OPTIMAL ALLOCATION OF TRANSMIT POWER AND BITS PER CHANNEL USE IN COMPETITIVE COGNITIVE RADIO NETWORKS

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

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By

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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.

Neelanjana Subin Ferdous

To My Son “Umair”

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List of Abbreviation

BER: Bit Error Rate

BTRC: Bangladesh Telecommunication Regulation Commission

CBS: Cognitive Base Station

CC: Control Channel

CCC: Common Control Channel

CDMA: Code Division Multiple Access

CR: Cognitive Radio

CRAHN: Cognitive Radio Ad Hoc Network

CRN: Cognitive Radio Network

CSI: Channel State Information

DSA: Dynamic Spectrum Access

FCC: Federal Communication Commission

HE: Homo Egualis

ISM: Industrial Scientific and Medical

M-ASK: M-ary Amplitude Shift Keying

MC-CDMA: Multi Carrier Code Division Multiple Access

MINLP: Mixed Integer Non-Linear Programming

M-PSK: M-ary Phase Shift Keying

M-QAM: M-ary Quadrature Amplitude Modulation

NE: Nash Equilibrium

NOMA: Non Orthogonal Multiple Access

NTIA: National Telecommunication and Information Administration

OFDMA: Orthogonal Frequency Division Multiple Access

OLPC: Outer Loop Power Control

PBS: Primary Base Station

PU: Primary User

QoS: Quality of Service

SINR: Signal to Noise plus Interference Ratio

SNR: Signal to Noise Ratio

SR: Secondary Receiver

ST: Secondary Transmitter

SU: Secondary User

VSF: Variable Spreading Factors

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Abstract

Cognitive radios (CRs) are considered as a possible enabling solution for Dynamic Spectrum Access (DSA) systems. In a DSA system, a cognitive radio adapts to the environment by sensing the spectrum and takes quick decision on appropriate transmission parameters to achieve certain performance goals. A cognitive radio network (CRN) is defined as a network of cognitive radios/secondary users (SUs). In a CRN, the resource allocation method is responsible for avoiding harmful interference at the primary users (PUs) while optimally utilizing the available resources. Resource allocation problem is usually based upon a system model. A competitive CRN corresponds to a system model where multiple SUs share a single channel and multiple channels are simultaneously used by a single SU to satisfy their bits/channel use requirements.

In this thesis, a competitive CRN is assumed and for such an environment a resource allocation optimization framework is proposed to determine the optimal transmit power and bits/channel use distribution for SUs with two objective functions - minimization of the total transmit power and maximization of the total bits/channel use, and set of constraints such as interference temperature threshold, power budget, quality of service (QoS) of SUs. An upper bound on probability of bit error and lower bound on minimum bits per channel use requirement are considered as QoS of the competing SUs. The users power budget is considered across channels to exploit better channel conditions and hence to improve bits/channel use capability of the resource allocation problem. An interference threshold constraint is considered in order to protect PU's transmission. Firstly, the proposed optimization framework is solved in a centralized manner, which shows that more transmit power is required

in a channel with higher noise power and bits/channel use increases with increasing signal to interference plus noise power ratio (SINR). Moreover, the simulation results also show that the framework is more capable of supporting high bits per channel use requirement than other existing frameworks. Finally, a user based distributed approach is developed to solve the proposed framework using "Game Theory." It is seen that user based distributed solution also follows centralized solution.

Chapter 1

Introduction

1.1 Cognitive Radio Networks

The advancements in information and communication technology have resulted in an explosion in the demand for wireless internet access through smart phones, tablets, and laptops. It is projected that this demand will continually increase in the foreseeable future. Furthermore, the use of wireless applications goes beyond personal communications services; they are used for sensing, monitoring, and control systems (e.g., in surveillance systems, embedded health monitoring systems, and traffic controlling systems). However, this advancement of various wireless services is somewhat limited by the scarcity of the radio spectrum under the current spectrum management policies.

In current spectrum management policy, the right to use the wireless spectrum in a country is controlled by the regulatory authorities. For example, United States spectrum is managed either by the Federal Communications Commission (FCC) for non-governmental applications or by the National Telecommunications and Information Administration (NTIA) for governmental applications. In Bangladesh, both commercial and government use of radio spectrum is managed by Bangladesh Telecommunication Regulation Commission (BTRC). These regulatory agencies divide the available spectrum into blocks. Licenses are issued for exclusive access for a given

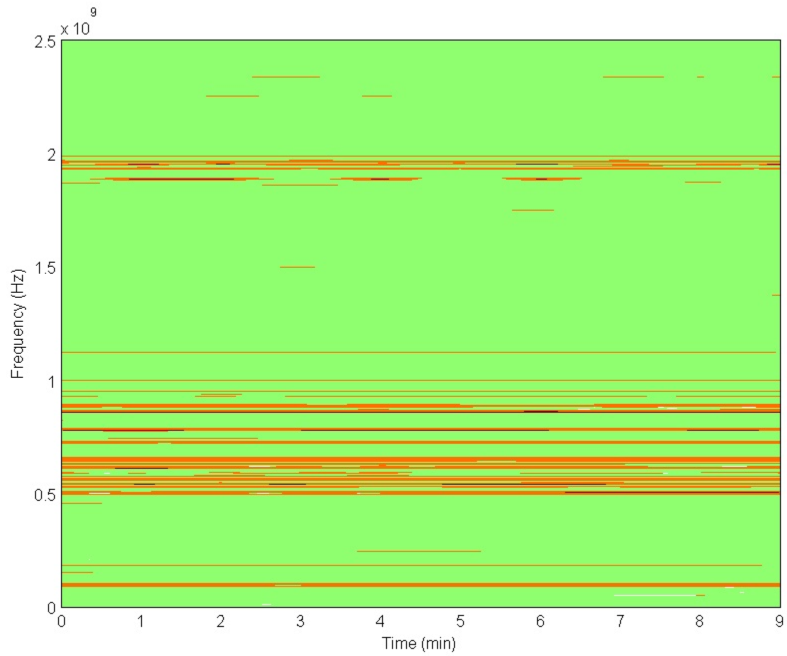

Figure 1.1: Measurements of spectral usage activity in downtown, Berkeley [1]

geographical region to some of the blocks. The blocks are termed as licensed bands and users with the right to access the licensed bands are referred to as primary users (PU). The regulatory authorities also allocate some spectrum blocks where users can operate without any license. These blocks are called unlicensed bands. Conventionally, PUs get the privilege to access the reserved bandwidth. Whereas, unlicensed bands promote coexistence of dissimilar radio systems in the same spectrum. As an

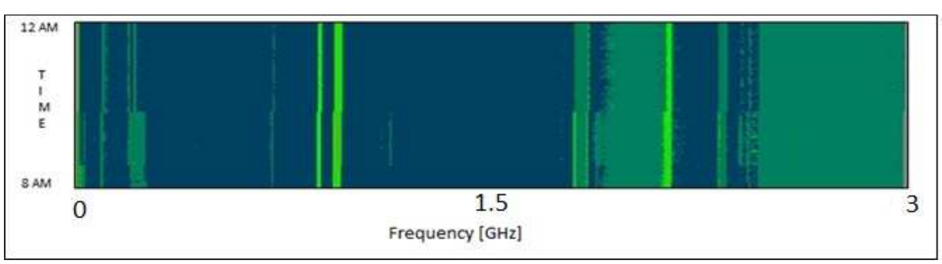

Figure 1.2: Measurements of spectral usage activity in Dhaka, Bangladesh [2]

example, the FCC has designated the industrial scientific and medical (ISM) bands, over which the immensely popular WiFi devices transmit. These unlicensed bands are filling up fast. Despite the popularity of the unlicensed bands, the vast majority of the frequency bands is in fact licensed. Moreover, recent measurements [3–5] show that a large portion of the licensed bands are partly or highly unoccupied in a given area at a given time. For instance, FCCs reference [6] states that the licensed bands utilization varies from 15% to 85%. The measured result of spectrum usage activity in downtown Berkeley, California are shown in Fig. 1.1 where green signifies no spectrum activities. Figure 1.2 represents the spectrum occupancy measurement for a period of time in Dhaka city where deep blue means no activity [2]. It can be observed from these figures that most part of the bands are unoccupied for most of the time. This inefficient usage of licensed bands has made the situation even worse.

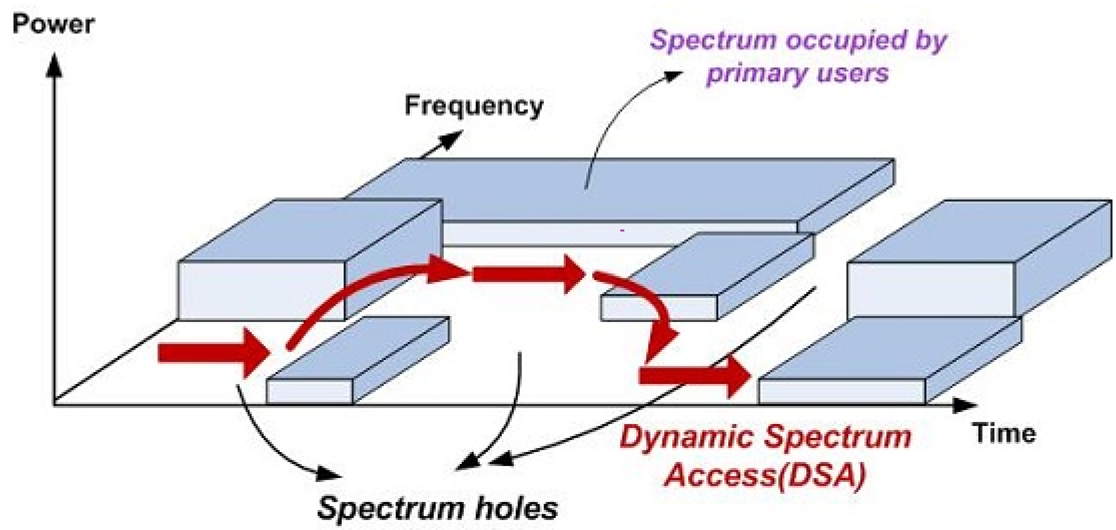

Figure 1.3: Specrum holes or white space.

Recently, spectrum sharing has been proven to be a solution to improve spectrum utilization. In a shared spectrum policy a user without license/secondary user (SU) is allowed to access the idle licensed frequency band and coexist with the PU as long as their operation is not harmful for the PUs. To enable SUs to coexist with other users in a frequency band, they must quickly identify and exploit available frequency bands per channels. They must also be willing to be interrupted and they must look for other channels to complete transmission. This concept is called Dynamic Spectrum Access (DSA). A cognitive radio (CR) is considered as a possible enabling solution for a DSA system. Mitola [7] proposed this novel idea of CR for the opportunistic use of the underutilized portion of the spectrum, while providing a solution to mitigate the spectrum scarcity problem. A CR is an intelligent wireless communications device which senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters [8, 9]. In DSA, the CRs access the frequency bands allocated to a licensed users when the transmission of the licensed users is detected to be inactive. These inactive spectrum bands are referred to as "spectrum holes" or "white spaces" as shown in Fig. 1.3. Spectrum holes represent the potential opportunities for non-interfering (safe) use of available spectrum. These CRs should have two main characteristics [10]: cognitive capability and reconfigurability. The cognitive capability is defined as the ability to sense the surrounding radio environment, analyze the sensed information, and make the spectrum access decision based on the analyzed information. Reconfigurability is defined as the ability of a CR to change its operating parameters based on the spectrum-analyzed information. Such CRs interconnect with other wireless devices opportunistically by forming cognitive radio networks (CRNs).

