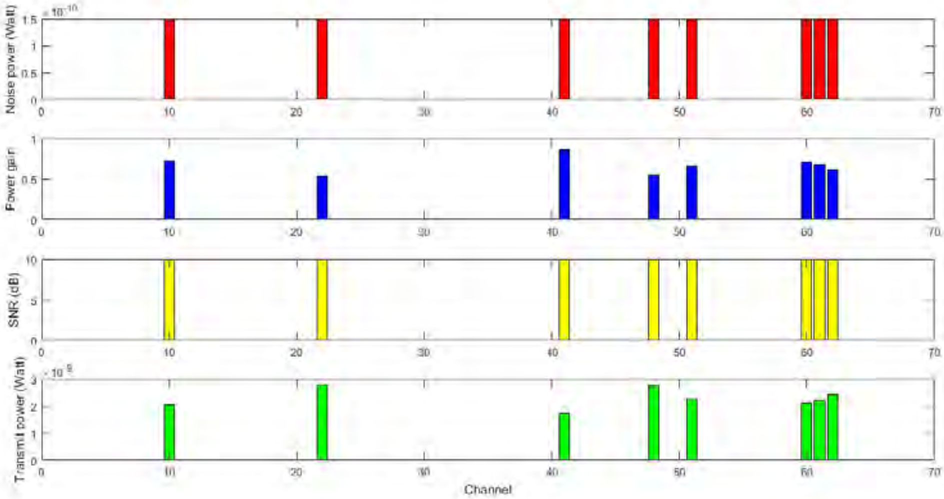


Figure 6.6: Allocation of BS's transmit power and resulting SNR for user 6.

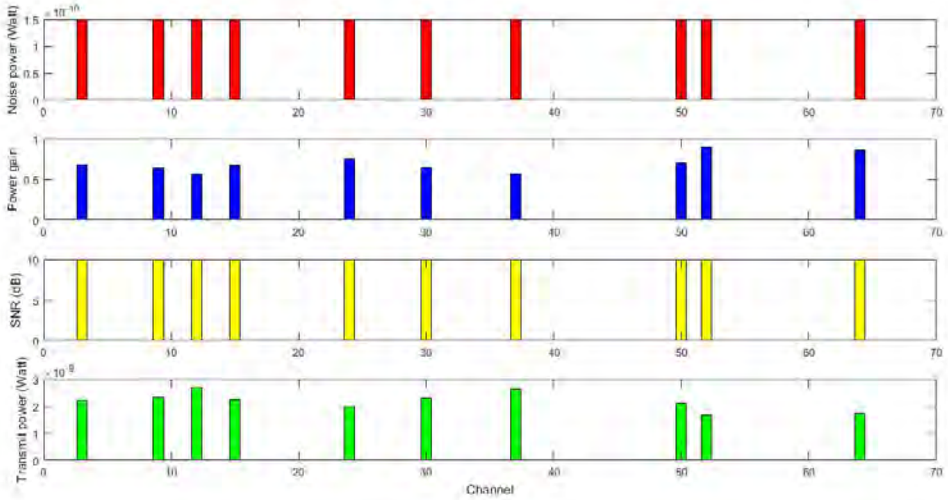


Figure 6.7: Allocation of BS's transmit power and resulting SNR for user 7.

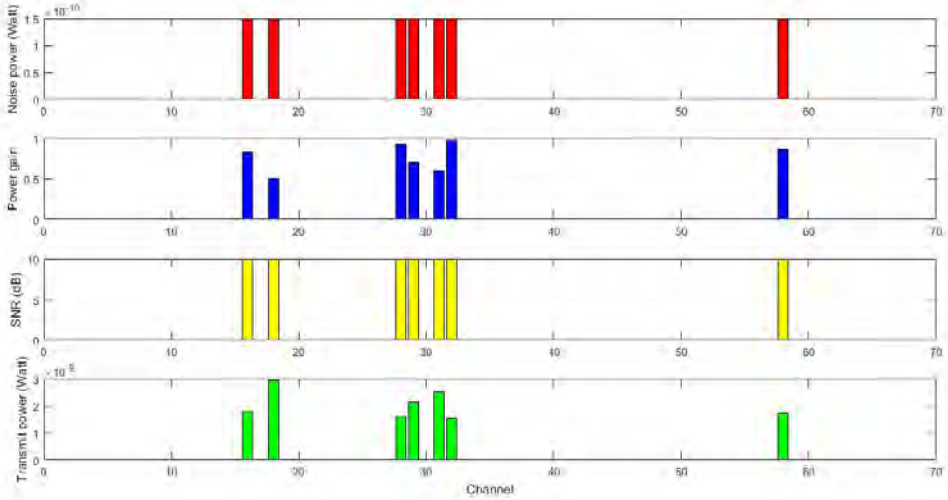


Figure 6.8: Allocation of BS's transmit power and resulting SNR for user 8.

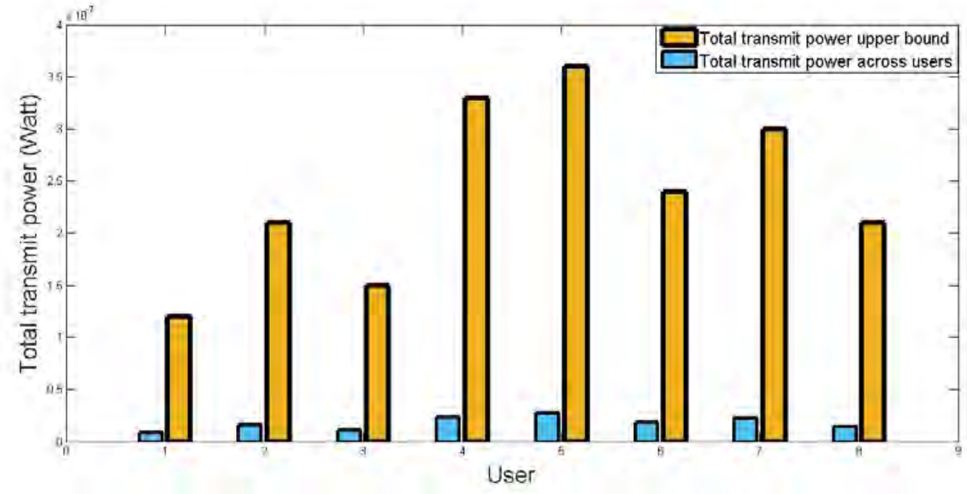


Figure 6.9: Allocation of BS's total transmit power across users.

6.2.1 Effect of SNR threshold

Now, we observe the impact of different SNR thresholds on the performance of the proposed optimization framework-I.
We consider the SNR threshold shown in Table 6.1 as example 1. Next we set the SNR threshold to 8 dB and term it as example 2. Whereas, we set the SNR threshold to 12 dB and term it as example 3. The rest of the system parameters are kept same as in Sec. 6.1.1 in all three example cases.

Figure 6.10 shows the total transmit power by the BS across users for all the three examples. Figure 6.10 shows that, with the increase in the value of SNR threshold, total transmit power by the BS also increases and vice versa. It is to be noted that, allocation of total transmit power by the BS across users is computed to be 8.85×10^{-8} Watt for example 2 and for example 3, it is computed to be 2.22×10^{-7} Watt. This is because, to achieve higher SNR threshold and to provide users with it, BS needs to increase the transmit power as well. But in every cases, it remains with in the upper limit of the channels and also within the power budget of BS.

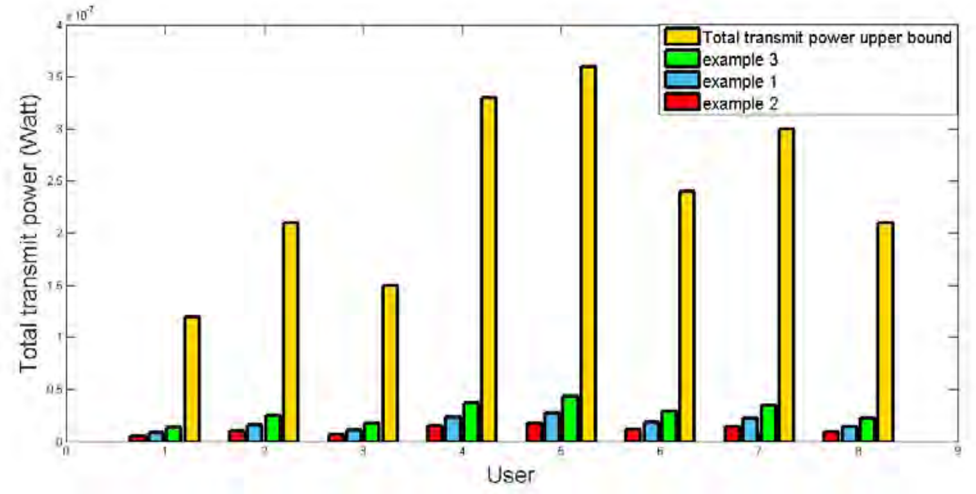


Figure 6.10: Allocation of BS's total transmit power across users for different SNR thresholds.

The pattern on allocation of BS's transmit power and obtained SNR across channels for different SNR thresholds are also observed for all the eight users and shown in Figs. 6.11-6.18. Channel noise power and power gain are also shown in the same plot. For all the cases, we see that, the BS requires to transmit with more power in a channel with smaller power gain and vice versa. With the increment in SNR threshold, transmit power also increases. So, it can be concluded that, transmit power increases with increase in SNR threshold but at the same time, obtained SNR remains same to the threshold value for all the cases.

6.2.2 Effect of BS's Power Budget

Next, we observe the impact of BS' power budget on the performance of the proposed optimization framework-I. Here, we consider the BS's power budget shown in Table 6.1 as example 1. For example 2, BS's power budget will be increased to 96 Watt

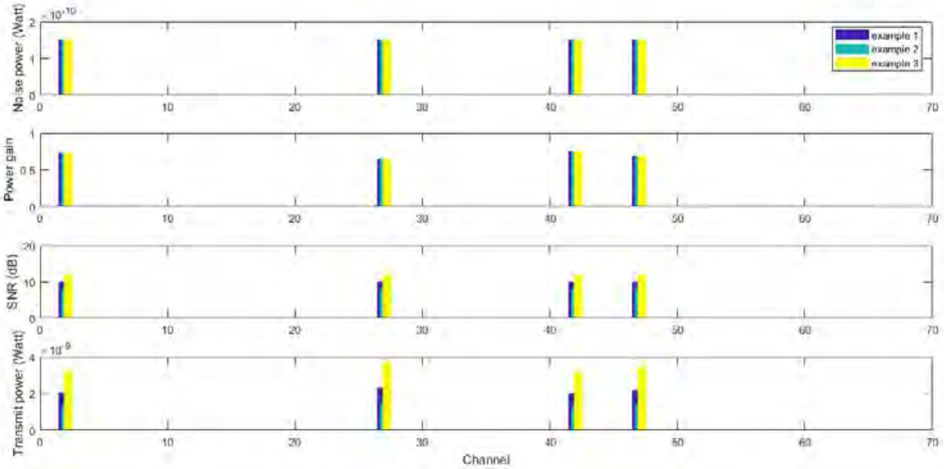


Figure 6.11: Allocation of BS's transmit power and resulting SNR of user 1 for different SNR thresholds.

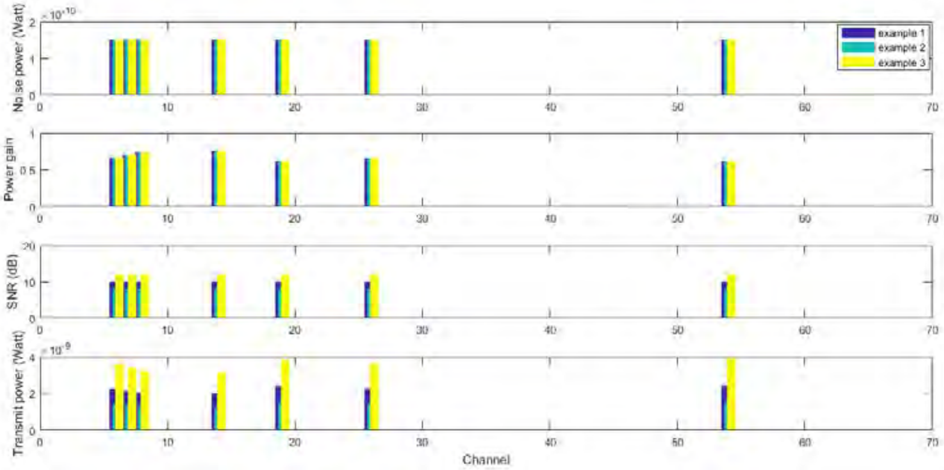


Figure 6.12: Allocation of BS's transmit power and resulting SNR of user 2 for different SNR thresholds.

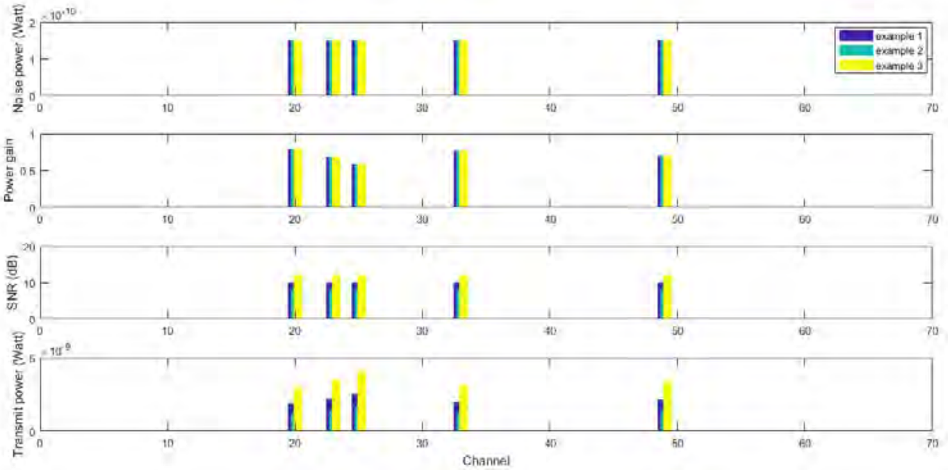


Figure 6.13: Allocation of BS's transmit power and resulting SNR of user 3 for different SNR thresholds.

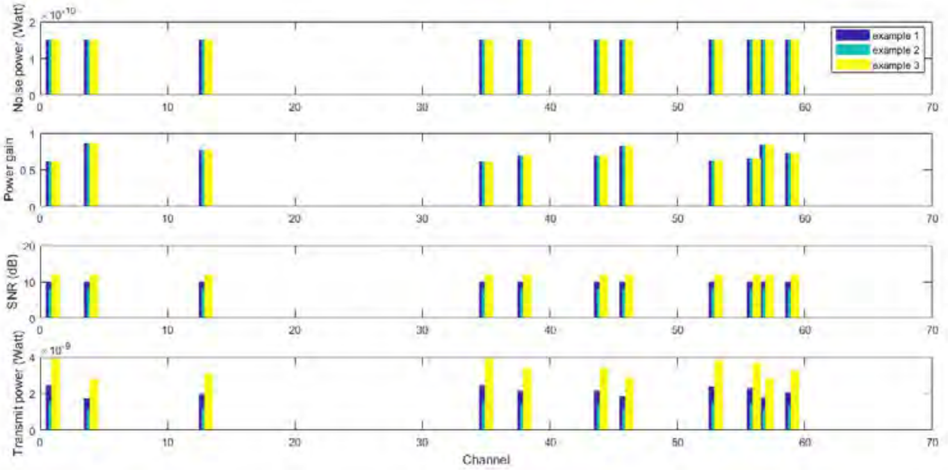


Figure 6.14: Allocation of BS's transmit power and resulting SNR of user 4 for different SNR thresholds.