1.2 Challenges in CRNs

The challenges in CRNs can be broadly listed as

1. Cognitive radio architecture and implementation issues [7–12],

2. Spectrum sensing hardware requirements [7], [13–15],

3. Spectrum sensing algorithms [16–18],

4. Resource management [19–23],

5. Fairness in resource allocation [24–26],

6. Policy challenges [27–30].

In this thesis, our focus is on finding optimal transmit power and bits/channel use (modulation order) for SUs in a CRN. Hence, we provide a literature review on power and bits/channel use allocation in the following section.

1.3 Literature Review

There has been extensive research done on power and rate allocation to secondary users (SUs) in the field of CRN. The authors in [31–34] study channel allocation. Whereas the authors in [35, 36] study channel and transmit power allocation and the authors in [19], [37–43] study transmit power and rate allocation. As our proposed work is on transmit power and rate allocation, we provide a little detailed overview on that only. The authors in [19] study multiple user cognitive radio ad hoc networks using orthogonal frequency division multiple access (OFDMA) scheme and develop an algorithm to find optimal subcarrier sets as well as transmit powers to secondary users with the objective of maximizing rate (in terms of Shannon channel capacity) under maximum power constraints on individual radios, non-zero minimum and maximum rate constraints. In [37], the authors consider a single pair secondary transmitter-receiver overlaying with multiple PUs and propose a close-to-optimal algorithm for OFDM-based CR systems to find rate (in terms of Shannon channel capacity) and transmit powers to SU with the objective of jointly maximizing SU rate (in terms of Shannon channel capacity) and minimizing SU transmit power while guaranteeing a SU target bit-error-rate (BER) per subcarrier, total transmit power limit, and an acceptable interference power to adjacent PUs. The authors in [39] consider a system model of single channel, a single pair secondary transmitter-receiver and a single pair primary transmitter-receiver. Here, a spectrum sensing based joint rate (in terms of Shannon channel capacity) and power allocation scheme for CRNs without primary users true state information is studied. The authors also provide sufficient condition under which it is beneficial for the SU to use the PU channel even the sensing result indicates that the PU is busy. The authors in [38] study a location awareness based cognitive radio ad hoc network (CRAHN) consists of a single pair secondary transmitter-receiver overlaying with a single pair primary transmitter-receiver. They propose an optimization framework to determine transmit power to SU to adequately adjust the secondary user rate to be as large as possible while respecting QoS to PU.

In [40], the authors study the CR transmission of a SU pair (using M-QAM modulation scheme) in the presence of another PU pair. They model the co-channel interference between SU and PU without causing Gaussian assumption and derive upper bound formula for the BER of M-ary quadrature amplitude modulation (M-QAM) signals in the presence of interference-plus-noise. Finally, they design an optimization problem to solve power and rate of SU with an objective to maximize the average spectral efficiency under constraints of the average power of the SU, average BER (for both PU and SU) and average interference level. In [41], the authors investigate the average spectral efficiency of the cognitive user that employs joint optimization of rate and outer loop power control (OLPC) for code division multiple access (CDMA) systems for a single secondary user under the constraints of average transmission power of the SU and predefined interference limit on the primary receiver. For a given BER, the optimum SNR target is formulated and the transmission rate of a SU is adapted using variable spreading factors (VSF) to attain the SNR target which is combined with the power adaption in the inner loop of SU. In [42], a protocol has been proposed for a cooperation cognitive radio model with a single pair of secondary transmitter-receiver and a single pair of primary transmitter-receiver. In this protocol, if the primary receiver fails to decode the data signal of the primary transmitter in the initial transmission, the secondary transmitter also recognize the ACK/NACK signals and simultaneously re transmits the data signal of the primary transmitter along with its data signal. The authors also consider an optimization problem to solve the optimal transmission rate and fraction of the transmission power with the constraint that the average throughput of the primary system with SU is no less than the primary system alone. This fraction of the transmission power is adjusted by the SU to give the additional average throughput gain to PU.

The authors in [19], [37–42] do not consider the scenario where multiple SUs can share a channel at a time. Also, they have not commented on bits/channel use.

In [43], the authors propose two centralized optimization frameworks (two stage and joint) to determine the distribution of power and bits/channel use to SUs in a competitive CRN. The objectives of the optimization frameworks are to minimize total transmission power, maximize total bits/channel use and also to maintain QoS. They consider BER and minimum bits/channel use requirement of SUs as QoS. The authors consider multiple ary quadrature amplitude modulation (M-ary QAM) scheme and transform the BER constraint in order to ensure optimality of the resulting solution. Here, it is also shown that joint allocation of transmit power and bits/channel use is more power economical. However, the authors in [43] consider channel based power budget for users. In addition, the optimization framework is also constrained by the total bits/channel use capability limit.

1.4 Motivation

It is commonly assumed that in a CRN, multiple channels may be available of different quality. Therefore, the SUs allotted to higher quality channels may gain an advantage over SUs allotted to the poorer channels. Also, some of the SUs may not attain minimum required bits/channel use by accessing only one channel. That is, in practice, a single SU may occupy more than one channel. Moreover, to increase spectral efficiency, multiple SUs may coexist in a channel according to its quality. Thus in a competitive CRN, multiple secondary users share a single channel and multiple channels are simultaneously used by a single secondary user (SU) to satisfy their bits/channel use requirements. Resource allocation in such a competitive CRN is an important consideration and to the best of our knowledge only the authors in [43] propose resource allocation frameworks to compute the distribution of transmit power and bits/channel use to SUs in a competitive environment. However, they consider channel based power budget for users. It is expected that users power budget across their intended channels take advantage of better channel conditions and hence result higher bits/channel use capability of the allocation problem [44]. In this context, we are motivated to develop the resource allocation problem with user based power budget across channels to exploit better channel conditions in order to support more bits/channel use than existing framework. Our proposed resource allocation framework aims to determine the best choice of power and bits/channel use (modulation order) jointly to SUs. The objectives of our proposed optimization framework are to minimize total transmission power, maximize total bits/channel use and also to maintain quality of service (QoS) of the SUs. Our measures for QoS include an upper bound on probability of bit error and lower bound on bits/channel use requirement of SUs. We consider M-ary Quadrature Amplitude Modulation (M-QAM) scheme.

The centralized solution of the proposed resource allocation frameworks demands extensive control signaling and is difficult to implement in practice if information exchange about all users and channels is limited. In this context, we are motivated to develop distributed user-based approaches to solve the proposed resource allocation framework and compare the performance between centralized and distributed approach.

1.5 Contributions

We consider a competitive CRN with multiple secondary users. We also assume that each channel can be used simultaneously by multiple secondary users via some form of non-orthogonal multiple access scheme, and a single secondary user can access several channels at the same time to achieve its minimum bits/channel use requirements. Each SU scans the spectrum bands at regular intervals and starts transmitting on particular channels once it determines that the channels are vacant. At any instant of time, if PU enters in any channel then SUs in that particular channel need to cease transmission through the channels. The key contributions of this thesis for such a CRN model are summarized below-

i We propose an optimization framework for resource allocation for SUs in a competitive CRN. Our objective is to determine the optimal distribution of power and bits/channel use that a SU has to employ across the channels that it uses in order to (1) minimize the total transmit power, and (2) maximize the total bits/channel use while maintaining the QoS requirements for all active SUs. The optimization problem is constrained by an upper bound on probability of bit error and lower bound on bits/channel use requirement of SUs to ensure QoS. The problem is also constrained by total power budget across channels for users. The proposed optimization framework is presented in Chapter 3.

ii We solve the proposed optimization framework in a centralized manner and analyze the allocation profile of transmit power and bits/channel use. It is seen that the allocated transmit power is proportional to the channel noise power and bits/channel use follows the signal to interference plus noise ratio (SINR). We also compare the results of our proposed optimization framework with that of [43]. Here, our proposed framework is seen to be more capable of supporting high bits/channel use requirement. That is, wider solution space is obtained with our proposed framework than the existing framework. Detailed solution of the proposed optimization framework in a centralized manner is provided in Chapter 4.

iii Finally, we develop a user-based distributed approach to solve the proposed optimization framework using "Game Theory." We analyze the existence of Nash Equilibrium (NE) for the game. An algorithm is developed to achieve NE. We also analyze the allocation profile of transmit power and bits/channel use and compare it with that of centralized solution. Detailed analysis of the distributed solution are provided in Chapter 5.

1.6 Thesis Outline

The thesis is organized as follows-

Chapter 1 introduces the topic of the thesis. It also lifts up the reviews of the related earlier 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 the theoretical aspects of cognitive radio network and resource allocation in cognitive radio networks.

Chapter 3 describes the proposed resource allocation framework.

Chapter 4 lifts up the solution of the proposed optimization framework in centralized manner. Graphical representation of the results are analyzed and compared with that of the existing framework.

Chapter 5 depicts the solution of the same proposed optimization problem considering the user based distributed approach. Game theory is used here to solve this distributed resource allocation framework. Additionally, the results for distributed approach are analyzed and compared with that of the centralized approach.

Chapter 6 briefly summarizes the overall thesis work and suggests the scope of future work.

Chapter 2

Resource Allocation in CRNS: Preliminaries

2.1 Introduction

In CRNs, dynamic spectrum access (DSA) is a key concept, which allows a cognitive radio (secondary user) in a network to opportunistically share the spectrum resources which are allocated to primary users. The spectrum can be accessed by secondary users when it is not being used by the primary users. Sharing the licensed spectrum by secondary users improves the overall spectrum utilization and at the same time the transmission power of secondary user causes interference to primary user. Therefore, secondary user network should be designed in a way to allocate its radio resources to satisfy its own QoS requirements while ensuring that the interference caused to the primary users is below the predefined threshold level. 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 and error coding). The techniques which involve strategies and algorithms for controlling transmission parameters are known as resource allocation in 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. 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.

2.2 Cognitive Radio Network Architectures

A cognitive radio network (referred to as secondary network or unlicensed network) coexists with primary networks (also referred to as licensed networks) within the same geographical area, at the same time and utilize the same frequency bands. The primary network can be classified as either a centralized (infrastructure-based) network or a distributed (ad-hoc) network. Similarly, based on the network architecture, the cognitive radio network can also be classified as either a centralized or a distributed network, as shown in Figs. 2.1 and 2.2, respectively. Generally, the PUs and the primary base stations (PBS) do not have the cognitive radio capabilities. Hence, it is the responsibility of SUs to sense the channel before cognitive transmission and vacate immediately after the appearance of primary users.

2.2.1 Centralized CRNs

Centralized CRNs [8], [10], [12] have a central controller or coordinator (shown in Fig. 2.1), e.g., a cognitive base station (CBS) or a central access point. This central controller can collect spectrum information from SUs over a licensed or unlicensed spectrum band (i.e., control channel (CC)), analyzes and makes information about spectrum availability (e.g., channels in which PUs are absent) known to SUs via CCs. A CBS provides resource (e.g., channel, bits/channel use and transmit power) for SUs.