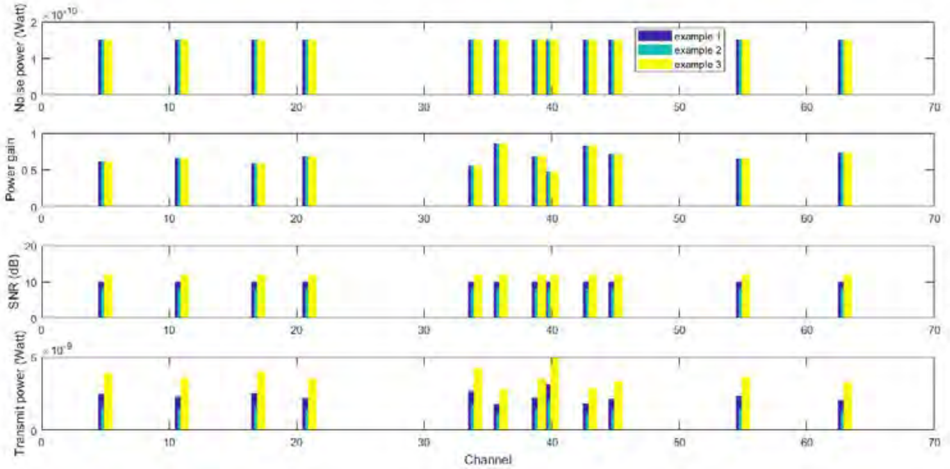


Figure 6.15: Allocation of BS's transmit power and resulting SNR of user 5 for different SNR thresholds.

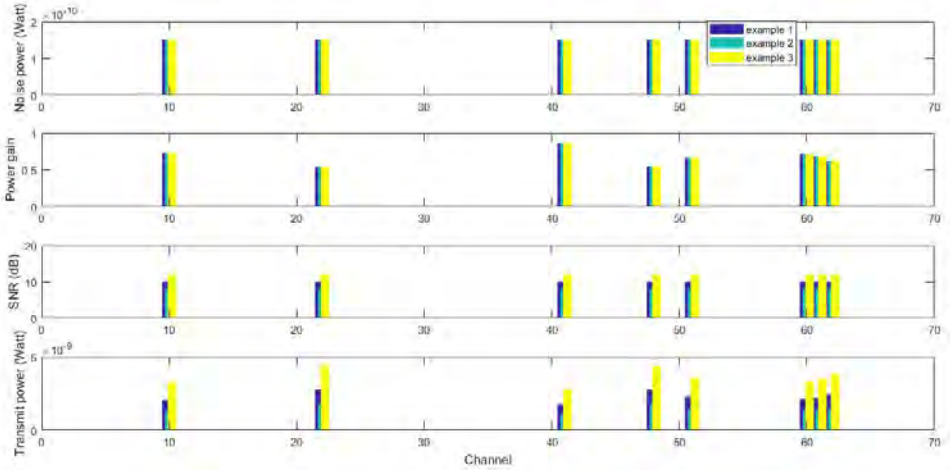


Figure 6.16: Allocation of BS's transmit power and resulting SNR of user 6 for different SNR thresholds.

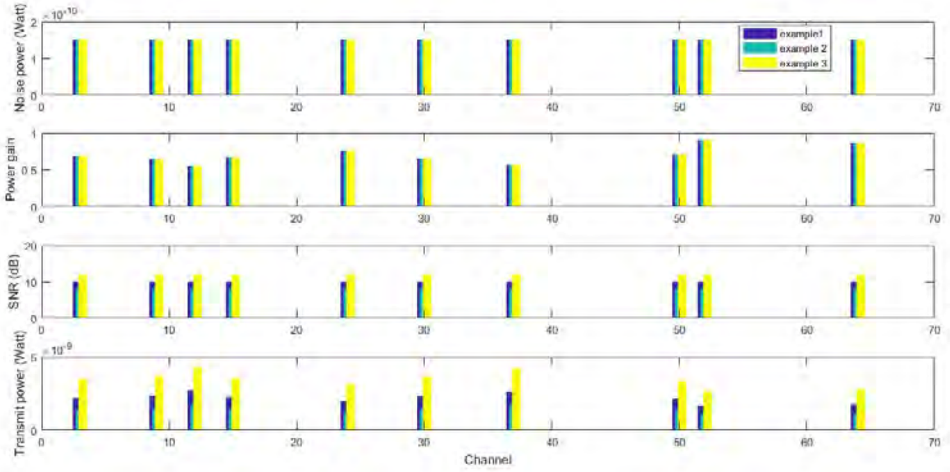


Figure 6.17: Allocation of BS's transmit power and resulting SNR of user 7 for different SNR thresholds.

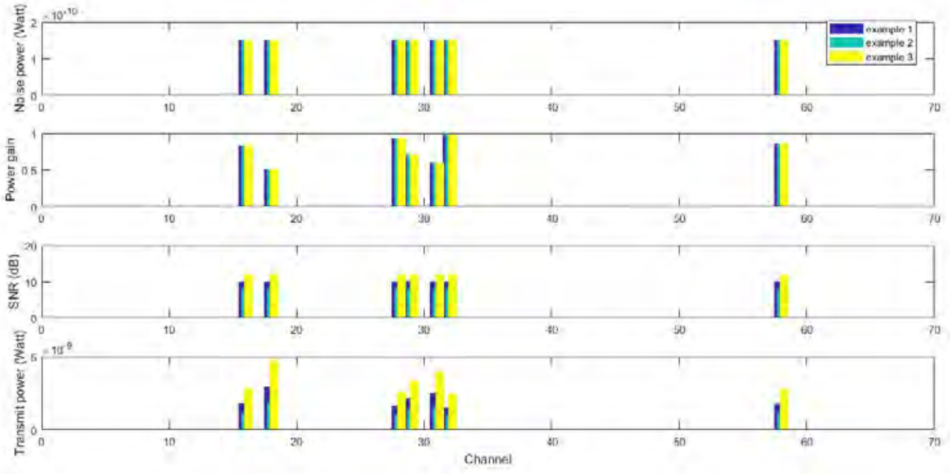


Figure 6.18: Allocation of BS's transmit power and resulting SNR of user 8 for different SNR thresholds.

whereas, for example 3 it will be reduced to 32 Watt. The rest of the system parameters are kept same as in Section 6.1.1 in all three examples.

Figure 6.19 depicts the allocation of total transmit power by the BS for different BS's power budget. Figure 6.19 shows that, BS's total transmit power for all three examples are identical. Hence, BS' power budget does not have any significant impact on the performance on the proposed framework-I in terms of total transmit power allocation once optimal transmit power is obtained. Once again, it is observed that, total transmit power in every case remains within the upper bound of channels and also within the BS's power budget.

The pattern on allocation of BS's transmit power and obtained SNR across channels for all three examples are also observed for all the eight users and shown in Figs. 6.20-6.27. Channel noise power and power gain are also shown in the same plot. We see that, transmit power is inversely proportional to the power gain. So, it can be implied that, framework-I spends more BS's transmit power when the power gain is minimum and vice versa, considering constant noise level. We also see that, transmit power across channels shows no change with the variation of BS' power budget if other parameters remain constant.

6.3 Result Analysis of proposed framework-II

In this section, we investigate the performance of the proposed resource allocation optimization framework-II for downlink cognitive OFDMA system.

First, we observe the performance of proposed framework-II in terms of the BS's allocated transmit power and resulting SNR across the channels for every SU. Figure 6.28 depicts the BS's transmit power and resulting SNR across channels for user 1. The channel noise power and channel power gain are also shown in the same figure.

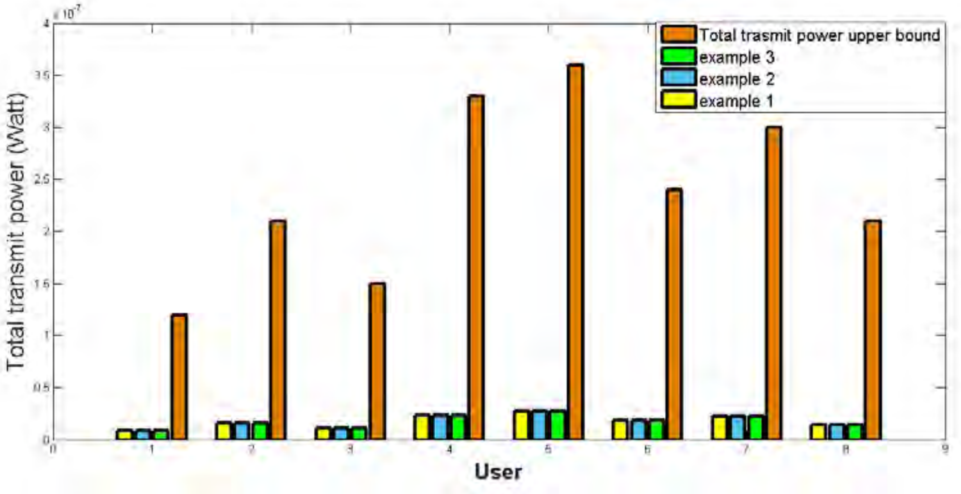


Figure 6.19: Allocation of BS's total transmit power across users for different BS's power budget.

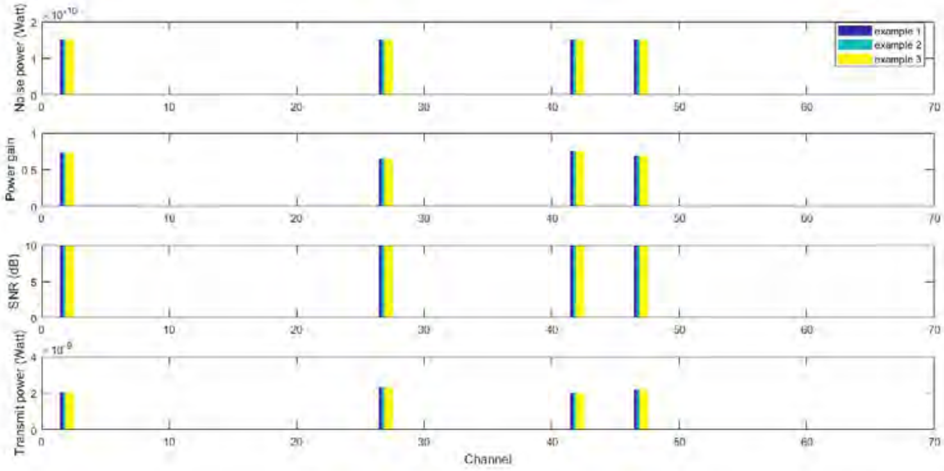


Figure 6.20: Allocation of BS's transmit power and resulting SNR of user 1 for different BS's power budget.

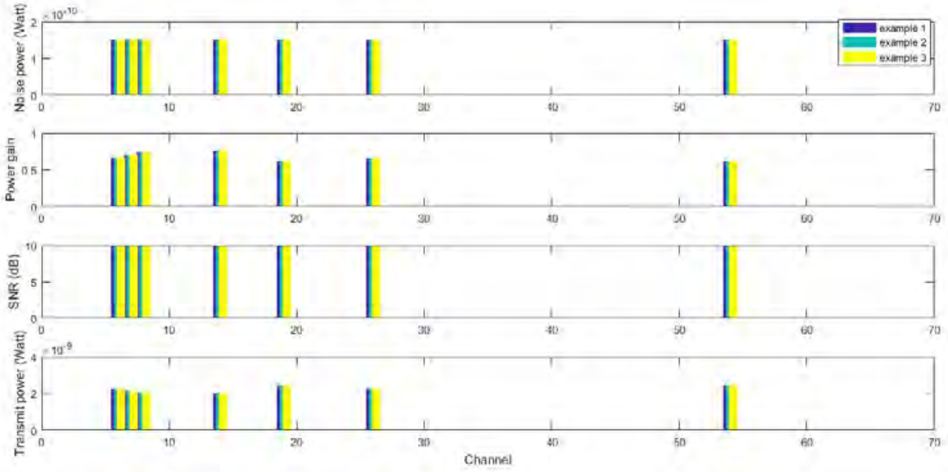


Figure 6.21: Allocation of BS's transmit power and resulting SNR of user 2 for different BS's power budget.

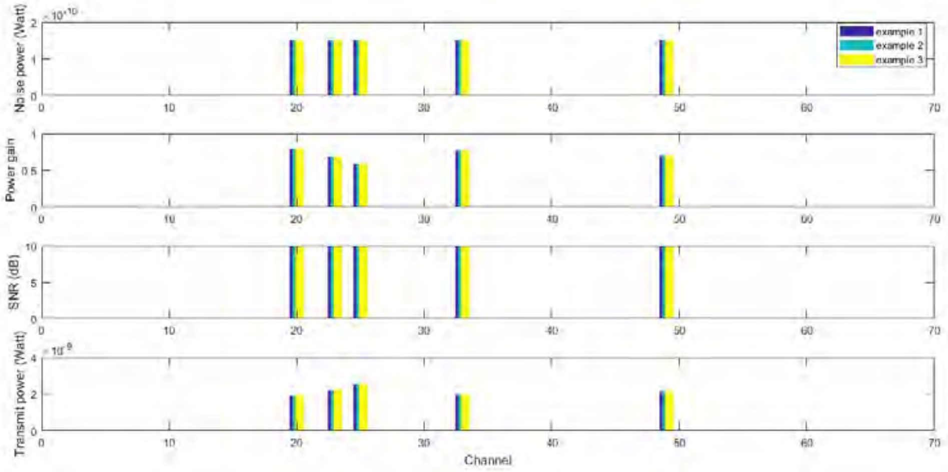


Figure 6.22: Allocation of BS's transmit power and resulting SNR of user 3 for different BS's power budget.

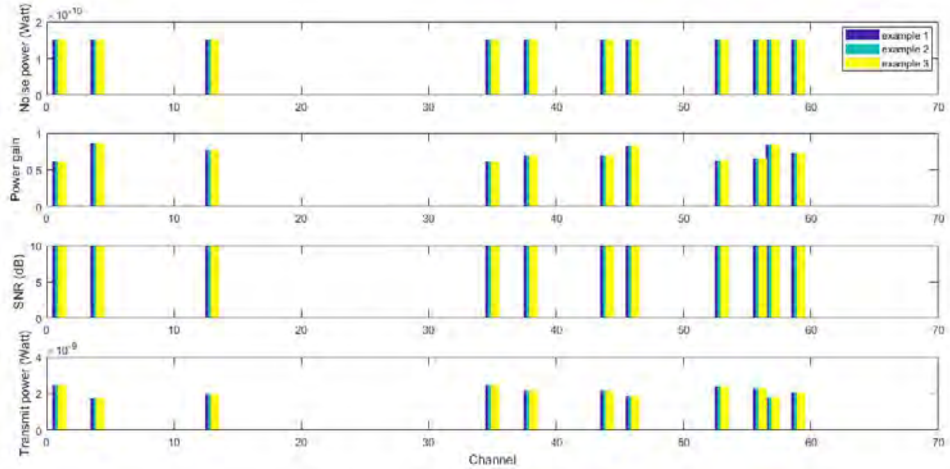


Figure 6.23: Allocation of BS's transmit power and resulting SNR of user 4 for different BS's power budget.

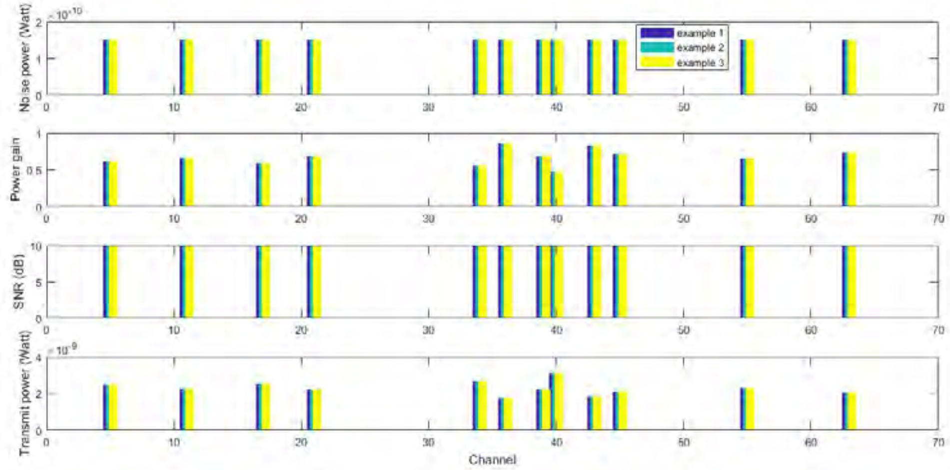


Figure 6.24: Allocation of BS's transmit power and resulting SNR of user 5 for different BS's power budget.