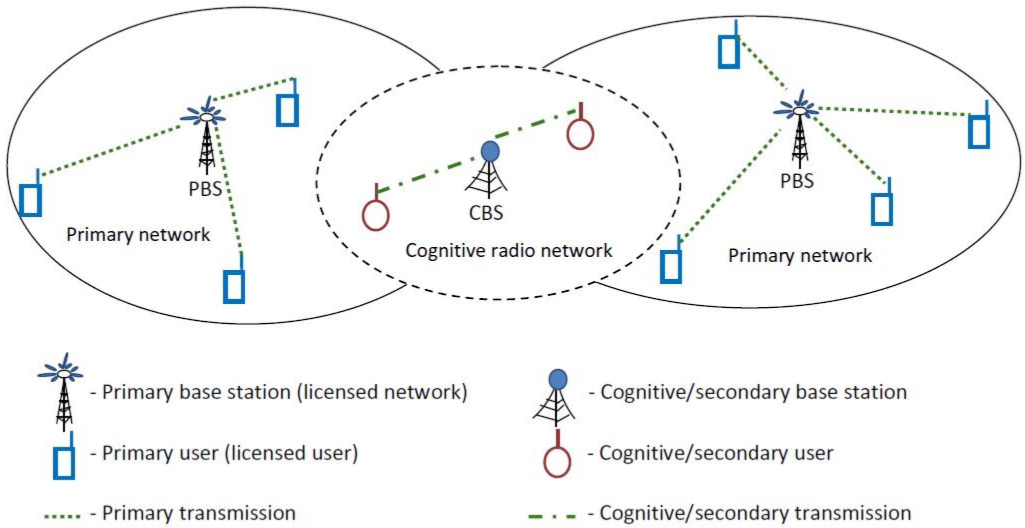

Figure 2.1: Centralized cognitive radio architecture.

2.2.2 Distributed CRNs

Distributed CRNs [8], [10], [12] are ad-hoc or point-to-point communications systems where SUs communicate over licensed or unlicensed bands opportunistically, as shown in Fig. 2.2. These distributed CRNs do not have a central controller to coordinate opportunistic spectrum access and spectrum access decisions are jointly coordinated via a common control channel (CCC) [45]. Hence, the signaling overhead in distributed CRNs is considerably small compared to centralized CRNs even with a larger number of SUs. However, the spectrum access decision taken by distributed CRNs based on local information may not be optimal.

2.3 Cognitive Radio Operational Models

The dynamic spectrum access models in CRNs can be typically categorized into three access models: underlay, overlay and interweave spectrum access models, as explained further below.

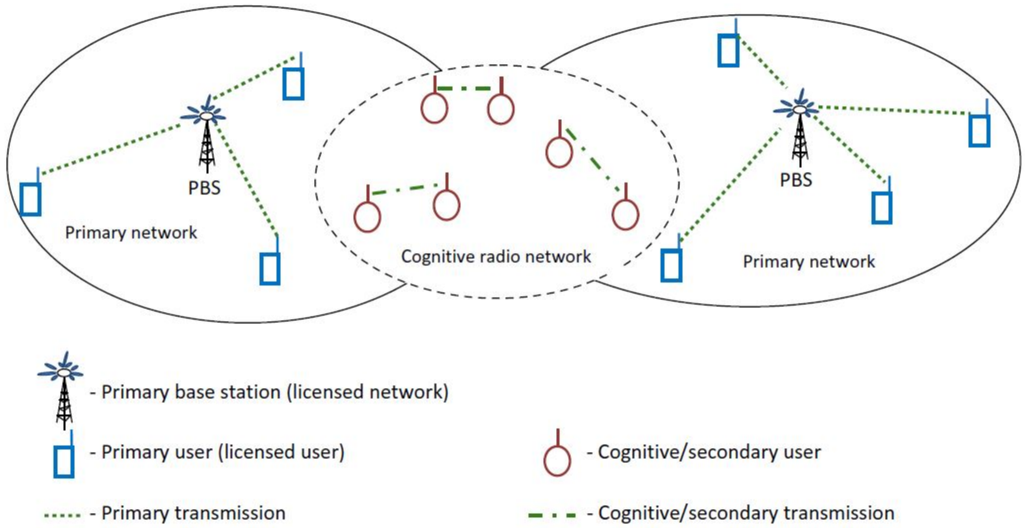

Figure 2.2: Distributed cognitive radio architecture.

2.3.1 Underlay Spectrum Access Model

Figure 2.3 (a) depicts the underlay spectrum access model. In this model, SUs are allowed to coexist simultaneously with the PUs, by guaranteeing that the interference perceived at the primary receivers is below a given threshold. Thus, SUs can transmit whenever they want apart from being waited for spectrum holes. This is possible by controlling the transmit power at the secondary transmitters. In addition, SU's received signal is also affected by the PU's interference. However, interference tolerance capabilities at the receivers enhance the overall performance of the CRN. Due to the interference constraints associated with underlay systems, the underlay technique is only useful for short range communications.

2.3.2 Overlay Spectrum Access Model

The overlay spectrum access model also permits SUs to co-exist with the PUs. In fact, each SU associates PU-cooperation to enhance the PU's signal-to-interference-plus noise ratio (SINR) while appropriately splitting it's transmit power between two

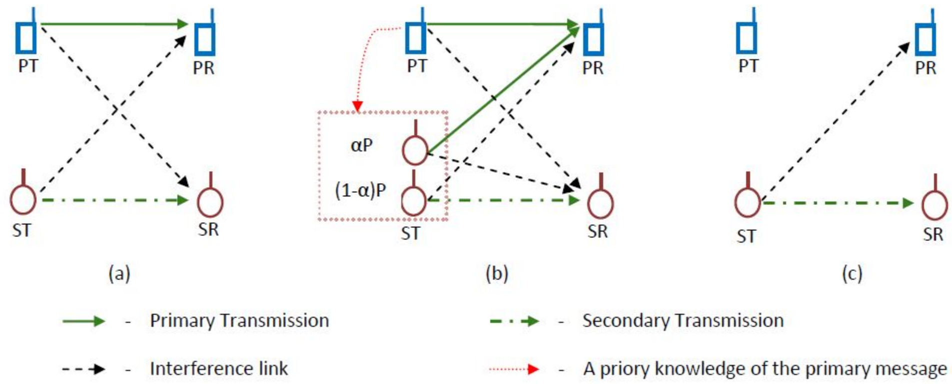

Figure 2.3: Cognitive radio operational models (a) Underlay operation, (b) Overlay operation, (c) Interweave Operation.

consecutive transmissions as shown in Fig. 2.3 (b). A fraction of transmit power (i.e., αP) is used to transmit the PU's signal. Meanwhile, the remaining part (i.e., $(1-\alpha P)$) is available to transmit SU's own signal. However, α has to be selected appropriately so that overall performance of the PU communication is not degraded. Furthermore, since the PU signal is known at the secondary transmitter (ST), channel coding can be successfully employed to cancel the interference at the secondary receiver (SR).

2.3.3 Interweave Spectrum Access Model

This spectrum access model can be employed to avoid interference to the PUs. In other words, each SU uses a fraction of time from its available time slot to detect the occupancy of the PU in that particular spectrum band. Within that time period, they perform sensing, to make a decision about the PU's activity (i.e., idle or active) on that specific spectrum band. Thus, the interweave spectrum access model decides access permission of the SUs based on sensing results. For example, a SU admits to a spectrum band if and only if the PU's spectrum is detected as idle and releases it whenever the PU returns. In this way, interference to the PR is avoided. Fig. 2.3 (c) shows the interweave spectrum access when PU is idle.

2.4 Resource Allocation in CRNs

The resource allocation scheme in a 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 and rate selection 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 CRNs.

2.4.1 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 PRs 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).

2.5 Resource Allocation Approaches in 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 [46]:

$$\text{To minimize :} \quad f_0(x)$$
$$\text{subject to}$$
$$f_i(x) \leq b_i, \; i = 1, 2, ...m. \tag{2.5.1}$$

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 2.5.1, 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.

2.5.1 Optimization Objectives

The essence of resource allocation in 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.

2.5.2 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 minimum data rate requirement. The minimum data rate requirement is 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.

2.6 Summary

In this chapter, some basic concepts of cognitive radio networks 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 Framework

In this chapter, we state our proposed resource allocation framework in a competitive CRN. We are interested to optimize the transmission parameters such as transmit power and bits/channel use (modulation order) of the SUs. We consider a competitive CRN model where a single SU can transmit over multiple channels and a single channel can be used by multiple users simultaneously. In such an environment we propose an optimization framework to estimate the best choice of transmit power and bits/channel use jointly for every SU with a view to (1) minimizing total transmission power; (2) maximizing total bits/channel use, while maintaining QoS of the active SUs. An upper bound on probability of bit error and lower bound on bits/channel use requirement of SUs are considered as benchmark to measure QoS.

The rest of the chapter is organized as follows. In Sec. 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 framework. Finally, Sec. 3.3 summarizes the chapter.

3.1 System Model

Let us consider a CRN comprised of M SUs. To access the licensed spectrum, the SUs continuously sense the spectrum and determine that L free channels are available for use in opportunistic way by multiple SUs. It is assumed that each channel can be used simultaneously by multiple SUs via some form of non-orthogonal multiple access scheme, and also a single SU can utilize several channels at the same time to satisfy their bits/channel use requirement. Our goal is to maintain QoS for these competing SUs by allocating the resources effectively. We consider probability of bit error and minimum bits/channel use requirement as benchmark to indicate QoS. An interference temperature threshold is also imposed to protect the PU transmission on any channel from any harmful interference. We again implore the following assumptions to enable mathematical tractability of the optimization framework: (1) CRN consists of a central controller that will accomplish the resource allocation and has access to all SUs channel and interference parameters (transmit power, bits/channel use). The controller computes transmit power and bits/channel use per SU in each channel based on channel quality, user's bits/channel use constraint and interference temperature threshold. It is also assumed that channel state information (CSI) and allotted power and bits/channel use are exchanged between controller and SUs on a dedicated control channel. (2) Every active SU radio has an upper limit on bits/channel use at which it can transmit. (3) Every active SU radio has an upper bound on total transmit power across channels. (4) All SUs employ same M-ary modulation scheme (M-ary QAM) with an adaptable modulation order M. (5) Simple path loss model for channel is considered. (6) Each SU has a lower bound requirement on bits/channel use and upper bound requirement on BER that is to be maintained. Finally, we assume that for optimization at each time instant, the number of SUs that may want to access to each of the channels is denoted by $\widetilde{N}_s(k)$ where $k = 1,\ 2,\ 3,\ \cdots,\ L$ which can be obtained by following the method described in [47]. Under this system model, we compute the the optimal transmit power and bits/channel use distribution jointly for the SUs. Table 3.1 defines most of the related terms used throughout the thesis.

$\widetilde{N}_s(k)$	Predicted number of users for k-th channel
$\sigma^2(k)$	Noise power in k-th channel
$\rho_{j,i}$	Orthogonality factor between user j and user i
$h_{i,i}(k)$	Power gain from i-th transmitter to i-th receiver in k-th channel
$h_{i,m}(k)$	Power gain from i-th transmitter at location m in k-th channel
$p_i(k)$	Transmit power per bit of i-th user in k-th channel
p_i^{max}	Maximum transmit power per bit of i-th user across its intended channels
$p_i^{max}(k)$	Maximum transmit power per bit of i-th user in k-th channel
$I_t(k)$	Interference temperature constraint in k-th channel
$b_i(k)$	Bits/channel use of i-th user in k-th channel
$b_i^{max}(k)$	Maximum bits/channel use of i-th user in k-th channel
R_i^l	Minimum required bits/channel use for i-th user
$p_{e,i}(k)$	BER for i-th user in k-th channel
$p_{e,i}^t$	BER threshold at receiver for i-th user in any channel
$\gamma_i(k)$	SINR per bit for i-th user in k-th channel
$\gamma_i^t(k)$	SINR per bit threshold at receiver for i-th user in k-th channel

Table 3.1: Notations.

3.2 Proposed Optimization Framework

The objectives of our proposed optimization framework are to (1) minimize the total transmit power, and (2) maximize the total bits/channel use while satisfying the QoS requirements of all active SUs. The mathematical description of the proposed bi-objective optimization corresponds to:

$$
\begin{aligned}
\text{Determine} \quad & [\mathbf{p}^T \ \mathbf{b}^T]^T \\
\text{To minimize:} \quad & F_1 = \sum_{k=1}^{L} \sum_{i=1}^{\widetilde{N}_s(k)} p_i(k) \text{ and} \\
\text{Maximize:} \quad & F_2 = \sum_{k=1}^{L} \sum_{i=1}^{\widetilde{N}_s(k)} b_i(k) \\
\text{subject to} \quad & \\
& C1: \ 0 \leq p_i(k), \ \forall \ i, \ k \\
& C2: \ \sum_{k=1}^{L} p_i(k) \leq p_i^{max}, \ \forall \ i \\
& C3: \ b_i(k) \in [1, \cdots, \ b_i^{max}(k)], \ \forall \ i, \ k \\
& C4: \ \sum_{i=1}^{\widetilde{N}_s(k)} p_i(k) h_{i,m}(k) \leq I_t(k), \ \forall \ k \\
& C5: \ \sum_{k=1}^{L} b_i(k) \geq R_i^l, \ \forall \ i \\
& C6: \ p_{e,i}(k) \leq p_{e,i}^t, \ \forall \ i, \ k.
\end{aligned} \tag{3.2.1}
$$

For M-QAM modulation scheme:

$$
p_{e,i}(k) \leqslant \frac{4}{b_i(k)} Q\left(\sqrt{\frac{3 \ b_i(k)\gamma_i(k)}{2^{b_i(k)}-1}}\right), \ \forall \ i, \ k, \text{odd } b_i(k), \tag{3.2.2}
$$

$$
p_{e,i}(k) = \frac{4}{b_i(k)} \left(1 - 2^{-\frac{b_i(k)}{2}}\right) Q\left(\sqrt{\frac{3 \ b_i(k)\gamma_i(k)}{2^{b_i(k)}-1}}\right), \ \forall \ i, \ k, \text{even } b_i(k). \tag{3.2.3}
$$

In the above,

$$
\gamma_i(k) = \frac{p_i(k) h_{i,i}(k)}{\sum_{j=1, \ j \neq i}^{\widetilde{N}_s(k)} p_j(k) h_{j,i}(k) {\rho_{j,i}}^2 + \sigma^2(k)}, \ \forall \ i, \ k. \tag{3.2.4}
$$

Here, $\mathbf{p} = [p_1(1), \cdots, \ p_{\widetilde{N}_s(1)}(1), \cdots, \ p_1(L), \cdots, \ p_{\widetilde{N}_s(L)}(L)]^T$ and $\mathbf{b} = [b_1(1), \cdots, \ b_{\widetilde{N}_s(1)}(1), \cdots, \ b_1(L), \cdots, \ b_{\widetilde{N}_s(L)}(L)]^T$; Constraint types $C1$ and

$C2$ represent the limit on transmit power; constraint type $C3$ indicates limit on bits/channel use; constraint type $C4$ indicates the interference temperature threshold constraint; constraint type $C5$ represents the required bits/channel use of users and finally constraint type $C6$ is BER constraint. As $C6$ is a nonlinear constraint and the value of $b_i(k)$ is discrete, the above optimization formulation is a constrained multi-objective mixed integer nonlinear programming (multi-objective MINLP) optimization problem. It is NP-hard in general. Relaxing the discrete condition on bits/channel use, $b_i(k)$ (as suggested in [46]) and considering $b_i(k)$ as continuous variable, the above optimization problem can be rewritten with constraint type $C3$ as:

$$C3 : 1 \leq b_i(k) \leq b_i^{max}(k), \ \forall \ i, \ k. \tag{3.2.5}$$

This results a non-convex optimization problem due to constraint type $C6$. As in [43] to ensure optimality of the above optimization problem, the constraint type $C6$ is modified into the following form

$$C7 : \ -\gamma_i(k) \leq -C_{qarg}(2^{b_i(k)} - 1), \ \forall \ i, \ k. \tag{3.2.6}$$

where C_{qarg} is computed using the method discussed in [43]. Here, C_{qarg} is a constant and can be determined using (1) minimum rate, $b_i^{min}(k) = 1$ (in our system); (2) $b_i^{max}(k)$, and (3) value of $p_{e,i}^t$ from $C7$. As an example, with $b_i^{min}(k) = 1$ to achieve $p_{e,i}^t = 10^{-3}$, Eq. (3.2.2) suggests that $\gamma_i(k)/(2^{b_i(k)} - 1)$ has to be greater than 4.08 and with $b_i^{max}(k) = 6$, Eq. (3.2.3) suggests that $\gamma_i(k)/(2^{b_i(k)} - 1)$ has to be greater than 0.50. From this, we can conclude that by setting $C_{qarg} = 4.08$, we can guarantee a BER that is less than or equal to 10^{-3} for the feasible values of $b_i(k)$. The following theorem discusses the convex approximation of constraint $C7$ [43].

Theorem 1. $-\gamma_i(k) \leq -C_{qarg}(2^{b_i(k)} - 1), \ \forall \ i, \ k$ *is a convex constraint.*

Proof. Equation (3.2.6) can be written as

$$\gamma_i(k) \geq C_{qarg}(2^{b_i(k)} - 1). \tag{3.2.7}$$

From Eqs. (3.2.4) and (3.2.7), we can write

$$\begin{aligned} p_i(k)h_{i,i}(k) \geq & \quad C_{qarg}(2^{b_i(k)}-1)\left(\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} p_j(k)h_{j,i}(k){\rho_{j,i}}^2+\sigma^2(k)\right) \\ = & \quad C_{qarg}\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} p_j(k)2^{b_i(k)}h_{j,i}(k){\rho_{j,i}}^2 + C_{qarg}2^{b_i(k)}\sigma^2(k) \\ & -C_{qarg}\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} p_j(k)h_{j,i}(k){\rho_{j,i}}^2 - C_{qarg}\sigma^2(k). \end{aligned} \tag{3.2.8}$$

Finally, rearranging Eq. (3.2.8), we get

$$\begin{aligned} & C_{qarg}\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} p_j(k)2^{b_i(k)}h_{j,i}(k){\rho_{j,i}}^2 + C_{qarg}2^{b_i(k)}\sigma^2(k) \\ & -C_{qarg}\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} p_j(k)h_{j,i}(k){\rho_{j,i}}^2 - p_i(k)h_{i,i}(k) - C_{qarg}\sigma^2(k)\leq 0. \end{aligned} \tag{3.2.9}$$

Here, $b_i(k)$, $p_i(k)$ and $p_j(k)$ are the optimization variables. $2^{b_i(k)}$ is a convex function. The second term is convex as it is a function of $2^{b_i(k)}$. The third and fourth terms are convex as these are linear functions of $p_j(k)$ and $p_i(k)$, respectively. The first term vanishes if $\rho_{j,i}=0$ and the entire inequality becomes convex i.e., users are orthogonal and constraint $C7$ is convex. However, if $\rho_{j,i}$ is not equal to zero, the component functions $p_j(k)2^{b_i(k)}$ can be linearized via Taylor expansion around a point of interest $[p_j^t(k)\ b_i^t(k)]^T$. In that case, the entire inequality Eq. (3.2.9) can be considered a convex inequality corresponding to

$$\begin{aligned} & C_{qarg}\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} \left(p_j^t(k)2^{b_i^t(k)} + 2^{b_i^t(k)}\left(p_j(k)-p_j^t(k)\right) + \right. \\ & \left. p_j^t(k)2^{b_i^t(k)}log_e 2\left(b_i(k)-b_i^t(k)\right)\right) h_{j,i}(k){\rho_{j,i}}^2 + C_{qarg}2^{b_i(k)}\sigma^2(k) \\ & -C_{qarg}\sum_{j=1\ j\neq i}^{\widetilde{N}_s(k)} p_j(k)h_{j,i}(k){\rho_{j,i}}^2 - p_i(k)h_{i,i}(k) - C_{qarg}\sigma^2(k)\leq 0 \end{aligned} \tag{3.2.10}$$

□

The optimization problem defined in Eq. (3.2.1) has two objective functions F_1 and F_2 that are mutually conflicting. That is, as each SU attempts to increase the bits/channel use in order to maximize F_2, the constraint $C6$ becomes difficult to satisfy unless more transmit power is used. Therefore, F_1 will increase if we attempt to increase F_2 and vice-versa. It is common to combine such mutually conflicting objectives into a single objective function using the “scalarization” approach [48] and look at pareto optimal solutions. The optimization problem with combined single objective can now be rewritten as:

$$\begin{aligned} \text{Minimize } \tau_1 F_1 - \tau_2 F_2 \\ \text{subject to} \\ C1,\ C2,\ C3,\ C4,\ C5,\ C7, \end{aligned} \tag{3.2.11}$$

where, τ_1 and τ_2 are the scalarization constants on F_1 and F_2, respectively. Finally, the solution obtained from the convex formulation Eq. (3.2.11) is being used as a starting point to search in the neighborhood for the optimal discrete valued $b_i(k)$ (denoted as $\mathbf{b}^{opt}$). We recalculate the optimal transmit power $\mathbf{p}^{opt}$ based on the new discrete solution using Eq. (3.2.6).

3.3 Summary

In this chapter, we describe our proposed resource allocation framework that provide the optimal transmit power and total bits/channel use (modulation order) distribution that each SU needs to employ in each channel while maintaining QoS in a competitive CRN.

Chapter 4

Centralized Solution of Proposed Resource Allocation Optimization Framework

In Chapter 3, we describe our proposed resource allocation framework to compute transmit power and bits/channel use (modulation order) for SUs in a competitive CRN. In this chapter, the proposed resource allocation problem is solved in a centralized manner. In a centralized manner, all active SUs convey their (1) QoS requirements, (2) power and bits/channel use limitations, and (3) Channel state information (CSI) in periodic intervals to the central controller. The controller computes power and bits/channel use per SU in each channel based on channel quality and interference threshold. We assume that CSI and allocated power and bits/channel use are exchanged between controller and SUs on a dedicated control channel. Here, we also present the simulation results to demonstrate the performance of the proposed framework in a centralized manner. Hereafter, the results for the proposed framework are compared with the results from [43].

The rest of the chapter is organized as follows. Section 4.1 describes the simulation setup for the proposed framework. Numerical results analysis for centralized approach are presented in Sec. 4.2. Finally, Sec. 4.3 summarizes the chapter.

4.1 Simulation Setup

We assume a CRN with L = 11 available channels and a total of M =10 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. Table 4.2 provides information on the channel quality for all L channels. Table 4.3 lists the minimum bits/channel use requirement for each SU and Table 4.4 lists the total transmit power upper bound of all SUs. Lastly, Table 4.5 provides all other system parameters that are required for our optimization framework. It is to be noted how the channel power gains such as $h_{i,i}(k)$, $h_{j,i}(k)$, $h_{i,m}(k)$ and orthogonality factor $\rho_{j,i}$ are set in simulation. We have mentioned in system model section in assumption 5 that simple path loss model for channel has been considered. In simulation, to simply the channel realization at some specific time, we use Rayleigh distribution to have channel power gains. We also normalize channel power gains properly so that none of the gains can go above 1. In practice, channel power gains will be obtained using channel estimation techniques.

User, 1	0	1	0	1	1	0	1	0	0	0	1
User, 2	0	0	1	0	1	1	1	0	1	1	0
User, 3	0	1	1	0	1	1	0	0	1	0	1
User, 4	1	0	1	1	0	1	1	0	1	1	0
User, 5	1	0	0	1	0	1	0	0	1	0	1
User, 6	0	0	1	0	1	0	1	1	1	1	0
User, 7	0	1	0	1	0	1	0	1	0	1	1
User, 8	1	0	1	0	1	0	1	1	0	1	0
User, 9	0	1	1	0	1	0	1	1	0	1	1
User, 10	0	1	1	0	1	0	1	0	0	1	1

Table 4.1: Usage pattern across channels.