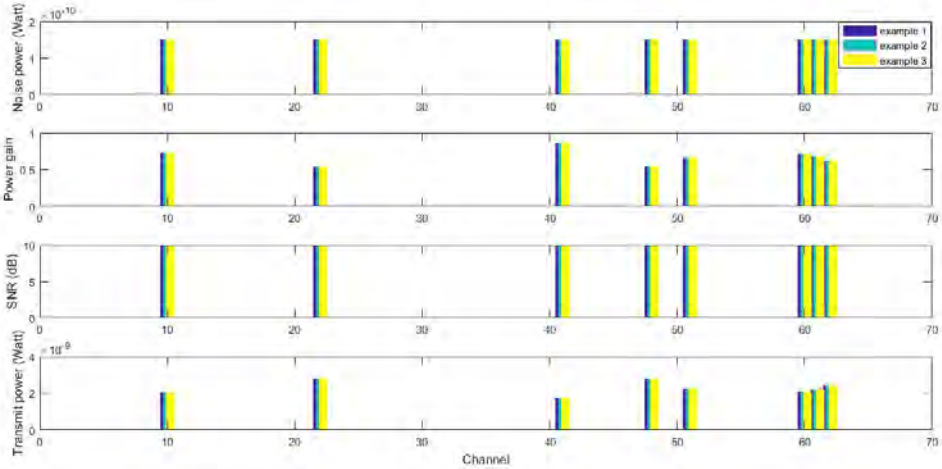


Figure 6.25: Allocation of BS's transmit power and resulting SNR of user 6 for different BS's power budget.

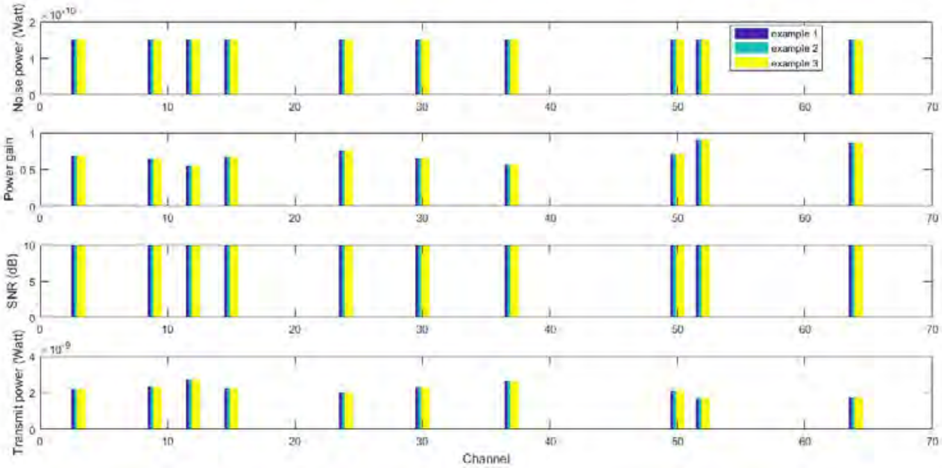


Figure 6.26: Allocation of BS's transmit power and resulting SNR of user 7 for different BS's power budget.

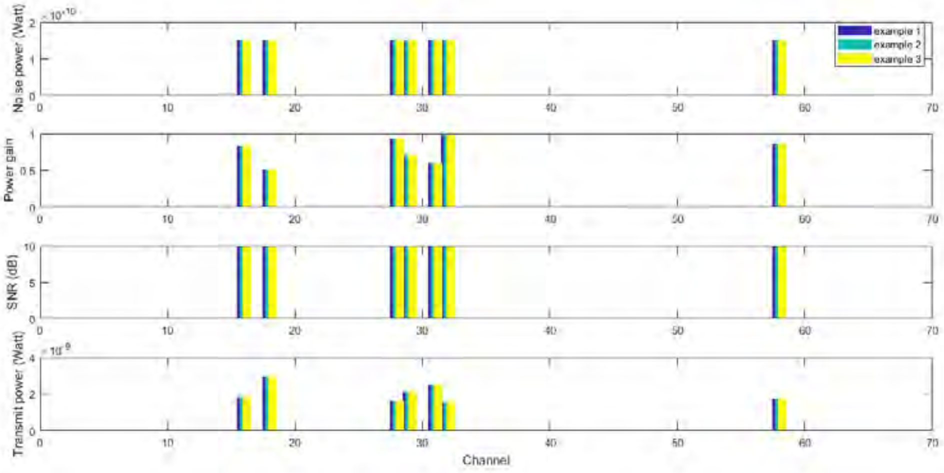


Figure 6.27: Allocation of BS's transmit power and resulting SNR of user 8 for different BS's power budget.

From Fig. 6.28, we see that, BS's transmit power shows no change with the variation of power gain across channel. But observation reveals that, obtained SNR is proportional to power gain of the channels. That means, resulting SNR in a transmission is more when channel power gain is higher and vice versa. Similar pattern on allocation of BS's transmit power and resulting SNR are also observed for rest of the seven users and shown in Figs. 6.29-6.35.

Total allocated transmit power by the BS obtained by proposed framework-II is shown in Fig. 6.36. It is observed that, the total power spent is with in the upper limit of the channels. Moreover, BS's total transmit power for all users across all subchannels is computed to be 8.66×10^{-7} Watt which is smaller than the total power budget at BS. That is, just like framework-I, framework-II also does not spend all of it's power as in existing frameworks based on capacity maximization. Figure 6.36 also shows the total bits/sec/Hz use across users. Minimum rate (bits/sec/Hz) requirement for all the users is also depicted in the same figure. All plots are shown as

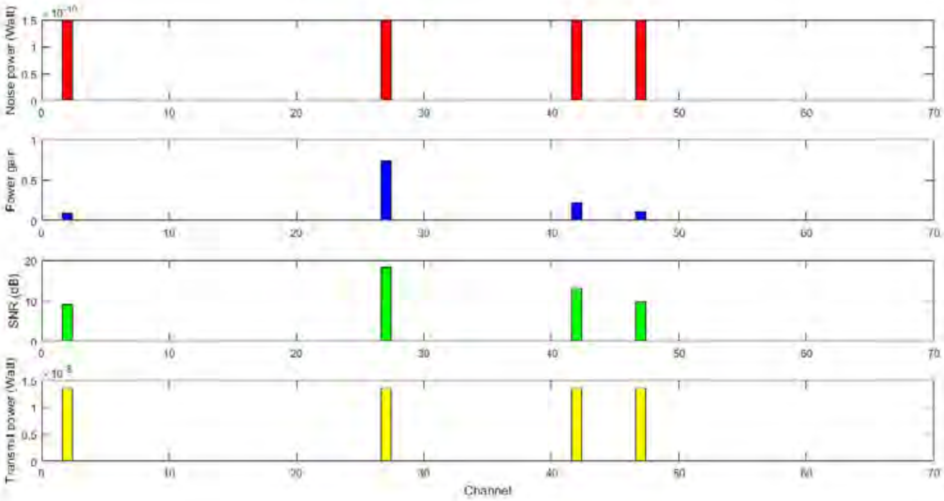


Figure 6.28: Allocation of BS's transmit power and resulting SNR for user 1.

bar plots. From this figure it can be seen that, proposed optimization framework-II is successful in satisfying both the BS's power budget and minimum rate (bits/sec/Hz) use requirement, for all users.

6.3.1 Effect of target BER

Figure 6.37 presents the allocation of BS's total transmit power and achieved rate (bits/sec/Hz) across users for two different BER values ($BER_{l,n}$), which are termed as example 1 and example 2, respectively. Total transmit power upper bound and minimum rate (bits/sec/Hz) requirement for users are also depicted in Fig. 6.37 where, minimum rate requirement is shown as a bar. Here, $BER_{l,n}$ is set to 10^{-3} and we term it as example 1 while, for example 2, $BER_{l,n}$ is set to 10^{-6}. It is to be noted that, smaller BER means better performance. The rest of the system parameters are kept same as in Sec. 6.1.2.

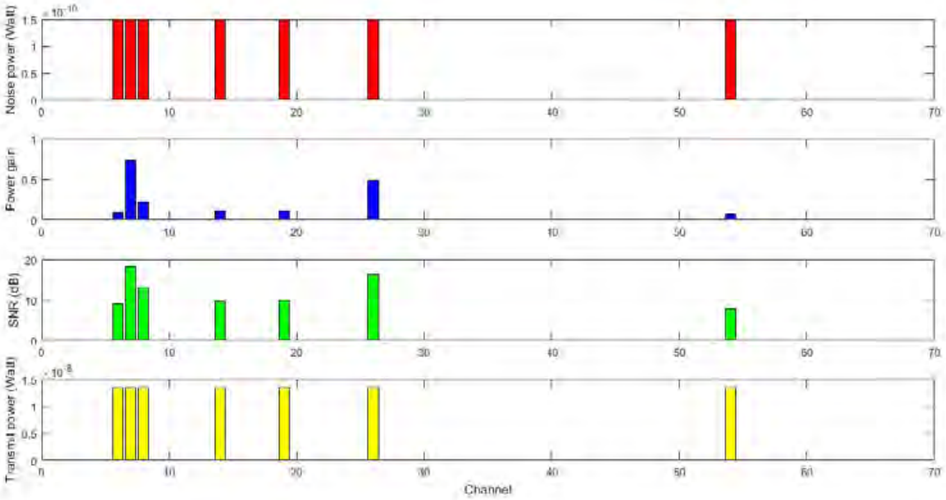


Figure 6.29: Allocation of BS's transmit power and resulting SNR for user 2.

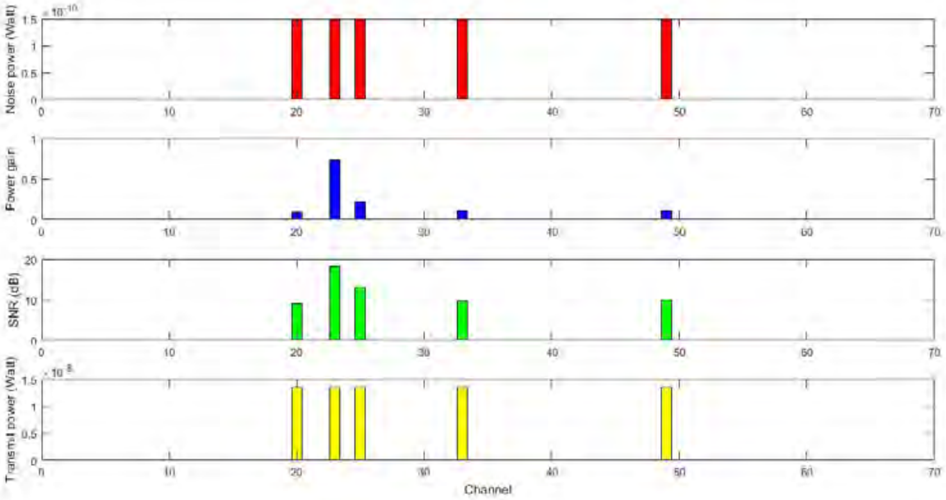


Figure 6.30: Allocation of BS's transmit power and resulting SNR for user 3.

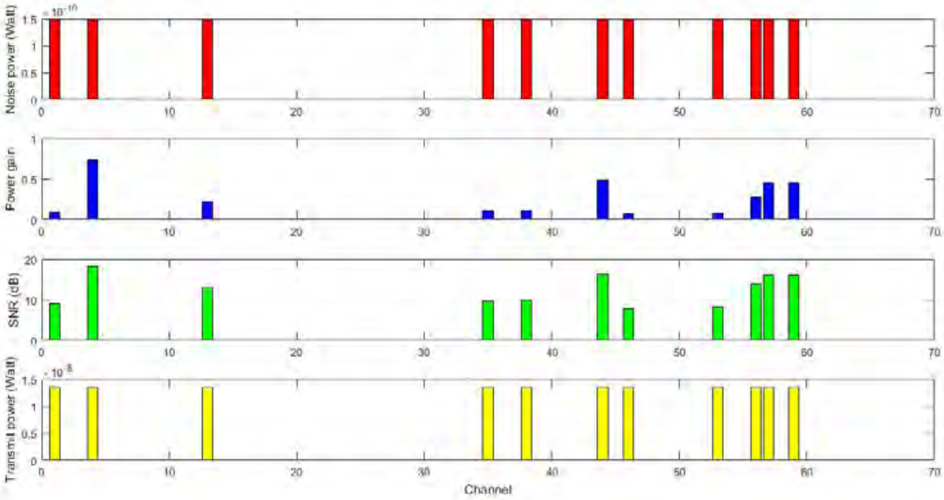


Figure 6.31: Allocation of BS's transmit power and resulting SNR for user 4.

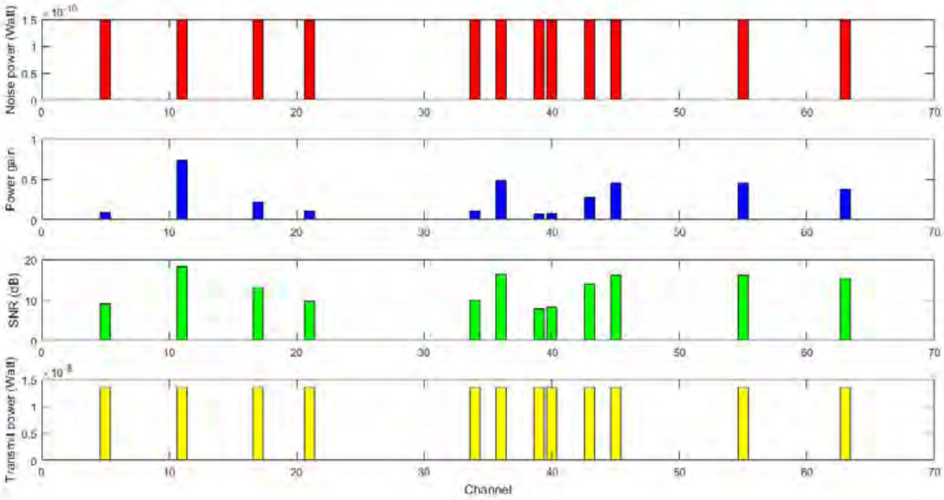


Figure 6.32: Allocation of BS's transmit power and resulting SNR for user 5.

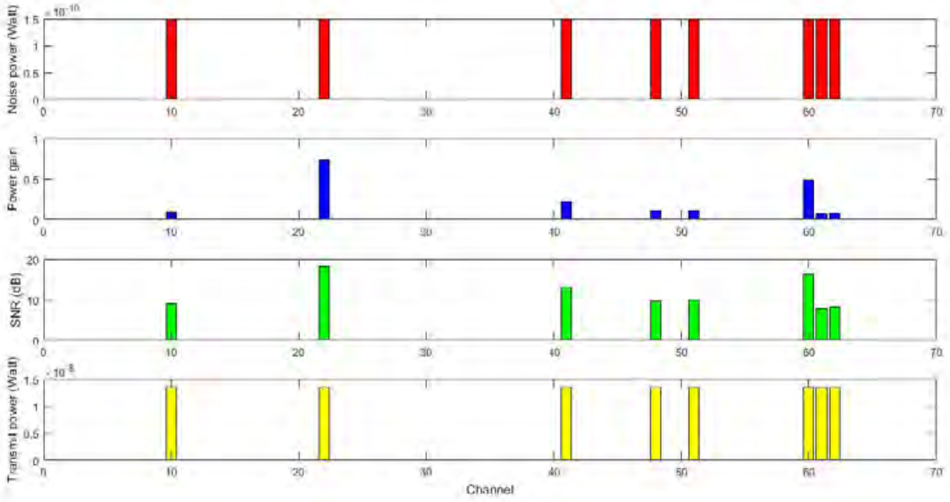


Figure 6.33: Allocation of BS's transmit power and resulting SNR for user 6.

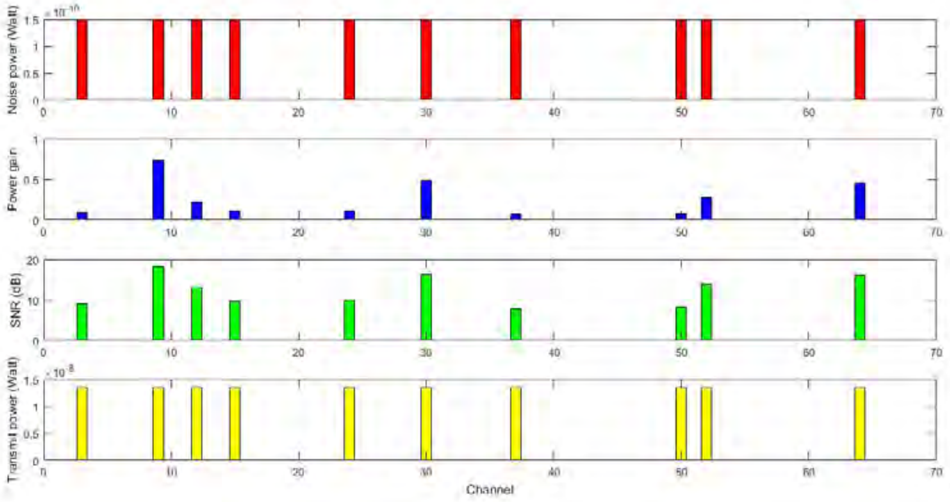


Figure 6.34: Allocation of BS's transmit power and resulting SNR for user 7.