Channel, k	1	2	3	4	5	6	7	8	9	10	11
$\sigma^2(k)$, $(\times 10^{-8})$	0.1	5	2.5	7.5	0.1	7.5	5	2.5	0.1	7.5	0.1

Table 4.2: Channel quality parameters.

User, i	1	2	3	4	5	6	7	8	9	10
R_i^l	5	7	6	8	10	9	7	8	7	7

Table 4.3: Minimum bits/channel use requirement of users.

User, i	1	2	3	4	5	6	7	8	9	10
p_i^{max}(Watt)	5	7	6	8	10	9	7	8	7	7

Table 4.4: Total transmit power upper bound of users.

$b_i^{max}(k)\ \forall\ i,\ k$	6
$p_{e,i}^t\ \forall\ i$	10^{-3}
$I_t(k)\ \forall\ k$	$200 \times \sigma^2(k)$
$\rho_{j,i}$	0.03125

Table 4.5: System parameters.

Our proposed framework can be used by MC-CDMA (multi carrier code division multiple access) system. MC-CDMA is associated with assigning codes to all of its users. This orthogonality factor is obtained from such codes. If the codes are orthogonal, users are orthogonal and $\rho_{j,i}$ is obtained as 0. If the codes are not orthogonal, users are not orthogonal and $\rho_{j,i}$ is obtained as some nonzero value. We set 0.03125 as $\rho_{j,i}$ to keep provision for non-orthogonal users. For the simulation parameters stated in this section, the value of C_{qarg} is obtained as 4.5.

Finally, the proposed optimization framework is solved using optimization toolbox in MATLAB. Specifically, we use function "fmincon." "fmincon" provides solution for an optimization framework with both linear and nonlinear constraints. It has four algorithms- trust-region-reflective, interior point, sequential quadratic programming (SQP) and active set. We use “Active set” algorithm to solve the proposed optimization problem. “Active set” method is briefly discussed in Appendix A.

4.2 Results Analysis

In this section, we investigate the performance of the proposed resource allocation framework solved in a centralized manner. Afterwards, a comparison between the performance of our proposed framework and the framework in [43] is shown.

First, we observe the performance of our proposed framework in terms of the allocated transmit power and bits/channel use across the channels for every SU. Figure 4.1 depicts the transmit power and bits/channel use allocation across channels (assuming scalarization parameters τ_1 and τ_2 to 0.5) for user 3 and 7, respectively. The channel noise power and resulting SINR are also shown in the figure. Here user 3 is active on channels 2, 3, 5, 6, 9 and 11 and user 7 is active on channels 2, 4, 6, 8, 10 and 11. From Fig. 4.1, we see for both users require to transmit with more power in a channel with more noise power. Allocation of bits/channel use is proportional to SINR. The similar pattern on allocation of transmit power and bits/channel use are also observed for rest of the eight users and shown in Figs. 4.2-4.5.

Figure 4.2 shows the power and bits/channel use distribution across channels for user 1 and 10, respectively. We can see, user 1 is active on channels 2, 4, 5, 7 and 11 whereas user 10 is active on channels 2, 3, 5, 7, 10 and 11. Next, the power and bits/channel use allocation for users 2 and 6, respectively is presented in Fig. 4.3. Here, user 2 operates on channels 3, 5, 6, 7, 9 and 10 and user 6 operates on channels 3, 5, 7, 8, 9 and 10. Then, Fig. 4.4 illustrates the same power and bits/channel use allocation profile for users 4 and 8, respectively. In this figure, we can see user 4 is present on channels 1, 3, 4, 6, 7, 9 and 10, while user 8 is present on channels 1, 3, 5, 7, 8 and 10. Lastly, the power and bits/channel use distribution for users 5 and 9, respectively is depicted in Fig. 4.5, where user 5 operates on channels 1, 4, 6, 9 and 11 whereas user 9 operates on channels 2, 3, 5, 7, 8, 10 and 11. It is evident from Figs. 4.1-4.5 that all SUs shows similar transmit power and bits/channel use allocation across channels for the proposed framework. Here, all users are required to transmit with more power in channels with more noise power. That is allocation of transmit power is proportional to noise power. Also, we can see from these figures that the allocation of bits/channel use increases with increasing SINR.

As we have transformed BER constraint of our proposed optimization framework to ensure optimality of solution, hence it is also important to see whether the transformed BER constraint is providing required BER threshold. Figures 4.6-4.15 show the obtained BER values for all the users. Form these figures, we can observe that for all users, the obtained BER values are within the given limit of BER threshold value, $p_{e,i}^{t}\ \forall\ i = 10^{-3}$.

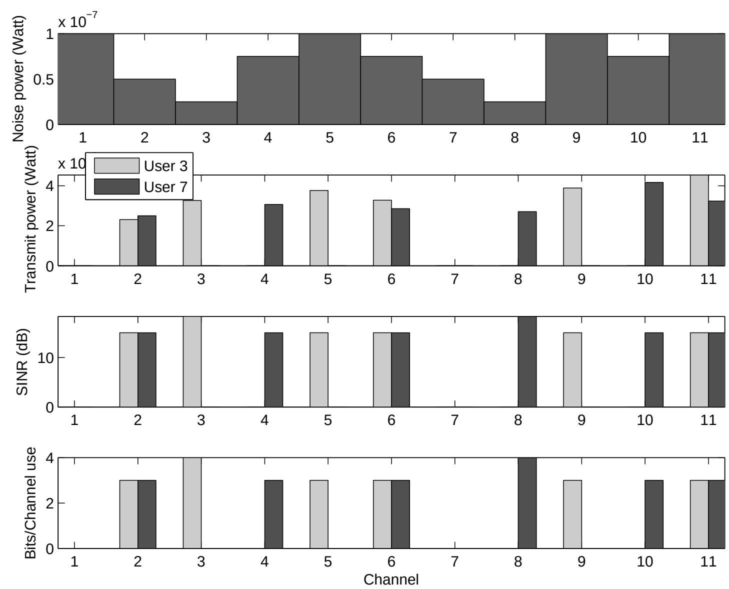

Figure 4.1: Allocation of transmit power and bits/channel use with channel noise power and SINR for users 3 and 7, respectively.

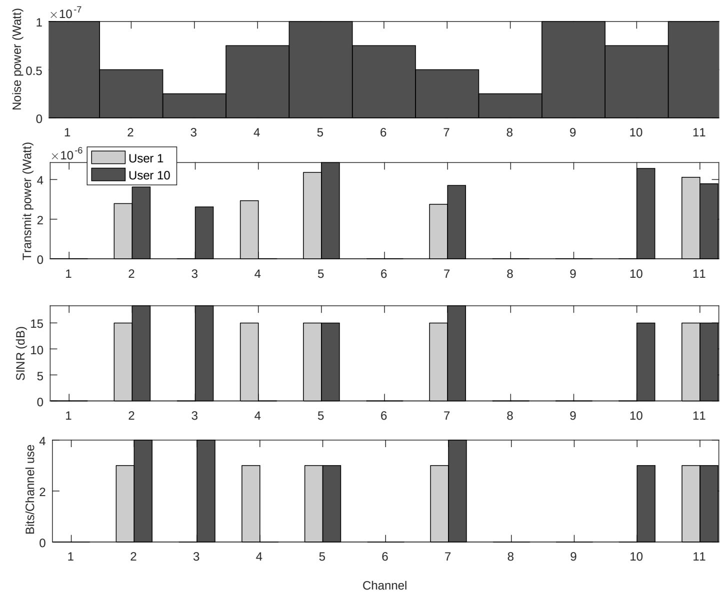

Figure 4.2: Allocation of transmit power and bits/channel use with channel noise power and SINR for users 1 and 10, respectively.

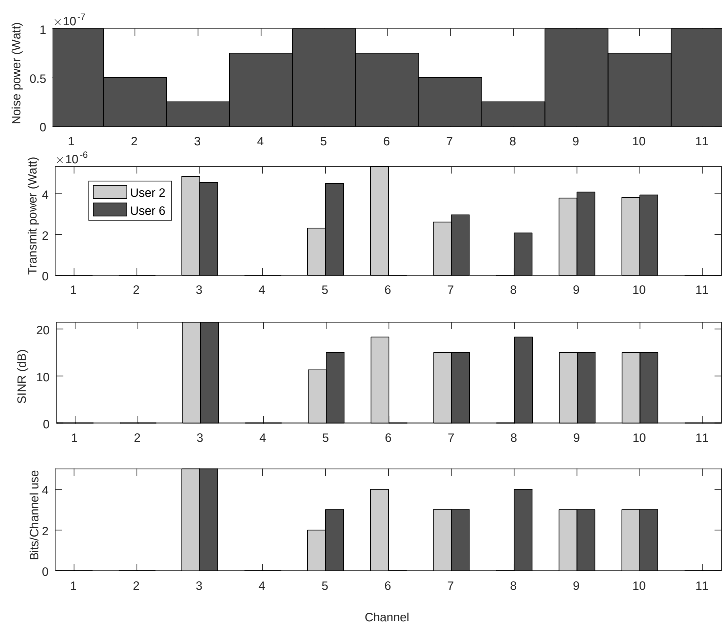

Figure 4.3: Allocation of transmit power and bits/channel use with channel noise power and SINR for users 2 and 6, respectively.

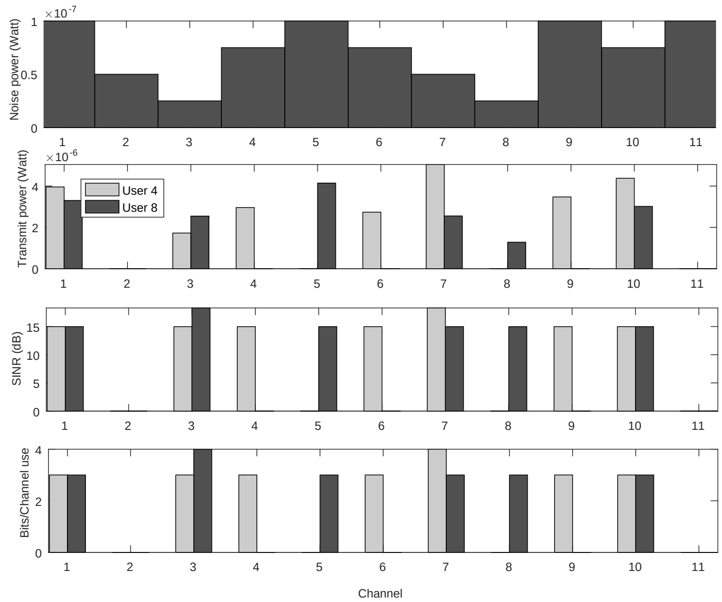

Figure 4.4: Allocation of transmit power and bits/channel use with channel noise power and SINR for users 4 and 8, respectively.