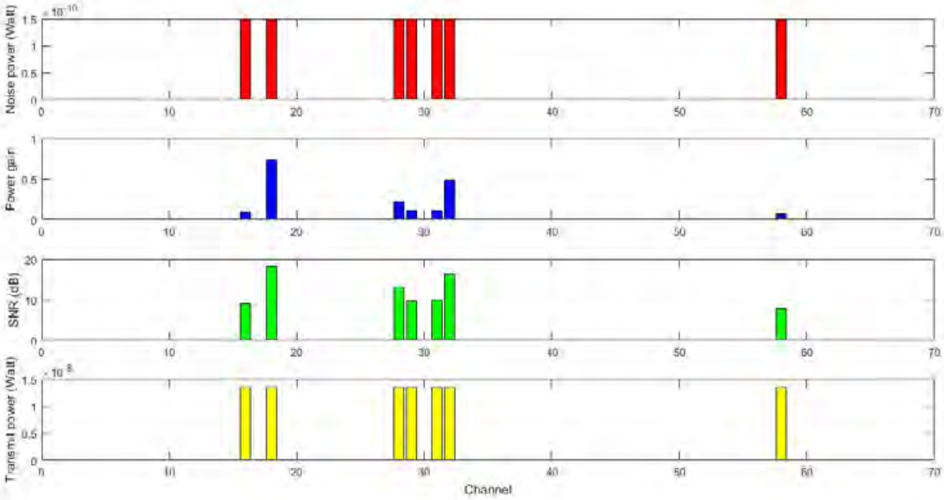


Figure 6.35: Allocation of BS's transmit power and resulting SNR for user 8.

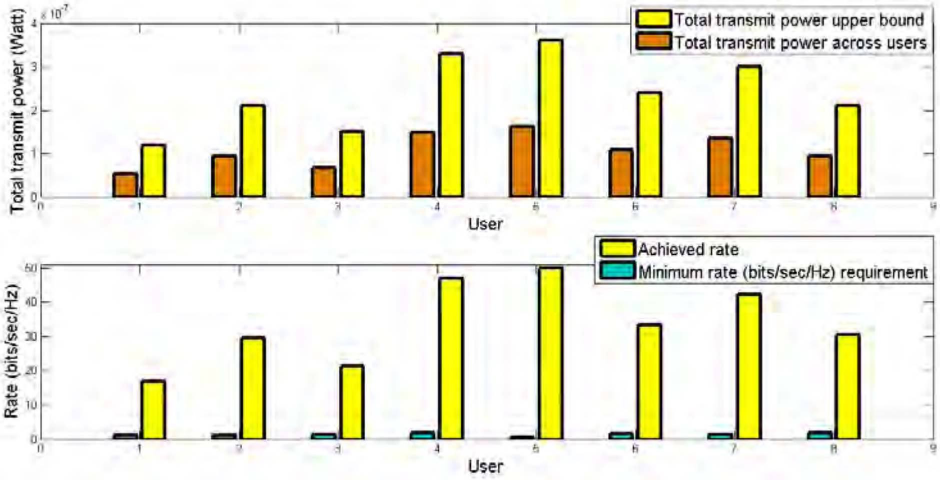


Figure 6.36: Allocation of BS's total transmit power and achieved rate (bits/sec/Hz) across users.

It is observed that, with the variation in target BER, total transmit power allocation by the BS shows no changes. Hence, we see that, target BER does not have any significant impact on the performance of the proposed framework in terms of total transmit power. From the figure it is obvious that, the proposed optimization framework-II is successful in satisfying the total transmit power upper bound of channels in both examples. Moreover, it is also successful in satisfying BS's power budget. Further observation reveals that, with the variation in target BER, achieved rate (bits/sec/Hz) across users shows changes accordingly. That is, achieved rate is more when target BER is higher and vice versa. Although, achieved rate for example 1 is higher compared to example 2, but the proposed optimization framework-II is successful in satisfying the minimum rate requirement for all users in both examples.

The pattern on allocation of BS's transmit power and resulting SNR for example 1 and 2 are also observed for all the eight users and shown in Figs 6.38-6.45. Noise power and power gain of channels for both examples are also shown in the figures. In all three example cases, we see that, BS's transmit power shows no change with the variation of power gain across channel. But observation reveals that, obtained SNR is proportional to power gain of the channels. That means, resulting SNR in a transmission is more when channel power gain is higher and vice versa.

6.3.2 Effect of Users' minimum rate requirement

Now, we observe the impact of users' minimum rate (bits/sec/Hz) requirement on the performance of the proposed optimization framework-II as it is one of the major QoS requirement. Here, we consider minimum rate requirement shown in Table 6.2 as example 1 and the minimum rate requirement of users shown in Table 6.4 as example 2. The rest of the system parameters are kept same as in Sec. 6.1.2 in both examples.

Figure 6.46 shows the allocation of BS's total transmit power and achieved rate

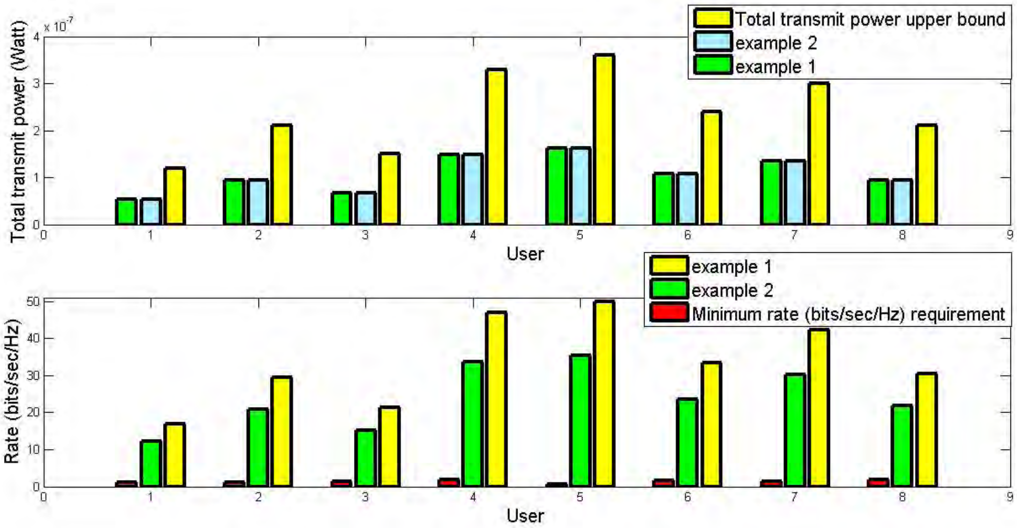


Figure 6.37: Allocation of BS's total transmit power and achieved rate (bits/sec/Hz) across users for different target BER.

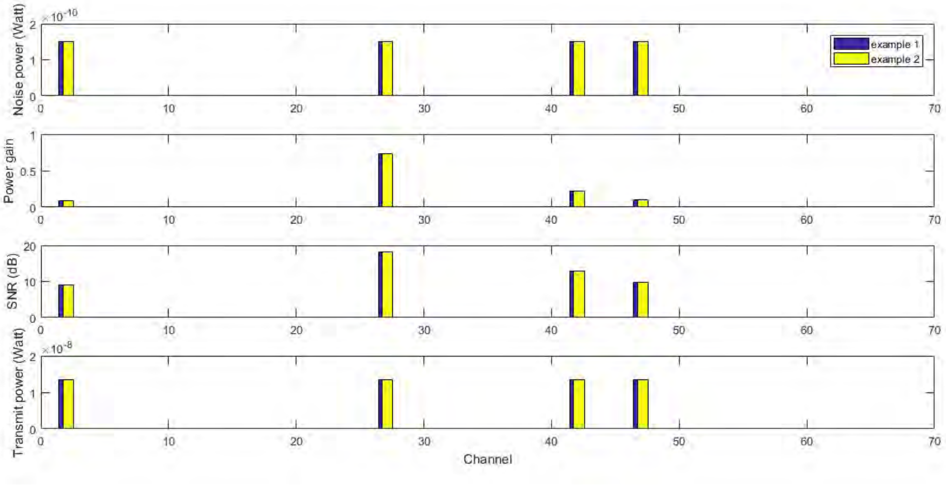


Figure 6.38: Allocation of BS's transmit power and resulting SNR of user 1 for different target BER.

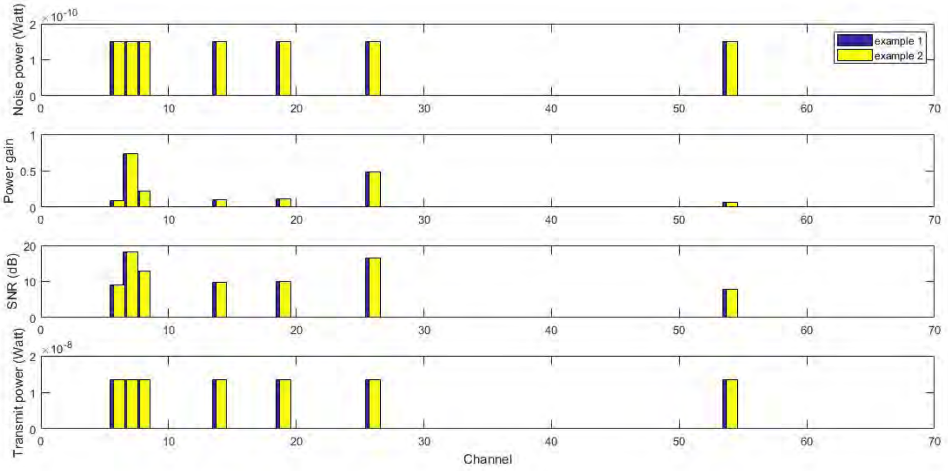


Figure 6.39: Allocation of BS's transmit power and resulting SNR of user 2 for different target BER.

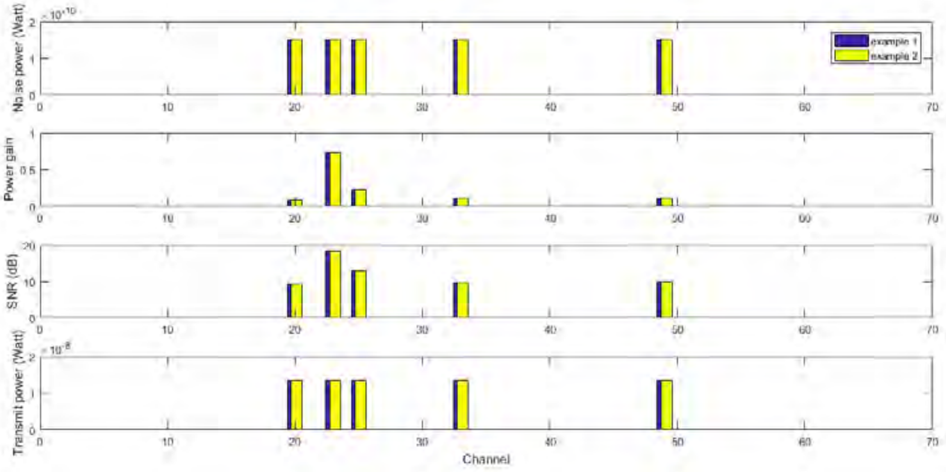


Figure 6.40: Allocation of BS's transmit power and resulting SNR of user 3 for different target BER.

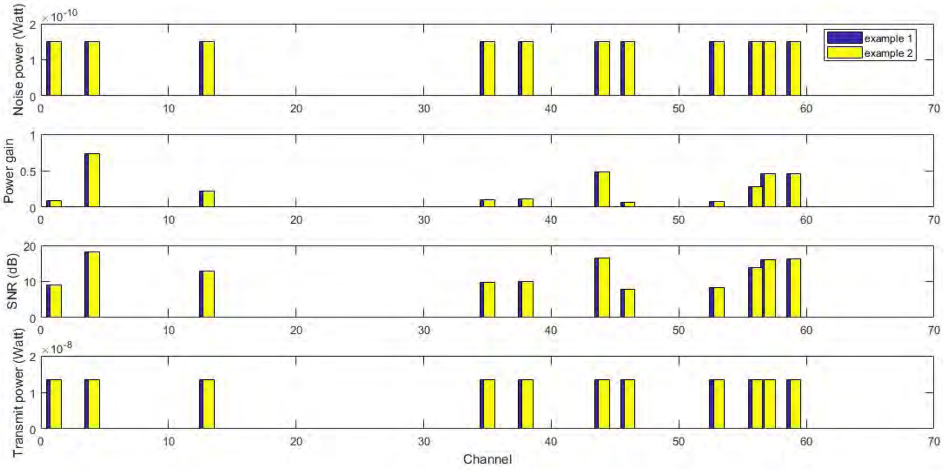


Figure 6.41: Allocation of BS's transmit power and resulting SNR of user 4 for different target BER.

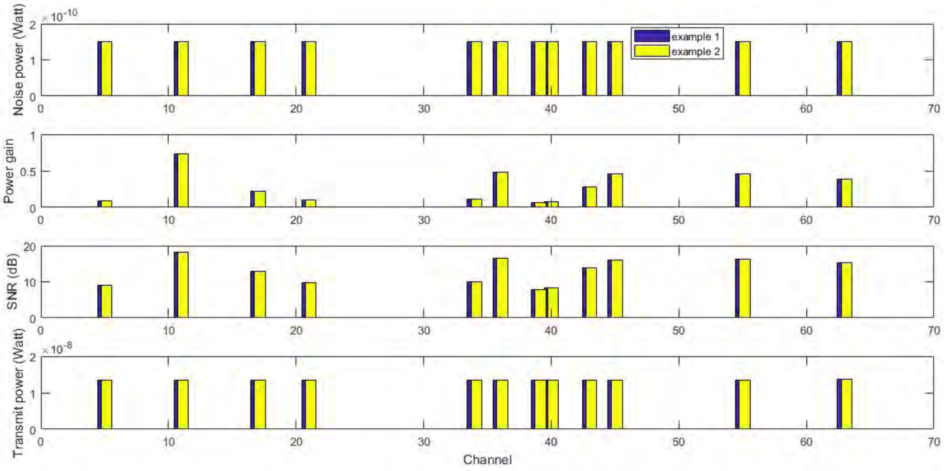


Figure 6.42: Allocation of BS's transmit power and resulting SNR of user 5 for different target BER.

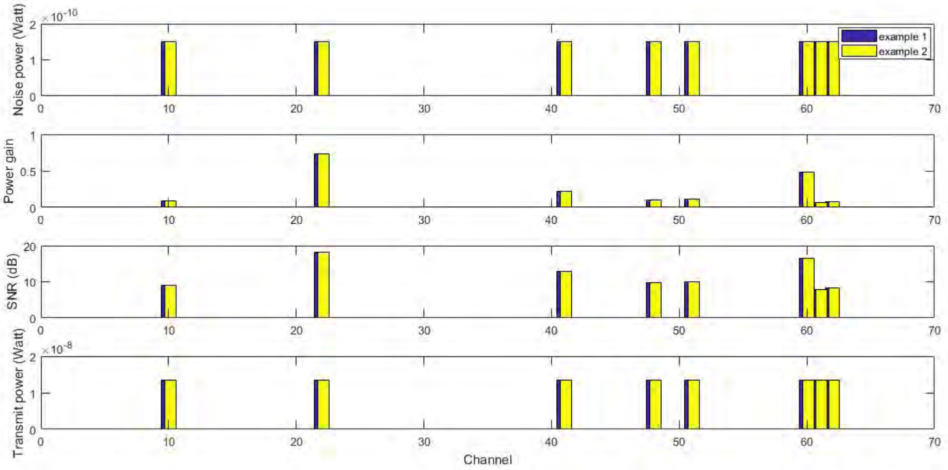


Figure 6.43: Allocation of BS's transmit power and resulting SNR of user 6 for different target BER.

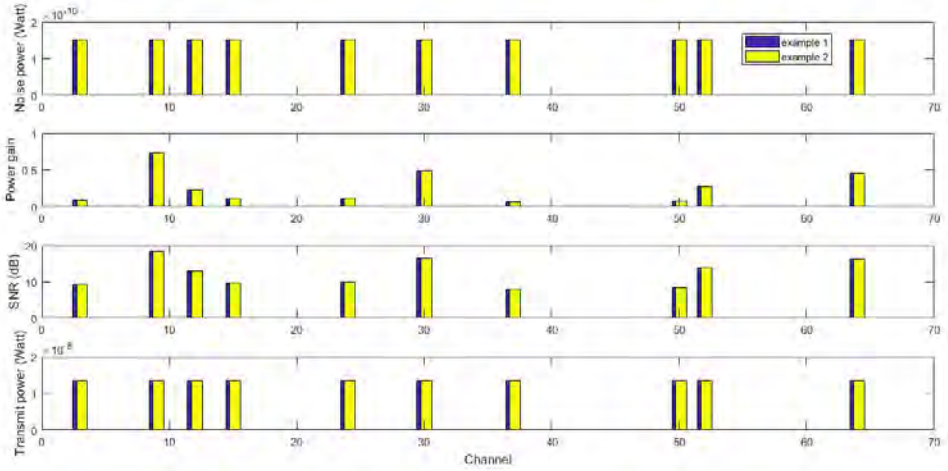


Figure 6.44: Allocation of BS's transmit power and resulting SNR of user 7 for different target BER.

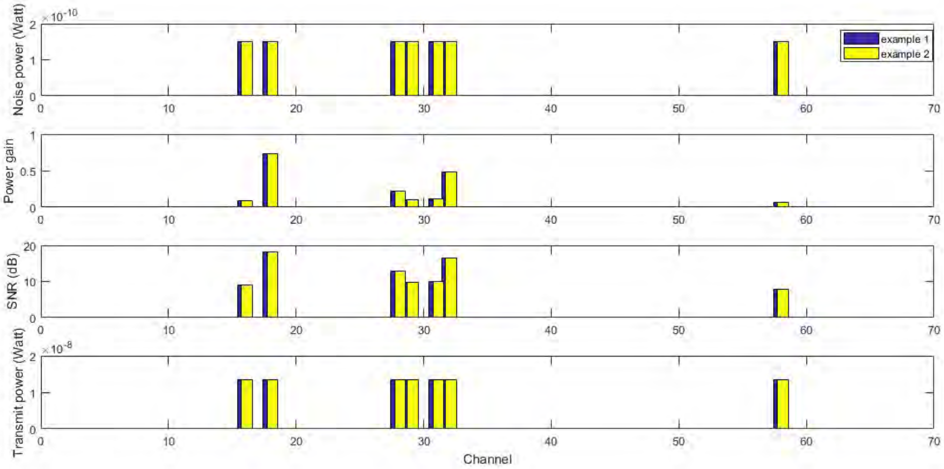


Figure 6.45: Allocation of BS's transmit power and resulting SNR of user 8 for different target BER.

(bits/sec/Hz) across users for examples 1 and 2 in the same plot. Figure 6.46 shows that, BS's total transmit power for both example 2 is higher compared to example 1. Hence, users' minimum rate requirement has significant impact on the performance on the proposed framework in terms of BS's total transmit power. It is observed that, for both the examples, total transmit power allocation is obtained with in the upper limit of channels, hence, proposed framework-II performs successfully with in total transmit power upper bound of users and also power budget of BS. Moreover, BS's total transmit power for all users across all subchannels is computed to be 1.01×10^{-6} Watt which is smaller than the total power budget at BS but higher than the obtained value of example 1. Minimum rate requirement of users for both examples are also depicted in the same figure. From figure 6.46 we see that, with the variation of users' minimum rate requirement, achieved rate shows obvious changes and it increases with the increment in minimum rate requirement. It is also evident that, the proposed optimization framework is successful in satisfying the minimum requirement for all users in every case.

User, l	1	2	3	4	5	6	7	8
R_l^{min}(bits/sec/Hz)	15	16.5	21	27	7.5	25.5	21	28.5

Table 6.4: Minimum rate (bits/sec/Hz) requirement of users for example 2.

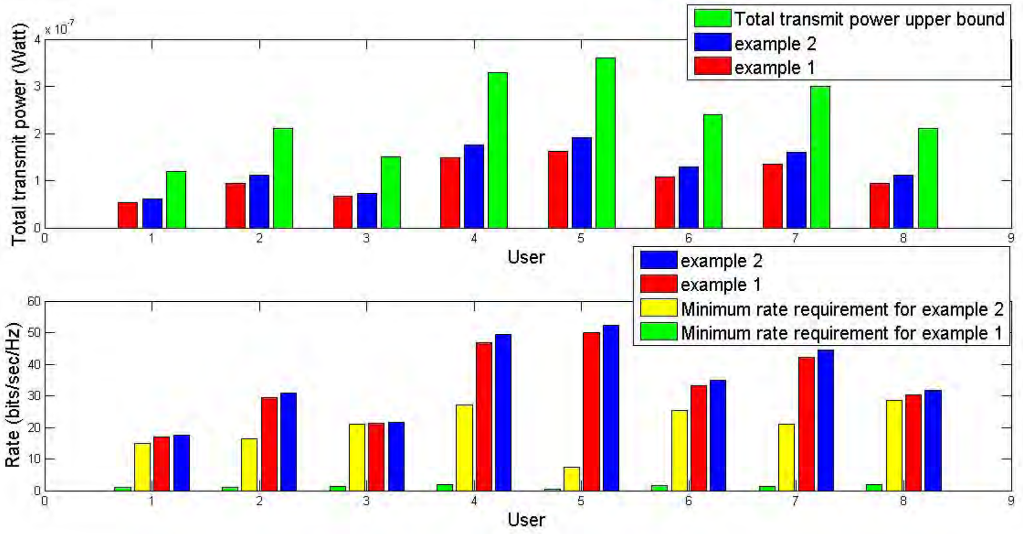


Figure 6.46: Allocation of BS's total transmit power and achieved rate (bits/sec/Hz) across users for different Users' minimum rate requirement.

The pattern on allocation of BS's transmit power and resulting SNR for different users' rate requirement are also observed for all the eight users and shown in Figs 6.47-6.54. These figures also show the power gain and noise power across channels. It is observed that, both resulting SNR and transmit power increases in example 2. Which means, variation in Users' minimum rate requirement shows significant impact on BS's power allocation and resulting SNR.

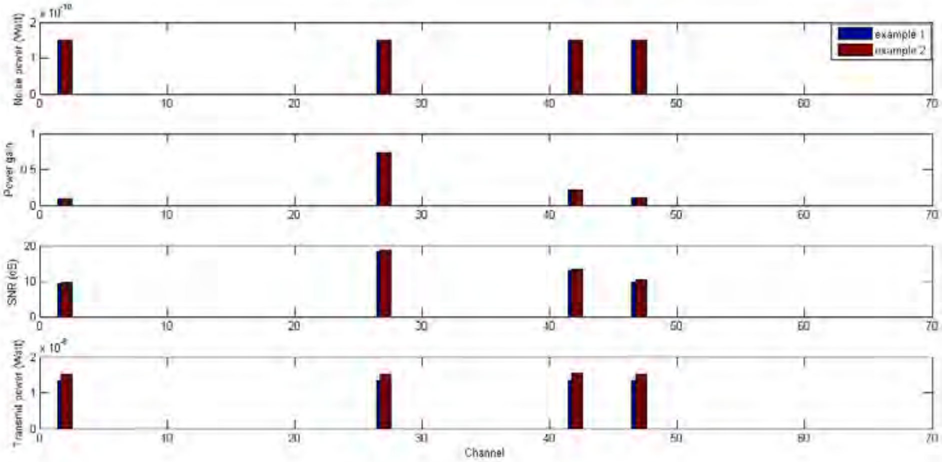


Figure 6.47: Allocation of BS's transmit power and resulting SNR of user 1 for different Users' minimum rate requirement.

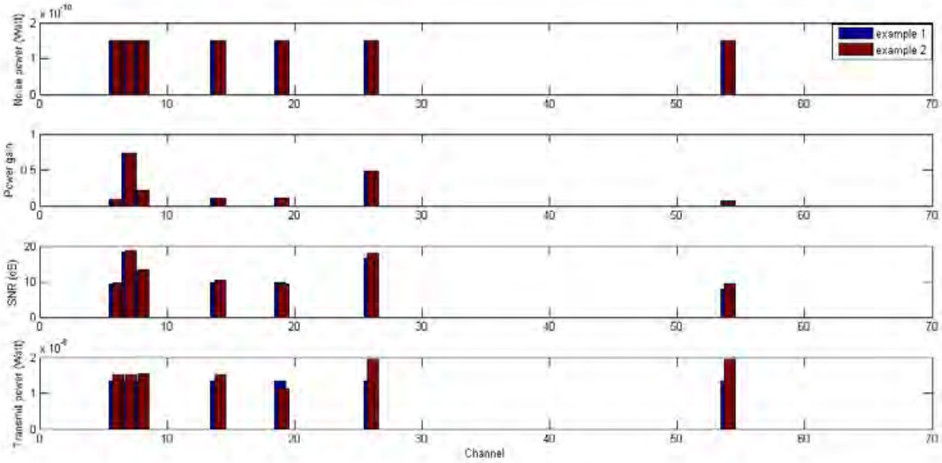


Figure 6.48: Allocation of BS's transmit power and resulting SNR of user 2 for different Users' minimum rate requirement.

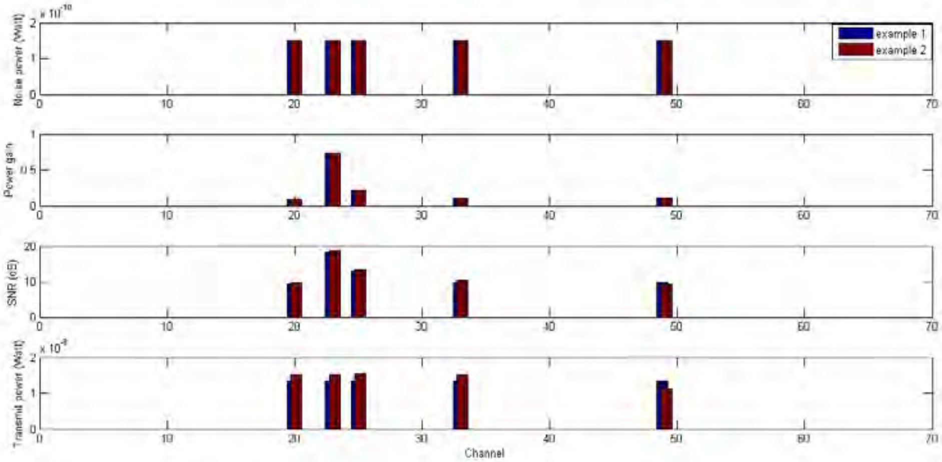


Figure 6.49: Allocation of BS's transmit power and resulting SNR of user 3 for different Users' minimum rate requirement.

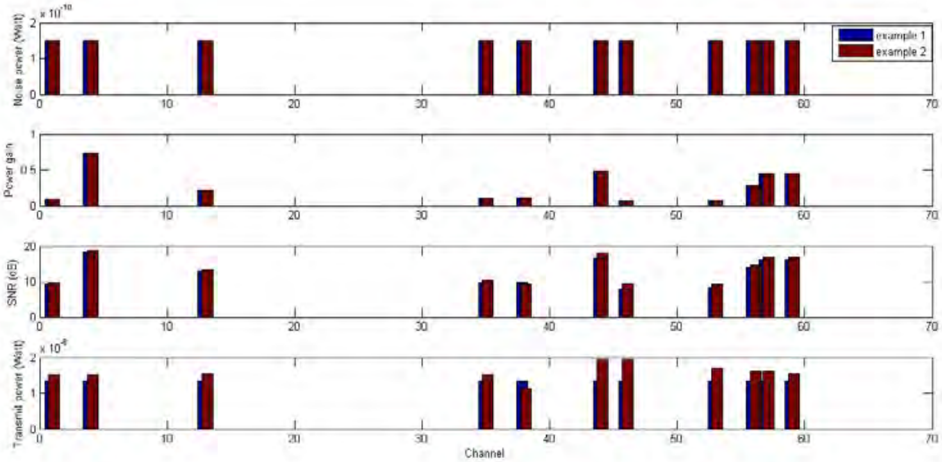


Figure 6.50: Allocation of BS's transmit power and resulting SNR of user 4 for different Users' minimum rate requirement.

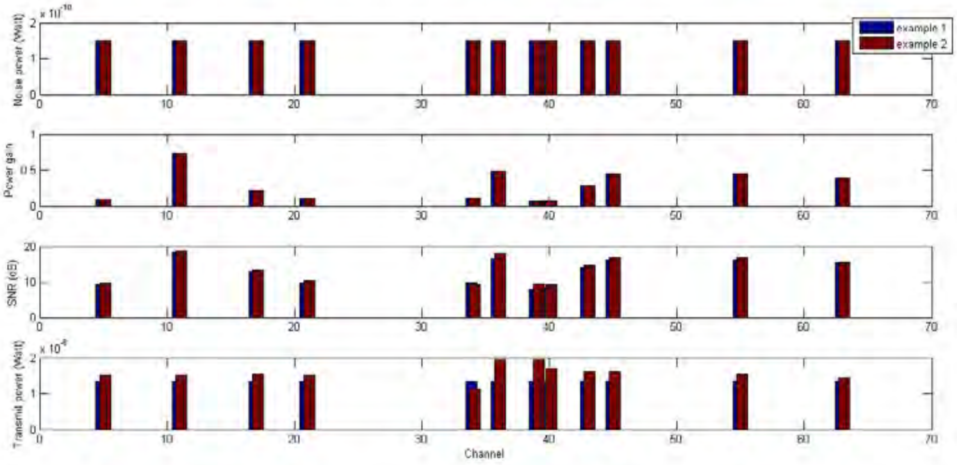


Figure 6.51: Allocation of BS's transmit power and resulting SNR of user 5 for different Users' minimum rate requirement.

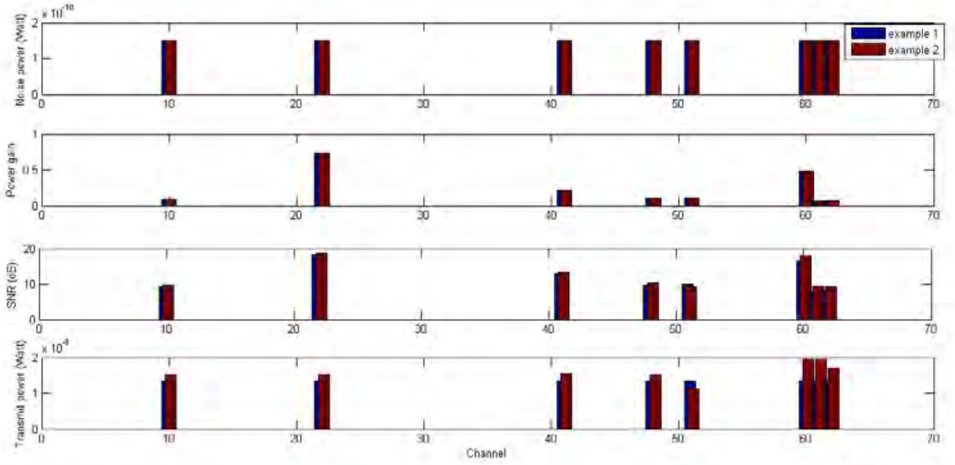


Figure 6.52: Allocation of BS's transmit power and resulting SNR of user 6 for different Users' minimum rate requirement.