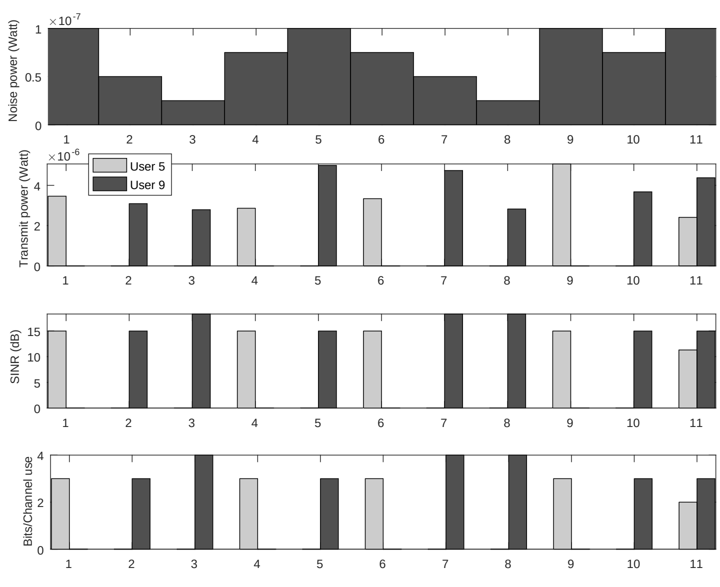

Figure 4.5: Allocation of transmit power and bits/channel use with channel noise power and SINR for users 5 and 9, respectively.

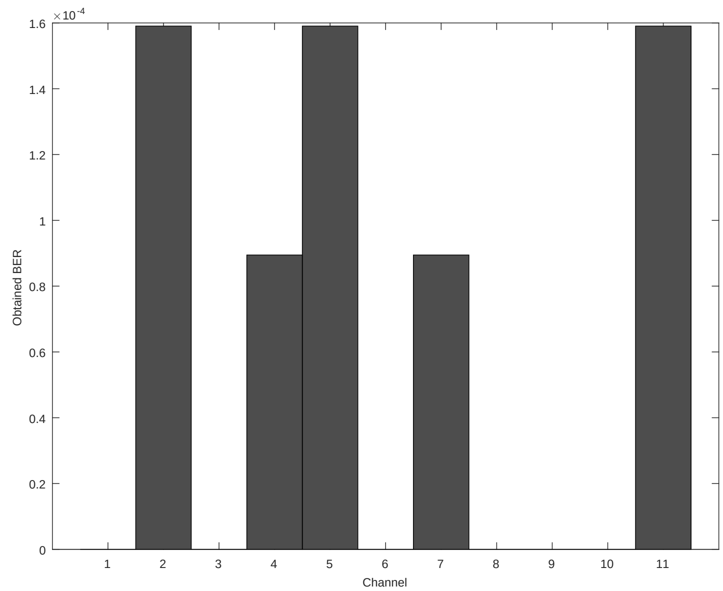

Figure 4.6: The obtained BER for user 1 across channels.

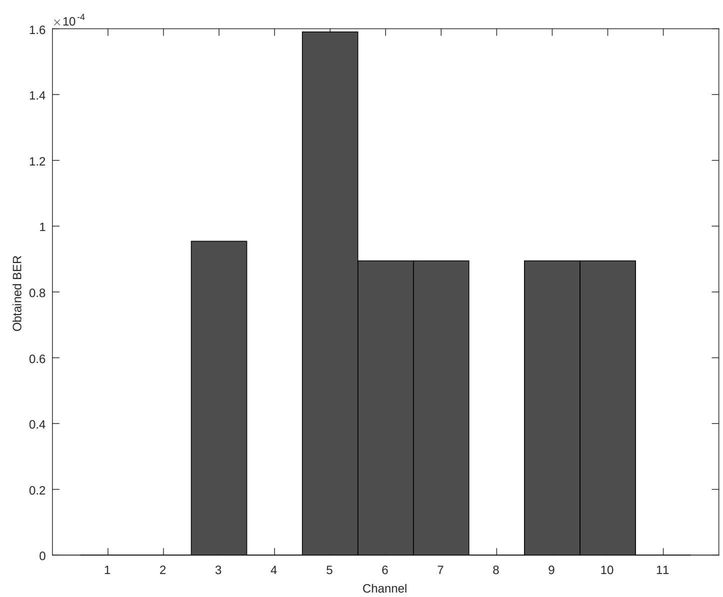

Figure 4.7: The obtained BER for user 2 across channels.

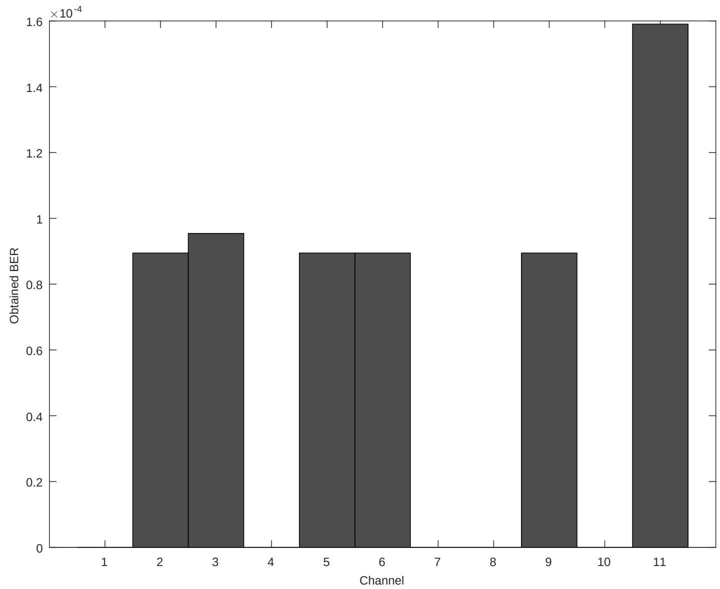

Figure 4.8: The obtained BER for user 3 across channels.

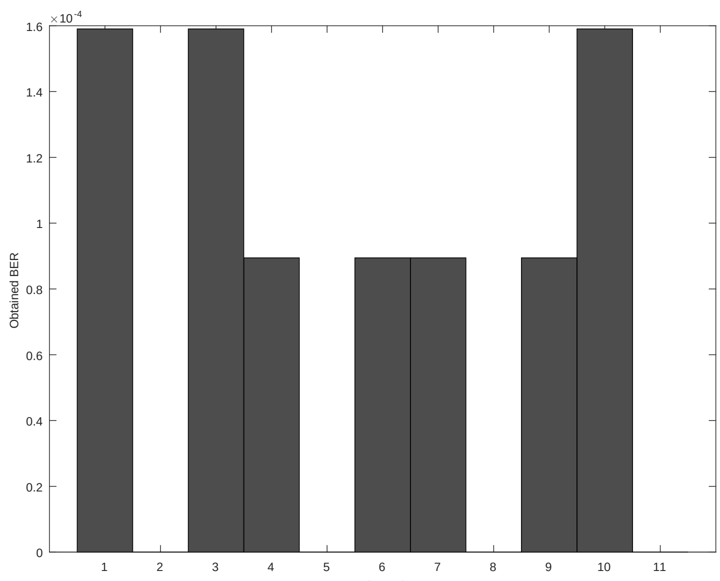

Figure 4.9: The obtained BER for user 4 across channels.

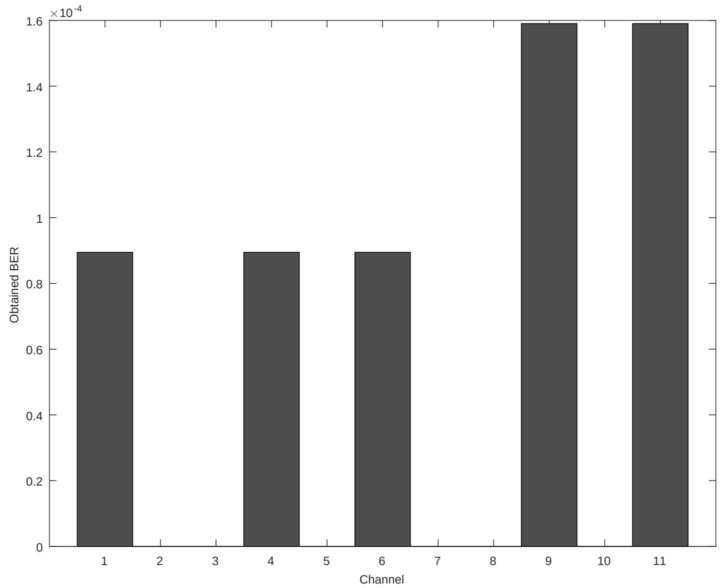

Figure 4.10: The obtained BER for user 5 across channels.

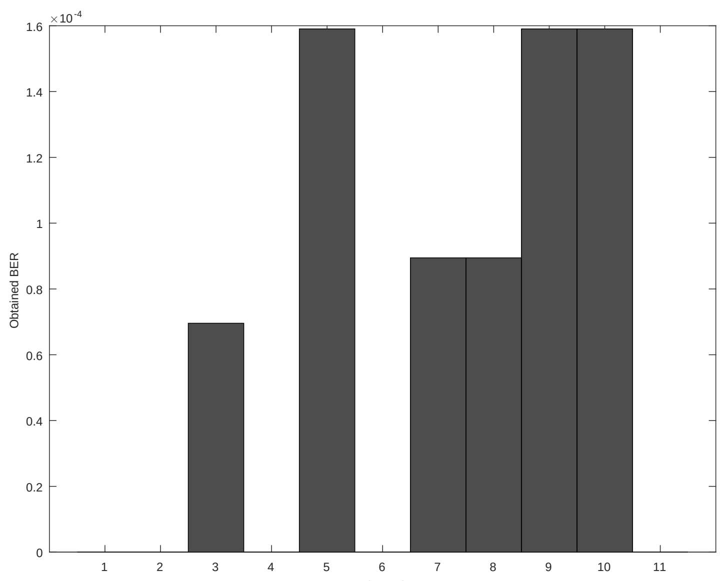

Figure 4.11: The obtained BER for user 6 across channels.

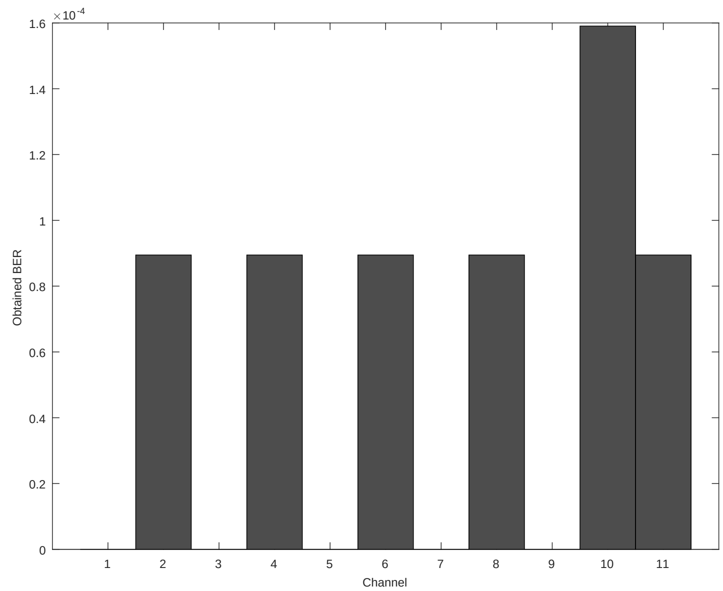

Figure 4.12: The obtained BER for user 7 across channels.

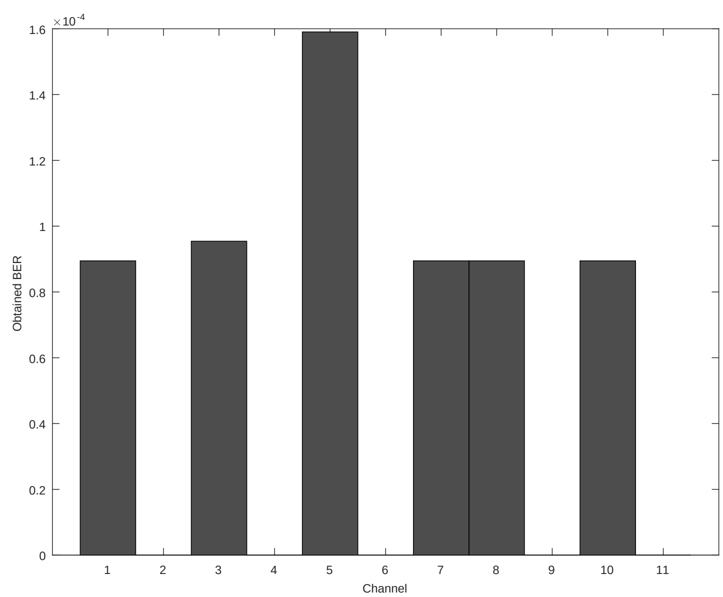

Figure 4.13: The obtained BER for user 8 across channels.