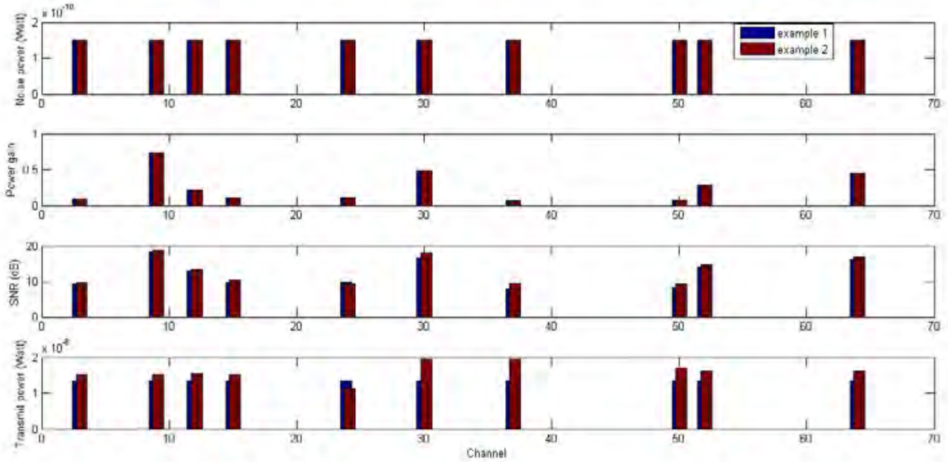


Figure 6.53: Allocation of BS's transmit power and resulting SNR of user 7 for different Users' minimum rate requirement.

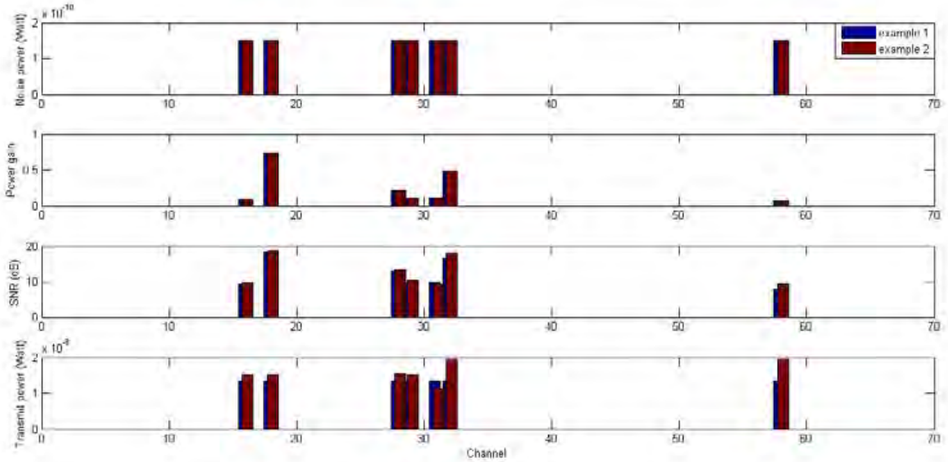


Figure 6.54: Allocation of BS's transmit power and resulting SNR of user 8 for different Users' minimum rate requirement.

6.3.3 Effect of BS's Power Budget

Now, we observe the impact of BS's power budget on the performance of the proposed optimization framework-II. Here, we consider the BS's power budget shown in Table 6.3 as example 1 and for example 2, BS's power budget is considered to be 120 Watt. The rest of the system parameters are kept same as in Sec. 6.1.2 in both examples. Figure 6.55 shows the allocation of total transmit power by the BS and achieved rate (bits/sec/Hz) across users for both example 1 and 2. Figure 6.55 also shows the total transmit power upper bound and minimum rate requirement of users where, all the plots are depicted as a bar. Figure 6.55 shows that, total transmit power for both the examples are identical. The study points that, as long as QoS constraints of the users are invariable, increasing the BS's power budget has no effect on the allocation of transmit power and hence, BS' power budget does not have any significant impact on the performance on the proposed framework-II. It is also observed that, with the increased value of BS' power budget, achieved rate shows no changes.

The pattern on allocation of BS's transmit power and resulting SNR for different BS's power budget are also observed for all the eight users and shown in Figs 6.56-6.63. These figures also show the noise power and power gain across channels. It is observed that, the changes in the figures of example 2 are identical to the changes of example 1. That is, resulting SNR is more in a channel with higher power gain whereas, transmit power remains constant all through the channels.

6.4 Comparison between framework-I and II

In this section, we compare the simulation results of proposed framework-I and II in between for downlink cognitive OFDMA system. For framework-I, we consider the system parameters as described in section 6.1.1. For framework-II system parameters described in section 6.1.2 will be followed.

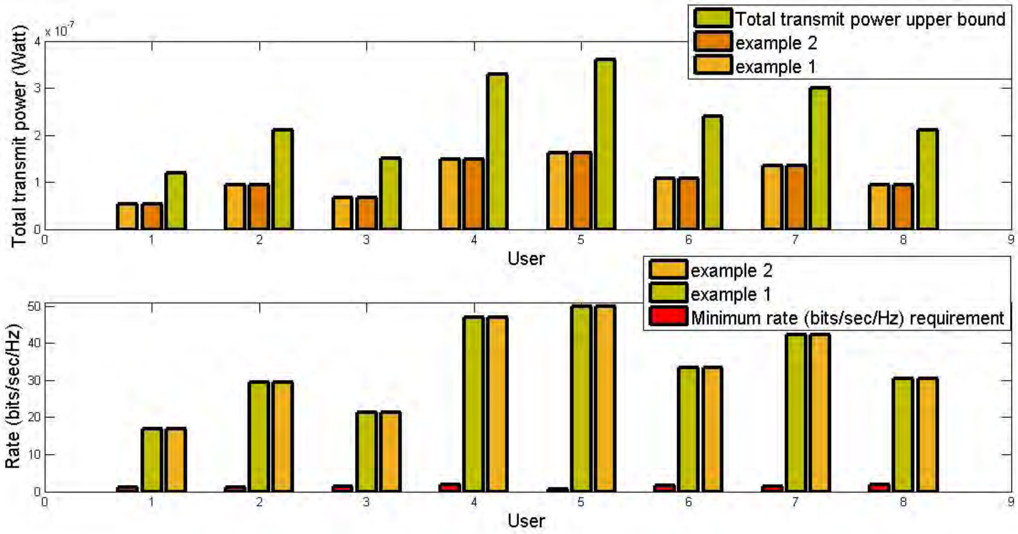


Figure 6.55: Allocation of BS's total transmit power and achieved rate (bits/sec/Hz) across users for different BS's power budget.

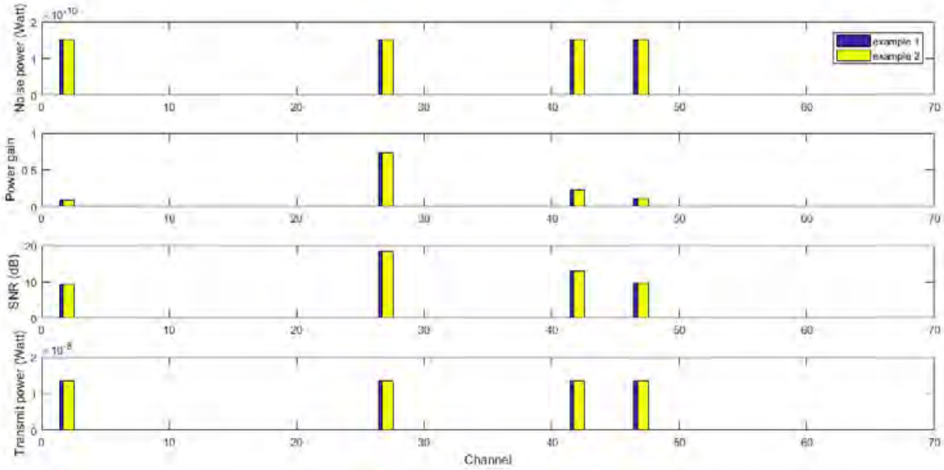


Figure 6.56: Allocation of BS's transmit power and resulting SNR of user 1 for different BS's Power Budget.

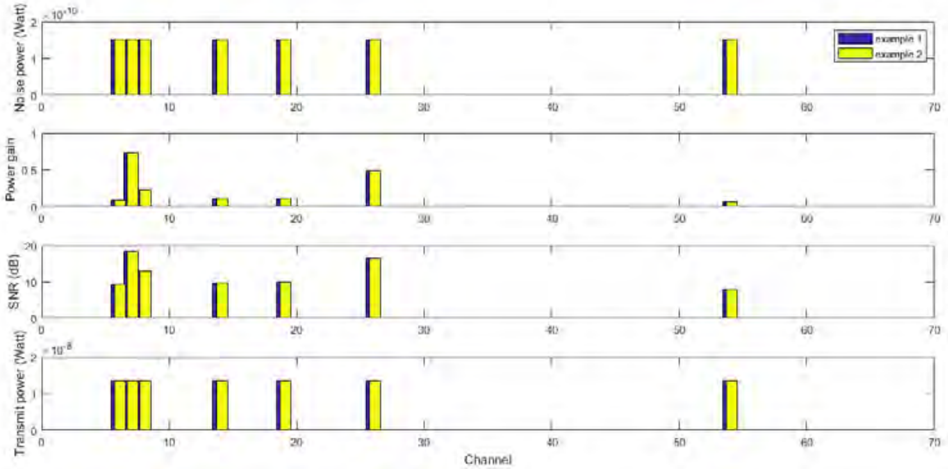


Figure 6.57: Allocation of BS's transmit power and resulting SNR of user 2 for different BS's Power Budget.

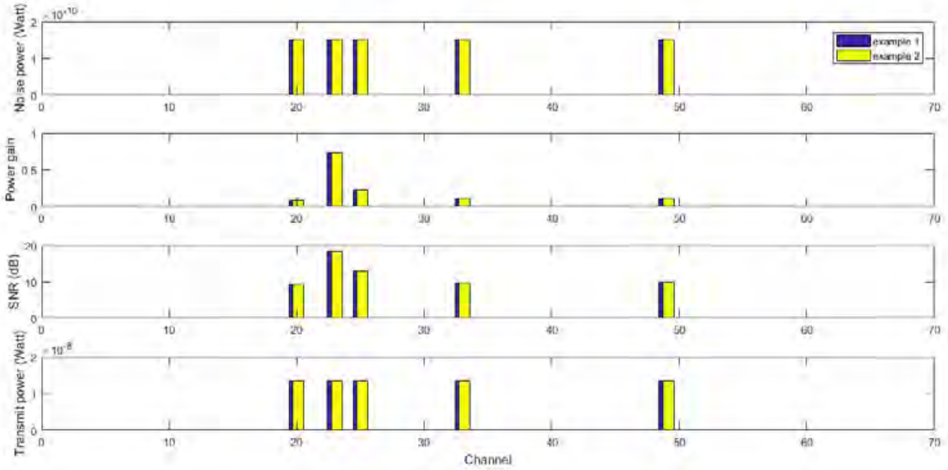


Figure 6.58: Allocation of BS's transmit power and resulting SNR of user 3 for different BS's Power Budget.

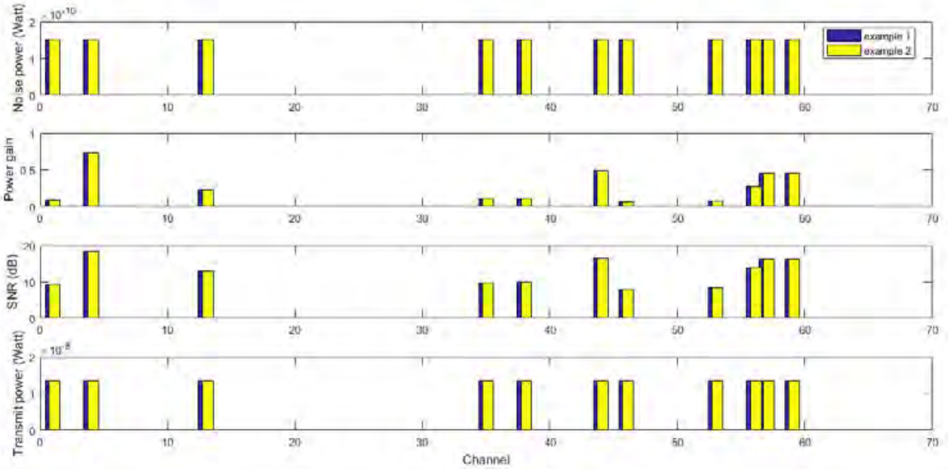


Figure 6.59: Allocation of BS's transmit power and resulting SNR of user 4 for different BS's Power Budget.

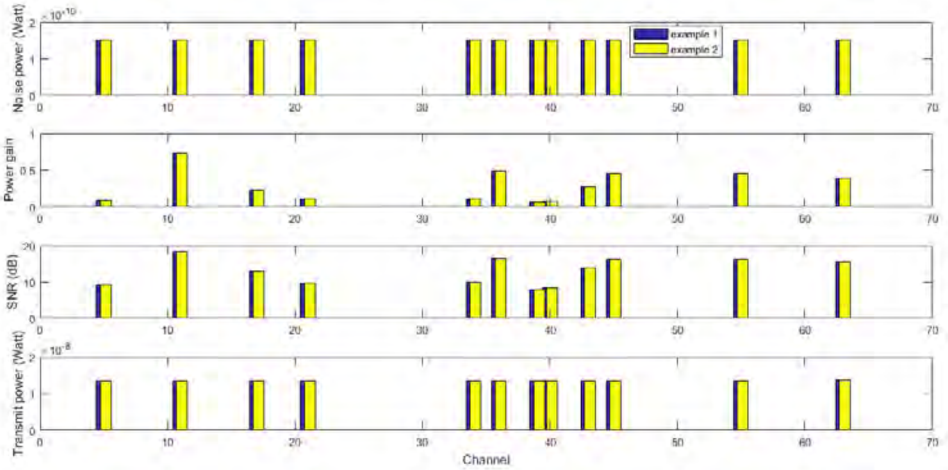


Figure 6.60: Allocation of BS's transmit power and resulting SNR of user 5 for different BS's Power Budget.

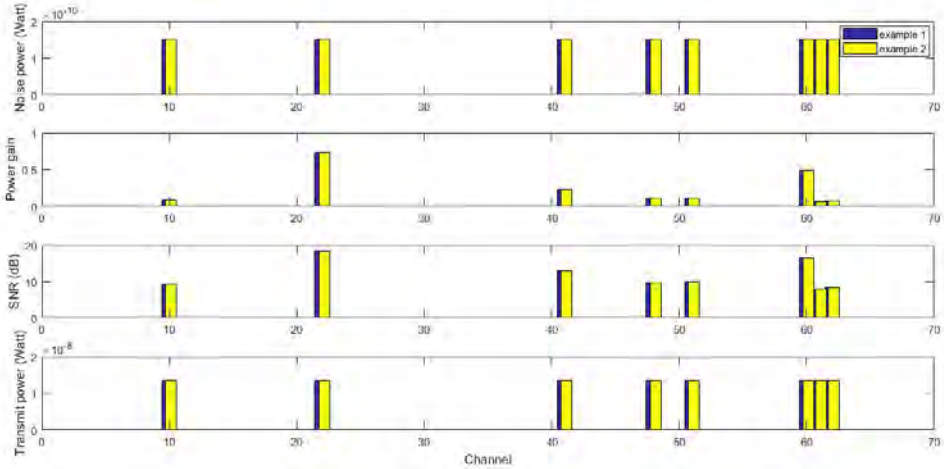


Figure 6.61: Allocation of BS's transmit power and resulting SNR of user 6 for different BS's Power Budget.

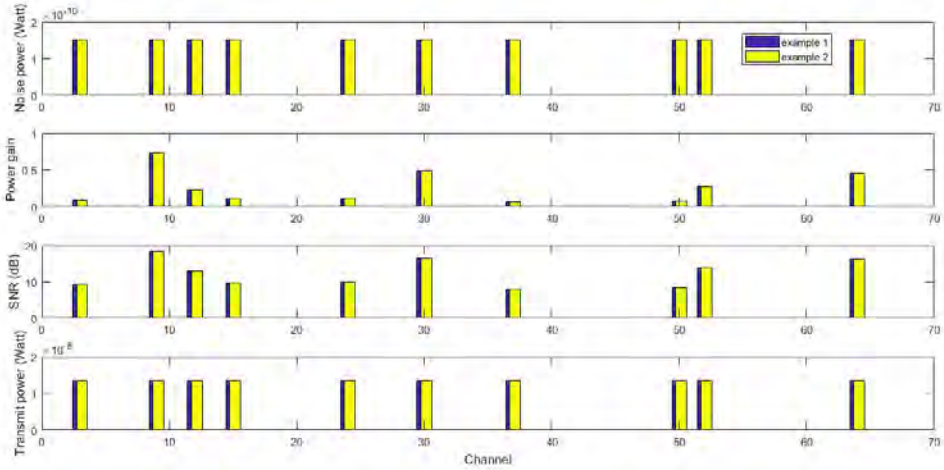


Figure 6.62: Allocation of BS's transmit power and resulting SNR of user 7 for different BS's Power Budget.

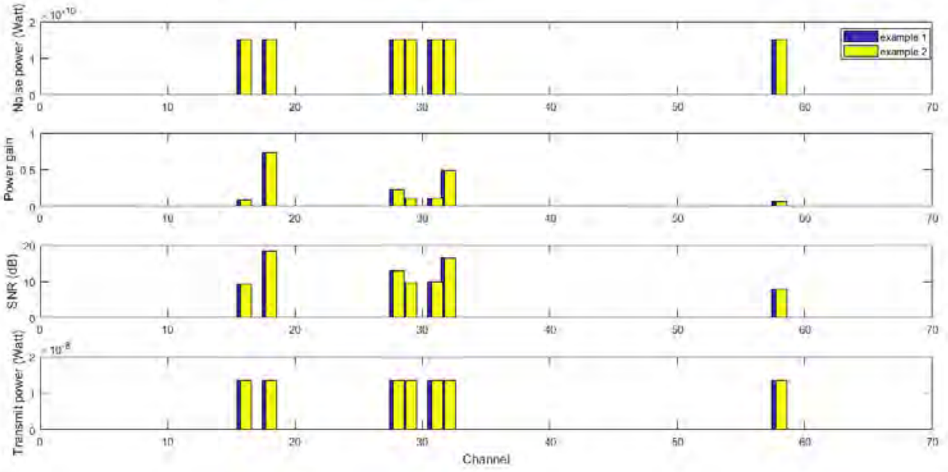


Figure 6.63: Allocation of BS's transmit power and resulting SNR of user 8 for different BS's Power Budget.

First, we observe their performance in terms of the allocation of total transmit power by the BS. Figure 6.64 shows total transmit power for both framework-I and II. It can be said that, framework-II follows higher values compared to framework-I, which is obvious.

Next, we observe their performance in terms of total bits/channel use across users. To do so, BER threshold is set to 10^{-3} and contellation size is set to 1 to 10 for both framework-I and II. For the selected bit allocation optimization algorithm, we assume M-QAM modulation scheme just like uplink cognitive OFDMA system.

Figure 6.64 shows total bits/channel across users for both the frameworks in same plot. Observation reveals that, just like total transmit power by the BS, total bits allocated per channel is higher for framework-2, which is obvious as framework-II needs to satisfy minimum rate requirement of it's users. As in framework-II, users

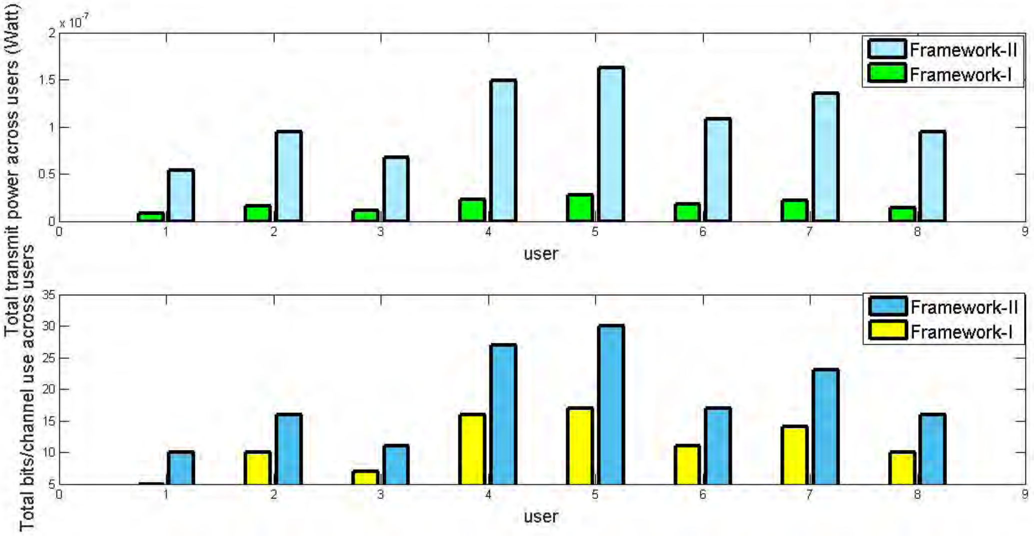


Figure 6.64: Allocation of BS's total transmit power and bits/channel across users.

are allocated a greater quantity of bits per channel, to provide the users with this, BS needs to increase the transmit power too which can be seen from 6.64. We can conclude that, minimum rate requirement threshold to attain a certain BER as a QoS metric is a better choice.

Finally, we compare the performance of the frameworks in terms of spectral efficiency (SE) and energy efficiency (EE). Fig. 6.65 depicts both SE and EE of users for framework-I and II. Observation reveals that, framework-II tends to be more spectral efficient whereas, framework-I presents more energy efficient characteristics.

6.5 Comparison with Resource Allocation Approach Based on Capacity Maximization

In this section, we aim at comparing the obtained solutions of our proposed method for downlink cognitive OFDMA system with the existing resource allocation techniques.

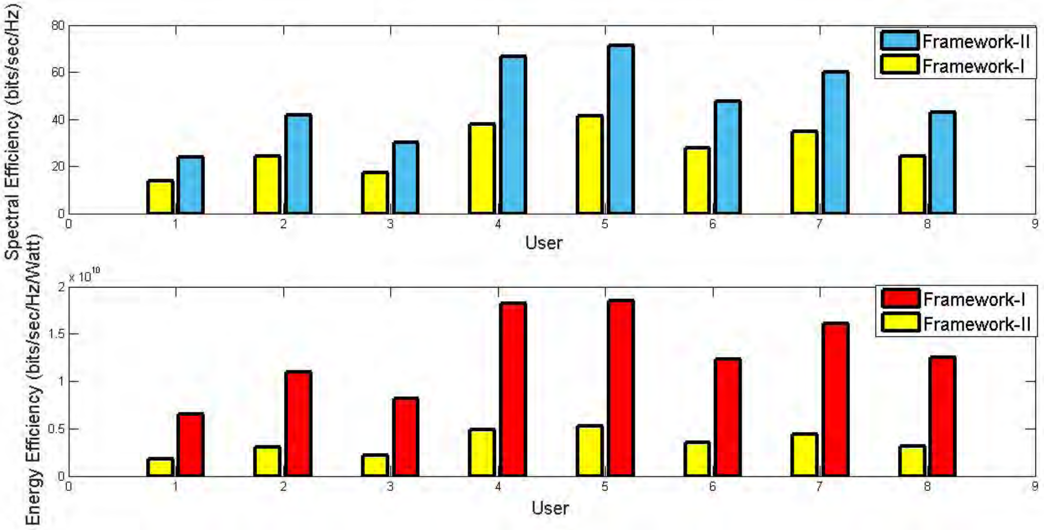


Figure 6.65: Spectral Efficiency and Energy Efficiency versus users.

We observe the outcomes of conventional capacity maximization based resource allocation technique and compare them with the proposed frameworks (framework-I and II) in terms of total transmit power, energy efficiency and spectral efficiency.

Figure 6.66 illustrates that, the allocation of total transmit power by the BS obtained from framework-I and II. Total transmit power obtained form capacity maximization approach is also shown in the same figure. For proposed framework-I and II we see that, BS's total power spent is with in the upper limit of channels and also satisfies BS's power budget. Where as, existing capacity maximization based approach spends all it's power which is very obvious from the figure. Hence, our proposed frameworks are very successful in terms of utilization of power budget.

Next, our field of interest is spectral efficiency of the frameworks. From Fig. 6.67 it is clearly observed that, capacity maximization based approach tends to be more spectral efficient compared to our proposed frameworks. At the same time,

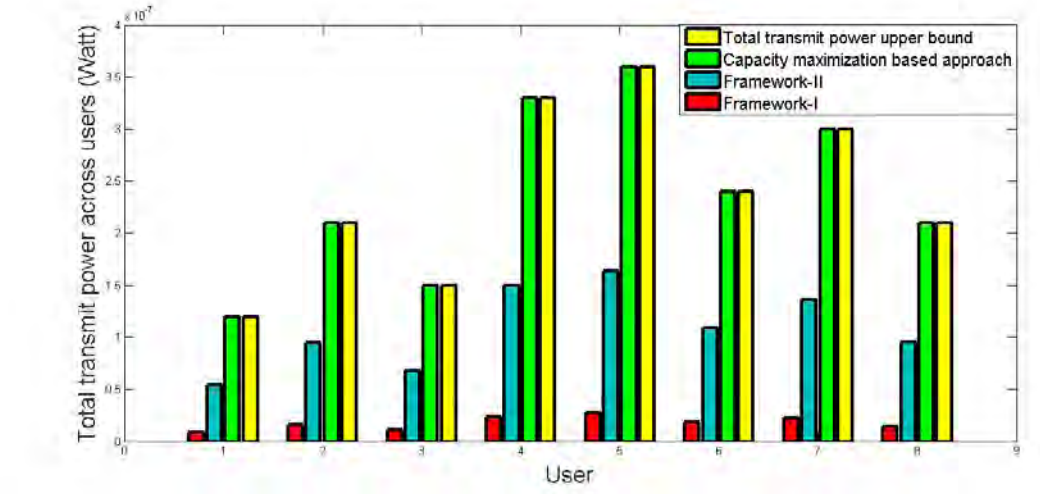


Figure 6.66: Allocation of BS's total transmit power across users.

framework-II presents more spectral efficient characteristics than framework-I. It is obvious due to the minimum rate requirement constraint. Unlike framework-I, users in framework-II needs to satisfy minimum rate requirement of users which results in higher bits/channel use and further increases spectral efficiency.

Finally, we will observe the frameworks in terms of energy efficiency. Fig. 6.68 illustrates energy efficiency of the frameworks in a single plot. It is observed that, our proposed frameworks are more energy efficient compared to the capacity maximization based approach. Which is obvious due to less power consuming characteristics of the frameworks. Hence, our proposed frameworks of specific QoS constrained resource allocation are very much successful in terms of satisfying BS's power budget and energy Efficiency compared to conventional capacity maximization based approaches.

6.6 Summary

In this chapter, the proposed optimization frameworks are solved and results are analyzed for downlink cognitive OFDMA system.

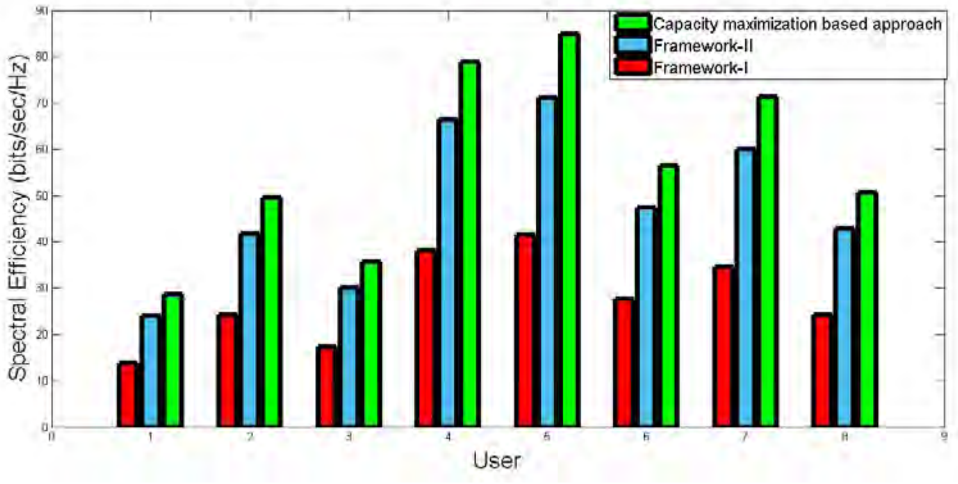


Figure 6.67: Spectral Efficiency versus users.

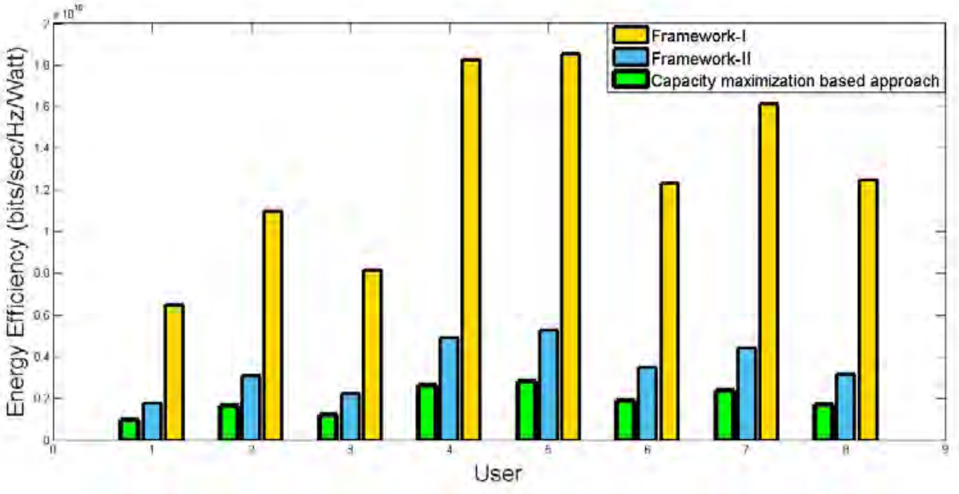


Figure 6.68: Energy Efficiency versus users.

Just like uplink cognitive OFDMA system, here simulation results of proposed framework-I illustrate that, more transmit power is required in a channel with smaller power gain. Same SNR is obtained across channels which is equal to SNR threshold. Higher SNR threshold results in higher total transmit power by the BS and vice versa. It is seen that, BS' power budget has no significant impact on the allocation of transmit power once the optimal transmit power is obtained. In all the cases, proposed framework-I operates successfully with in the BS's power budget.

Framework-II shows that, the variation in allocation of BS's transmit power remains almost similar with the change in power gain of the channel whereas, unequal SNR is obtained across channels. Higher SNR is obtained in a channel with higher power gain. It is seen that, different BS' power budget and target BER of users have no significant impact on the allocation of total transmit power once the optimal transmit power is obtained. However, higher value of target BER and users' minimum rate (bits/sec/Hz) requirement has resulted in higher achieved rate (bits/sec/Hz).

Comparison between the two frameworks and existing capacity maximization based resource allocation framework clearly reveals that, framework-II uses higher values of BS's total transmit power and provides higher total bits/channel allocation than framework-I. Moreover, both the frameworks work with in the power budget of the BS. That is, both of them do not spend all of their power as in existing frameworks based on capacity maximization. Observation reveals that, Framework-II is more spectral efficient than framework-I whereas, framework-I is more energy efficient than framework-II. Both the frameworks are more energy efficient compared to conventional capacity maximization based approaches.

We can conclude that, downlink cognitive OFDMA system shows no significant changes from uplink cognitive OFDMA system. Successful satisfaction of BS's power budget through both the frameworks is also marked here. Achieved rate is also observably satisfying the constrained minimum rate requirement of framework-II.

Finally, comparison with conventional capacity maximization based resource allocation approach reveals that, both of the proposed frameworks are very much successful in terms of utilization of power budget of users and Energy Efficiency compared to conventional capacity maximization based resource allocation approaches.

Chapter 7

Conclusion and scope for the future works

7.1 Conclusion

In this thesis, we have considered a cognitive OFDMA system. Two optimization frameworks namely framework-I and II are developed for such system. Our target is to find QoS constrained optimal allocation of transmit power with a goal of minimizing total transmit power. It is known that, CR is considered to enhance spectrum utilization efciency by dynamically sharing the spectrum between licensed/ primary users (PUs) and unlicensed/secondary users (SUs). This is achieved by permitting SUs opportunistic access to the white spaces within PUs spectrum while controlling the interference to PUs. In cognitive OFDMA system, multiple secondary users compete for multiple subchannels/subcarriers. It is assumed that, subchannel allocation to each of the users is already decided.

At first, we have stated the frameworks for uplink cognitive OFDMA system. For such system, as a measure of QoS, framework-I is constrained by SNR threshold. Whereas, framework-II is constrained by minimum rate (bits/sec/Hz) requirement of users to obtain a certain BER. In such an environment, our proposed optimization frameworks intend to determine the optimal allocation of transmit power of SUs.

The objective for both the optimization frameworks is to minimize the total transmit power while satisfying the specific QoS requirements for all SUs. For both the frameworks, we have considered Interference Temperature threshold imposed to protect the PU transmission. Simple path loss model is also a major consideration. However, the problem is also constrained by total transmit power upper bound of users.