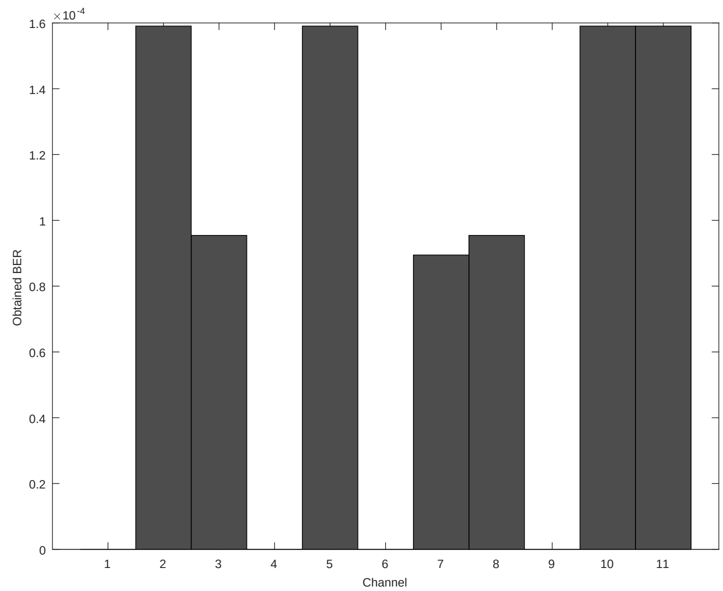

Figure 4.14: The obtained BER for user 9 across channels.

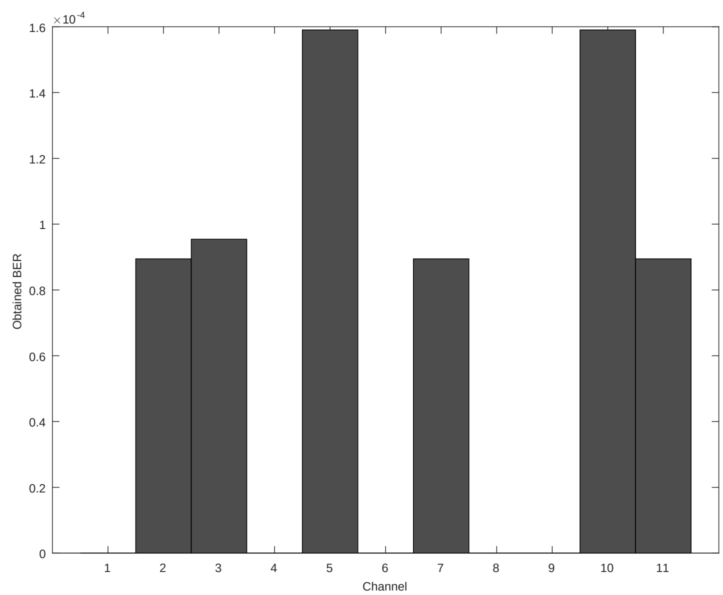

Figure 4.15: The obtained BER for user 10 across channels.

Figure 4.16 shows the total allocated power and total bits/channel use across users. Minimum bits/channel use requirement for all the users is also depicted in Fig. 4.16 as a bar. From this figure it can be seen that our proposed optimization framework is successful in satisfying the minimum bits/channel use requirement for all users. The total allocated power and total bits/channel use across users using allocation framework in [43] is also shown in Fig. 4.16. It is seen from this figure that the proposed framework allocates more bits/channel use than in [43]. Though more transmit power is required than in [43]. However, the spent power is within its limit.

The channel bits/channel use supporting capability obtained from our proposed framework along with [43] is shown in Fig. 4.17. From this figure, we see that the proposed framework is more capable in supporting bits/channel use. It is important to note that in [43], the channel bits/channel use supporting capability upper bound i.e., $b_{ch}^t(k)$ is calculated by following the concept shown in [49] as:

$$b_{ch}^t(k) = \frac{1}{2} log_2 \left(1 + \frac{\sum_{i=1}^{\widetilde{N}_s(k)} p_i^{max}(k) h_{i,i}(k)}{\sigma^2(k)} \right).$$

The framework in [43] provides channel total bits/channel use within its bound. However, in proposed framework we relax the bound on channel total bits/channel use i.e., power per channel per user upper bound and consider an upper bound on total transmit power across channels for users. This consideration makes the proposed framework more capable in supporting channel total bits/channel use and hence in supporting higher users' minimum bits/channel use requirement. As for example, the framework in [43] fails to provide solution for a scenario where R_i^l is doubled for users and all other parameters are kept as same they were. Whereas, our proposed framework is successful for this scenario. The total allocated power and total bits/channel use across users obtained by proposed framework for this case is shown in Fig. 4.18.

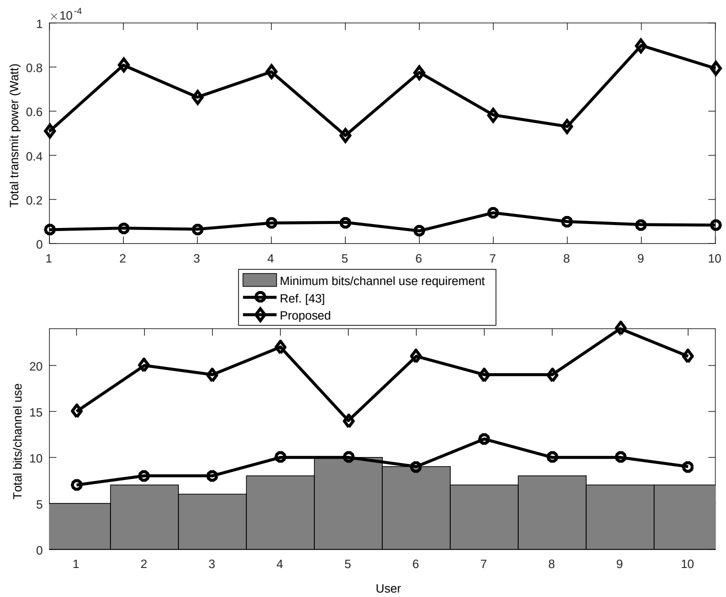

Figure 4.16: Allocation of total transmit power and total bits/channel use across users.

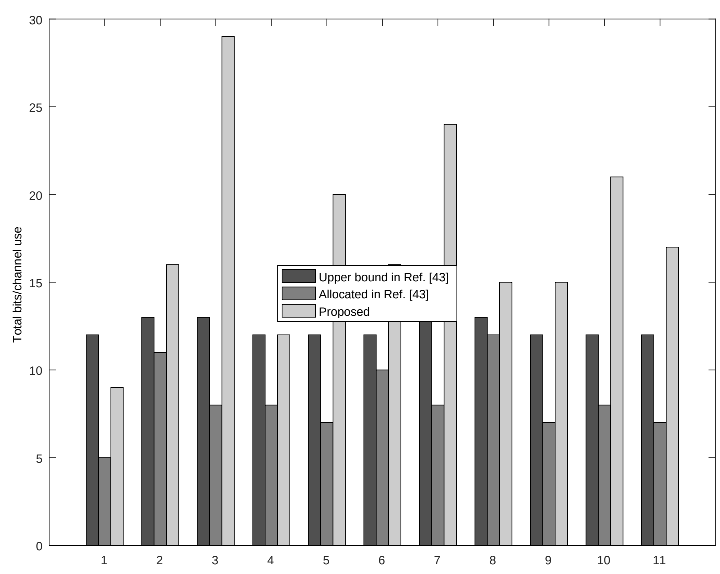

Figure 4.17: Channel bits/channel use supporting capability.

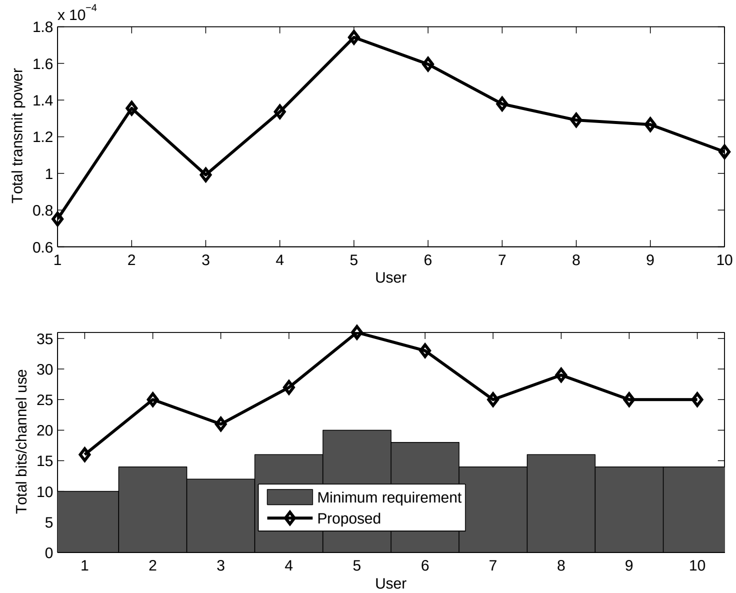

Figure 4.18: Allocation of total transmit power and total bits/channel use across users.

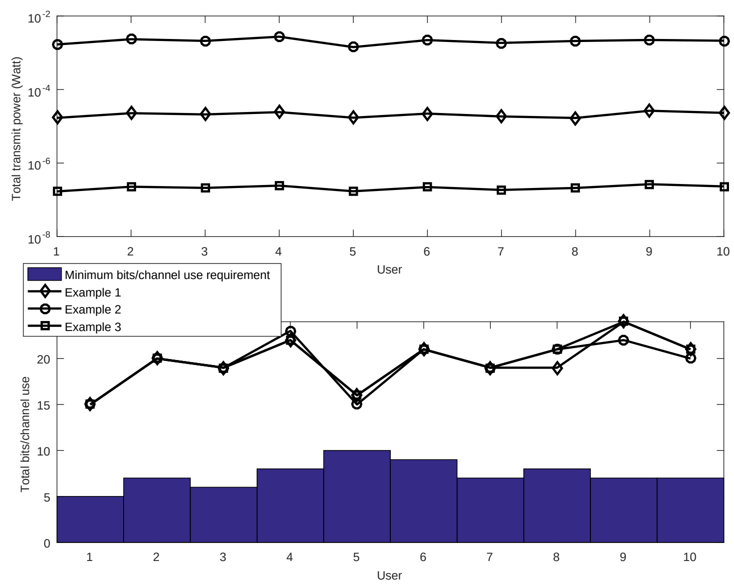

Figure 4.19: Allocation of total transmit power and total bits/channel use across users for different noise levels.