Next, we have solved the proposed optimization framework-I and II for uplink cognitive OFDMA system. From the simulation results of framework-I, it is seen that, more transmit power is required in a channel with less power gain and vice versa. It can be said that, following the objective function, framework-I allocates transmit power just to attain SNR threshold. Higher SNR threshold results in higher total transmit power across users and vice versa. It is seen that, users power budget has no significant impact on the allocation of transmit power once the optimal transmit power is obtained. In all the cases, proposed framework-I operates successfully with in the total transmit power upper bound of users. However, in framework-II resulting SNR is more in a channel having higher power gain and vice versa. It is observed that, framework-II is always successful in satisfying minimum rate requirement (bits/sec/Hz) of users. It is seen that, different users power budget and target BER of users have no significant impact on the allocation of total transmit power once the optimal transmit power is obtained. Moreover, higher value of target BER and users minimum rate requirement has resulted in higher achieved rate (bits/sec/Hz). It is to be added that, total transmit power is more when minimum rate requirement of users is higher. Further observation reveals that, framework-II allocates more transmit power and bits/channel use compared to framework-I as it needs to satisfy minimum rate requirement of users. So, it can be said that, minimum rate requirement threshold to attain a certain BER as a QoS metric is a better choice. Framework-I is more energy efficient whereas, framework-II is more spectral efficient. It is also seen that, our proposed frameworks are more energy efficient compared to other existing capacity maximization based resource allocation frameworks and none of them spends all their power as in the existing framework. Thus the proposed frameworks achieve wider solution space than other existing capacity maximization based framework in terms of both utilization of power budget and energy efficiency.

Later, we have also considered a downlink cognitive OFDMA system. Framework-I is constrained by SNR threshold as a measure of QOS whereas, framework-II is constrained by minimum rate (bits/sec/Hz) requirement of users. Here, both the frameworks are also constrained by BS's power budget. Similar results are also observed in downlink cognitive OFDMA system. For downlink cognitive OFDMA system it is significantly observed that, successful satisfaction of BS's power budget is ensured by both the frameworks. Framework-II is always successful in satisfying minimum rate (bits/sec/Hz) requirement of users. Simulation results of proposed framework-I illustrate that, more BS's transmit power is required in a channel with smaller power gain. Same SNR is obtained across channels which is equal to SNR threshold. Higher SNR threshold results in higher BS's total transmit power and vice versa. It is seen that, BS's power budget has no significant impact on the allocation of BS's transmit power once the optimal transmit power is obtained. In all the cases, proposed framework-I operates successfully with in the total transmit power upper limit of channels and BS's power budget. Framework-II shows that, the variation in allocation of BS's transmit power remains almost similar with the change in power gain of the channel whereas, unequal SNR is obtained across channels. Higher SNR is obtained in a channel with higher power gain. It is seen that, different BS's power budget and target BER of users have no significant impact on the allocation of total transmit power once the optimal transmit power is obtained. However, higher value of target BER and minimum rate requirement have resulted in higher rate (bits/sec/Hz). Comparison between the two frameworks and existing capacity maximization based resource allocation framework clearly reveals that, framework-II uses higher values of BS's total transmit power than framework-I. Moreover, both the frameworks work with in the total transmit power upper bound. That is, both of them do not spend all of their power as in existing frameworks based on capacity maximization. Observation reveals that, Framework-II is more spectral efficient than framework-I whereas, framework-I is more energy efficient than framework-II. Both the frameworks are more energy efficient compared to conventional capacity maximization based approaches. It can be concluded that, successful satisfaction of the BS's power budget through both the frameworks is marked. Achieved rate is observably satisfying the constrained minimum rate requirement of framework-II. Finally, comparison with conventional capacity maximization based resource allocation approach reveals that, both of the proposed frameworks are very much successful in terms of utilization of power budget of BS and energy efficiency compared to conventional capacity maximization based resource allocation approaches.

7.2 Scope for the Future Work

Some possible future extensions of this existing work have been listed below:

1. In our thesis, we have considered SNR threshold constraint as a measure of QoS in framework-I, whereas, framework-II is constrained by minimum rate (bits/sec/Hz) to attain a certain BER. It would be very much interesting to convert our proposed frameworks into some new formulation which is hybrid in nature and to observe the effect of it in the obtained results. That means, a hybrid/joint framework which is constrained by both of the QoS requirements can be a potential scope for future research.

2. This thesis considers simple path loss model. Hence, it might be a great choice to formulate some new optimization problem under different channel uncertainties considering channel estimation errors along with SU spectrum sensing error both for uplink and downlink cognitive OFDMA system. For example,

an optimal power loading algorithm to optimize the energy efficiency (EE) of OFDMA based cognitive radio systems under different channel uncertainties can be considered. It can be achieved by limiting the co-channel interference (CCI) and adjacent channel interference (ACI) to specific PUs' receivers below certain thresholds with a predefined probability, and by ensuring the SUs' QoS in terms of a minimum supported rate. Imperfect channel state information (CSI) on the links between the SU transmitter and receiver pairs can also be considered. Since the interference constraints would meet statistically in our consideration, the SU transmitter does not require perfect CSI feedback from the PUs receivers and hence, the effect of limited sensing capabilities of the SU can be considered additionally.

3. We have considered a single parameter (transmit power) based resource allocation scheme for cognitive OFDMA system in our research work. Resource allocation schemes for both uplink and downlink cognitive OFDMA systems can be studied differently considering more than one parameter such as, channel and transmit power based, transmit power and modulation order based or minimum required rate and specified power budget for the secondary user (SU) based while restricting the interference to primary users (PUs) in a statistical manner.

Bibliography

[1] R. W. Brodersen, A. Wolisz, D. Cabric, S. M. Mishra, and D. Willkomm, "Corvus: a cognitive radio approach for usage of virtual unlicensed spectrum," *Berkeley Wireless Research Center (BWRC) White paper*, 2004.

[2] D. Čabrić, S. M. Mishra, D. Willkomm, R. Brodersen, and A. Wolisz, "A cognitive radio approach for usage of virtual unlicensed spectrum," in *Proc. of 14th IST mobile wireless communications summit*, pp. 1–4, 2005.

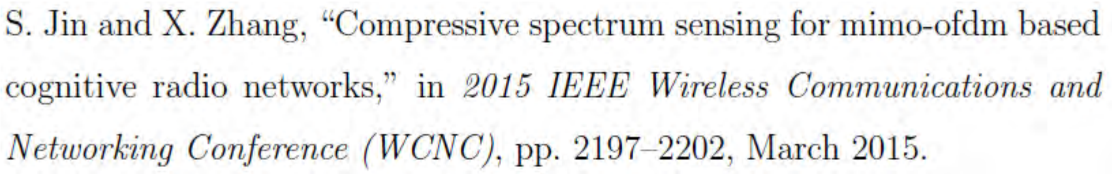
[3] M. Vilimpoc and M. McHenry, "Dupont circle spectrum ulitzation during peak hours," 2006.

[4] P. Kolodzy and I. Avoidance, "Spectrum policy task force," *Federal Commun. Comm., Washington, DC, Rep. ET Docket*, no. 02-135, 2002.

[5] J. Mitola, "Cognitive radio—an integrated agent architecture for software defined radio," 2000.

[6] S. Wang, W. Shi, and C. Wang, "Energy-efficient resource management in ofdm-based cognitive radio networks under channel uncertainty," *IEEE Transactions on Communications*, vol. 63, pp. 3092–3102, Sept 2015.

[7] W. L. Chin, C. W. Kao, and T. N. Le, "Advanced spectrum sensing for ofdm-based cognitive radio networks using cyclic prefix," in *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, pp. 1–5, Sept 2014.

[8] 
S. Jin and X. Zhang, “Compressive spectrum sensing for mimo-ofdm based cognitive radio networks,” in *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 2197–2202, March 2015.

[9] T. Khumyat and P. Uthansakul, “Channel allocation based on game theory in cr networks over rayleigh fading channel,” in *2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, pp. 1–4, June 2016.

[10] S. Sengottuvelan, J. Ansari, P. Mhnen, T. G. Venkatesh, and M. Petrova, “Channel selection algorithm for cognitive radio networks with heavy-tailed idle times,” *IEEE Transactions on Mobile Computing*, vol. 16, pp. 1258–1271, May 2017.

[11] S. K. Singh, A. Kaushik, and D. P. Vidyarthi, “A model for cognitive channel allocation using ga,” in *2016 Second International Conference on Computational Intelligence Communication Technology (CICT)*, pp. 528–532, Feb 2016.

[12] M. Nabil and M. ElNainay, “Fuzzy-based assignment algorithm for channel sensing task in cognitive radio networks,” in *2016 IEEE Symposium on Computers and Communication (ISCC)*, pp. 843–848, June 2016.

[13] H. S. Lang, S. C. Lin, and W. H. Fang, “Subcarrier pairing and power allocation with interference management in cognitive relay networks based on genetic algorithms,” *IEEE Transactions on Vehicular Technology*, vol. 65, pp. 7051–7063, Sept 2016.

[14] F. F. Digham, “Joint power and channel allocation for cognitive radios,” in *2008 IEEE Wireless Communications and Networking Conference*, pp. 882–887, March 2008.

[15] Q. Cheng and B. Kollimarla, “Joint channel and power allocation based on user satisfaction for cognitive radio,” in *2009 43rd Annual Conference on Information Sciences and Systems*, pp. 579–584, March 2009.

[16] M. Canales, J. R. Gallego, and R. Ciria, “Distributed channel allocation and power control in cognitive radio networks using game theory,” in *2011 IEEE Vehicular Technology Conference (VTC Fall)*, pp. 1–5, Sept 2011.

[17] J. Zhang, T. Lv, H. Gao, and Y. Lu, “Joint uplink power and subchannel allocation in cognitive radio network,” in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 306–311, April 2012.

[18] L. Li, X. Changqing, F. Pingzhi, and H. Jian, “Resource allocation in orthogonal frequency division multiple accessbased cognitive radio systems with minimum rate constraints,” *International Journal of Communication Systems*, vol. 27, no. 8, pp. 1147–1159.

[19] D. B. Rawat and C. Bajracharya, “Channel and power adaptation for cognitive radios in multiuser ofdm systems,” in *2016 IEEE Radio and Wireless Symposium (RWS)*, pp. 129–132, Jan 2016.

[20] C. S. Chabalala, R. V. Olst, and F. Takawira, “Optimal channel selection and power allocation for channel assembling in cognitive radio networks,” in *2015 IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, Dec 2015.

[21] N. Shami and M. Rasti, “A joint multi-channel assignment and power control scheme for energy efficiency in cognitive radio networks,” in *2016 IEEE Wireless Communications and Networking Conference*, pp. 1–6, April 2016.

[22] L. Sboui, Z. Rezki, and M. S. Alouini, “Energy-efficient power allocation for underlay cognitive radio systems,” *IEEE Transactions on Cognitive Communications and Networking*, vol. 1, pp. 273–283, Sept 2015.

[23] E. Bedeer, O. Amin, O. A. Dobre, M. H. Ahmed, and K. E. Baddour, "Energy-efficient power loading for ofdm-based cognitive radio systems with channel uncertainties," *IEEE Transactions on Vehicular Technology*, vol. 64, pp. 2672–2677, June 2015.

[24] J. Mao, G. Xie, J. Gao, and Y. Liu, "Energy efficiency optimization for ofdm-based cognitive radio systems: A water-filling factor aided search method," *IEEE Transactions on Wireless Communications*, vol. 12, pp. 2366–2375, May 2013.

[25] S. Wang, M. Ge, and W. Zhao, "Energy-efficient resource allocation for ofdm-based cognitive radio networks," *IEEE Transactions on Communications*, vol. 61, pp. 3181–3191, August 2013.

[26] M. Zhou and X. Zhao, "Energy-efficient power allocation algorithm in cognitive radio networks," *IET Communications*, vol. 10, no. 17, pp. 2445–2451, 2016.

[27] D. Bepari and D. Mitra, "Improved power loading scheme for orthogonal frequency division multiplexing based cognitive radio," *IET Communications*, vol. 9, no. 16, pp. 2033–2040, 2015.

[28] M. Monemi, M. Rasti, and E. Hossain, "On joint power and admission control in underlay cellular cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 265–278, Jan 2015.

[29] C. Pan, J. Wang, W. Zhang, B. Du, and M. Chen, "Power minimization in multi-band multi-antenna cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 13, pp. 5056–5069, Sept 2014.

[30] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in *Mobile Multimedia Communications, 1999. (MoMuC '99) 1999 IEEE International Workshop on*, pp. 3–10, 1999.

[31] R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, *OFDM-Based Cognitive Radios for Dynamic Spectrum Access Networks*, pp. 165–188. Boston, MA: Springer US, 2007.

[32] C. Raman, R. D. Yates, and N. B. Mandayam, "Scheduling variable rate links via a spectrum server," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 110–118, Nov 2005.

[33] L. Cao and H. Zheng, "Distributed spectrum allocation via local bargaining," in *2005 Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2005. IEEE SECON 2005.*, pp. 475–486, Sept 2005.

[34] J. Huang, R. A. Berry, and M. L. Honig, "Spectrum sharing with distributed interference compensation," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 88–93, Nov 2005.

[35] W. Krenik and A. Batra, "Cognitive radio techniques for wide area networks," in *Proceedings. 42nd Design Automation Conference, 2005.*, pp. 409–412, June 2005.

[36] V. Brik, E. Rozner, S. Banerjee, and P. Bahl, "Dsap: a protocol for coordinated spectrum access," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 611–614, Nov 2005.

[37] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 131–136, Nov 2005.

[38] H. Zheng and L. Cao, "Device-centric spectrum management," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 56–65, Nov 2005.

[39] P. Papadimitratos, S. Sankaranarayanan, and A. Mishra, "A bandwidth sharing approach to improve licensed spectrum utilization," *IEEE Communications Magazine*, vol. 43, pp. supl.10–supl.14, Dec 2005.

[40] Q. Zhao, L. Tong, and A. Swami, "Decentralized cognitive mac for dynamic spectrum access," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 224–232, Nov 2005.

[41] R. Etkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands," *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 517–528, April 2007.

[42] M. Z. Win and R. A. Scholtz, "Impulse radio: how it works," *IEEE Communications Letters*, vol. 2, pp. 36–38, Feb 1998.

[43] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, and C. E. Wheatley, "On the capacity of a cellular cdma system," *IEEE Transactions on Vehicular Technology*, vol. 40, pp. 303–312, May 1991.

[44] R. Menon, R. M. Buehrer, and J. H. Reed, "Outage probability based comparison of underlay and overlay spectrum sharing techniques," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 101–109, Nov 2005.

[45] J. Wang, "Narrowband interference suppression in time hopping impulse radio," in *IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall. 2004*, vol. 3, pp. 2138–2142 Vol. 3, Sept 2004.

[46] C. Rose, S. Ulukus, and R. D. Yates, "Wireless systems and interference avoidance," *IEEE Transactions on Wireless Communications*, vol. 1, pp. 415–428, Jul 2002.

[47] U. Berthold and F. K. Jondral, "Guidelines for designing ofdm overlay systems," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pp. 626–629, Nov 2005.

[48] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Magazine*, vol. 42, pp. S8–14, Mar 2004.

[49] T. Weiss, J. Hillenbrand, A. Krohn, and F. K. Jondral, "Mutual interference in ofdm-based spectrum pooling systems," in *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring (IEEE Cat. No.04CH37514)*, vol. 4, pp. 1873–1877 Vol.4, May 2004.

[50] I. Cosovic, S. Brandes, and M. Schnell, "A technique for sidelobe suppression in ofdm systems," in *GLOBECOM '05. IEEE Global Telecommunications Conference, 2005.*, vol. 1, pp. 5 pp.–, Nov 2005.

[51] L. Akter and B. Natarajan, "Qos constrained resource allocation to secondary users in cognitive radio networks," *Computer Communications*, vol. 32, no. 18, pp. 1923 – 1930, 2009. Cognitive Radio and Dynamic Spectrum Sharing Systems.

[52] S. T. Chung and A. Goldsmith, "Degrees of freedom in adaptive modulation: a unified view," in *IEEE VTS 53rd Vehicular Technology Conference, Spring 2001. Proceedings (Cat. No.01CH37202)*, vol. 2, pp. 1267–1271 vol.2, 2001.