4.2.1 Effect of Noise Level

Now, we observe the impact of different noise levels on the performance of the proposed optimization framework. Consequently, we consider the channel quality parameter shown in Table 4.2 as example 1, the channel quality parameter shown in Table 4.6 as example 2 and the channel quality parameter shown in Table 4.7 as example 3. The rest of the system parameters are kept same as in Sec. 4.1 in all three example cases. Figure 4.19 shows the allocation of total transmit power and total bits/channel use across users for examples 1, 2 and 3. User's minimum bits/channel use requirement for all the users is also depicted in this figure as a bar. Figure 4.19 shows that the total transmit power allocation is proportional to the noise power. However, the total bits/channel use allocation are identical for all three examples and our proposed optimization framework successfully achieves the minimum bits/channel use requirement for all the users in all three example cases. So, it can be implied that the framework spends more transmit power in order to maximize the total bits/channel use with the increase of noise levels. Figure 4.20 illustrates the allocation of transmit power and bits/channel use across channels (assuming scalarization parameters τ_1 and τ_2 to 0.5) for user 1 for examples 1, 2 and 3. The resulting SINR are also shown in the figure. In this figure, it can be observed that in all three example cases, with the increasing noise level the allocation transmit power also increases to ensure the same SINR value as expected. The similar pattern on allocation of transmit power and bits/channel use for three different noise levels are also observed for rest of the nine users and shown in Figs 4.21-4.29.

Channel, k	1	2	3	4	5	6	7	8	9	10	11
$\sigma^2(k)$, $(\times 10^{-6})$	0.1	5	2.5	7.5	0.1	7.5	5	2.5	0.1	7.5	0.1

Table 4.6: Channel quality parameters for Example 2.

Channel, k	1	2	3	4	5	6	7	8	9	10	11
$\sigma^2(k)$, $(\times 10^{-10})$	0.1	5	2.5	7.5	0.1	7.5	5	2.5	0.1	7.5	0.1

Table 4.7: Channel quality parameters for Example 3.

4.2.2 Effect of BER Threshold

Figure 4.30 presents the allocation of total transmit power and total bits/channel use across users for two different BER threshold ($p^t_{e,i}$) values, i.e., example 1 and example 2. Minimum bits/channel use requirement for all the users is also depicted in Fig. 4.30 as a bar. Here, for example 1, $p^t_{e,i}$ is set to 10^{-3} and for example 2, $p^t_{e,i}$ is set to 10^{-4}. The rest of the system parameters are kept same as in Sec. 4.1. The value of C_{qarg} is computed following the method discussed earlier in Sec 4.1 and $C_{qarg} = 6.19$ is set to guarantee a BER that is less than or equal to 10^{-4}. Fig. 4.30 illustrates that to achieve minimum buts/channel use requirement with the reduced BER threshold the allocated total transmit power for Example 2 is more with compare to example 1. In this figure, although, the bits/channel use allocation for example 2 is reduced but the proposed optimization framework is successful in satisfying the minimum bits/channel use requirement for all users. Now, for this same set up, the transmit power and bits/channel use allocation across channels (assuming scalarization parameters τ_1 and τ_2 to 0.5) for user 1 is depicted in Fig. 4.31. The resulting SINR are also shown in the figure. Figure 4.31 illustrates that with decrease in BER threshold, the allocation of transmit power increases resulting higher SINR. Similar pattern on allocation of transmit power and bits/channel use for different BER threshold are also observed for rest of the nine users and shown in Figs 4.32-4.40.

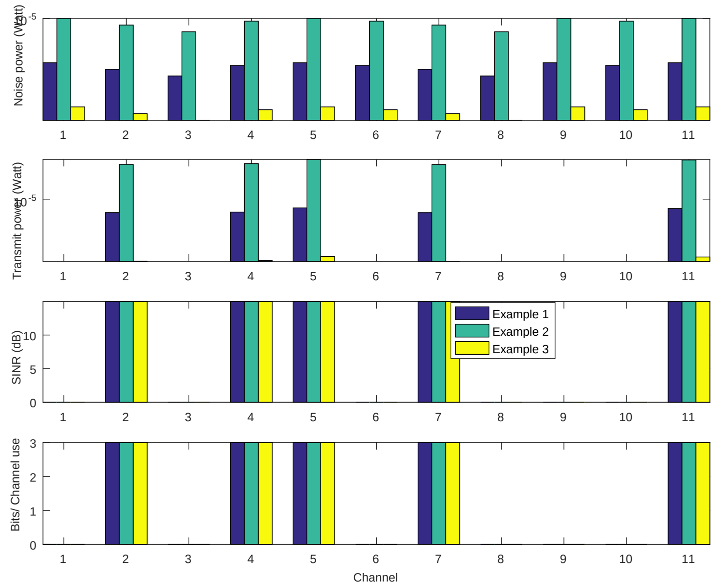

Figure 4.20: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 1 for different noise levels.

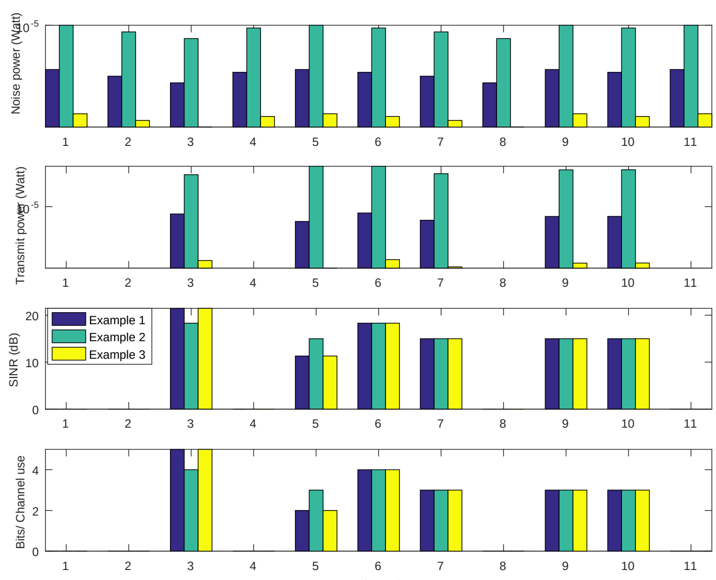

Figure 4.21: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 2 for different noise levels.

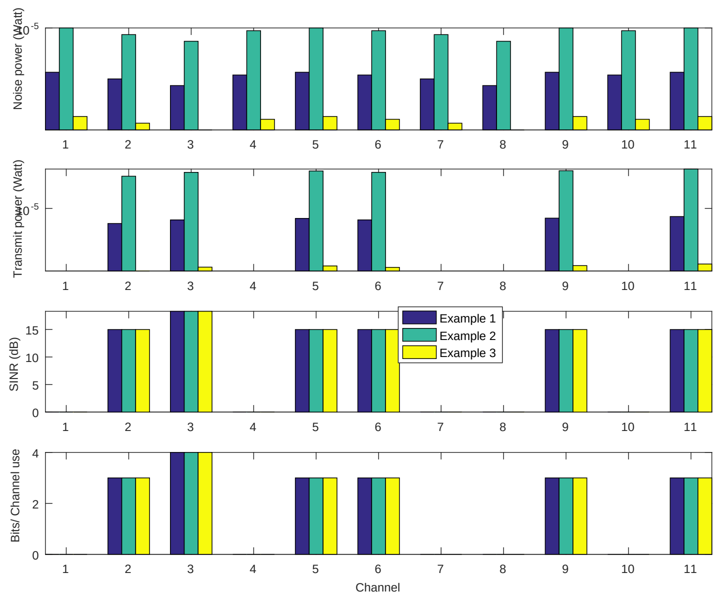

Figure 4.22: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 3 for different noise levels.

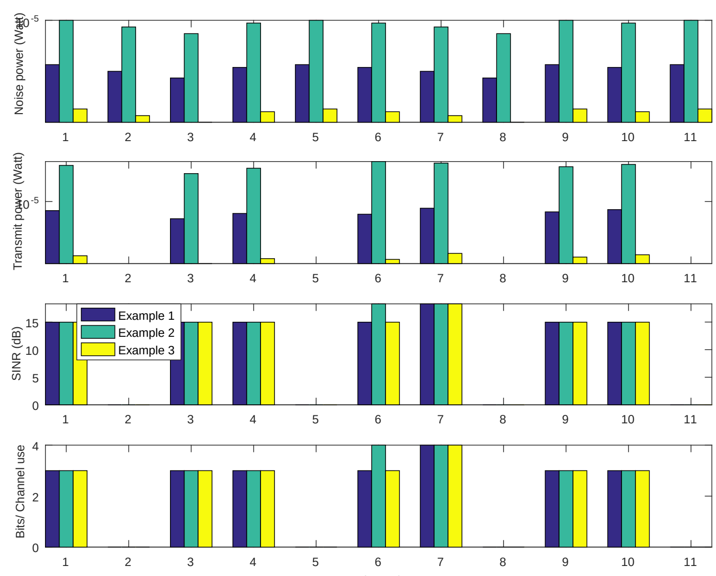

Figure 4.23: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 4 for different noise levels.

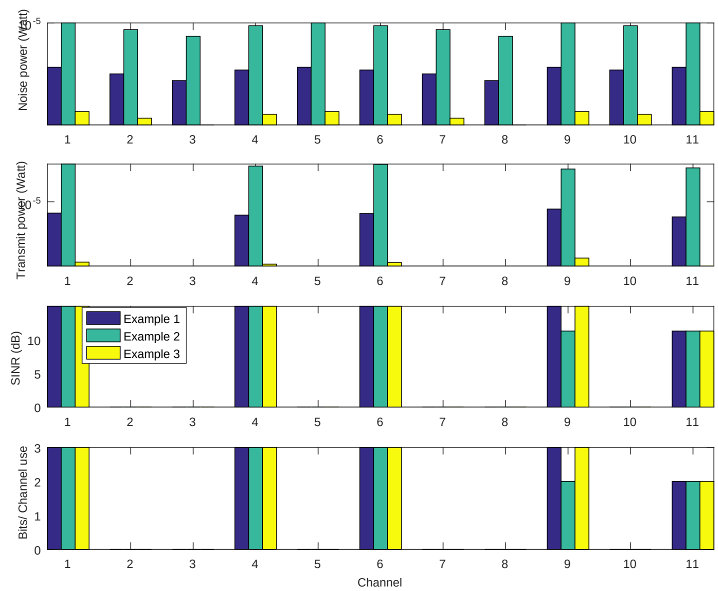

Figure 4.24: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 5 for different noise levels.

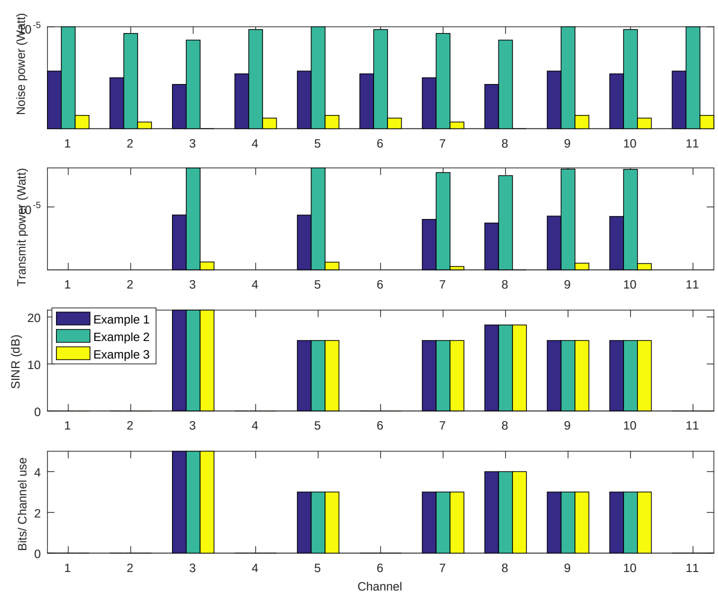

Figure 4.25: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 6 for different noise levels.

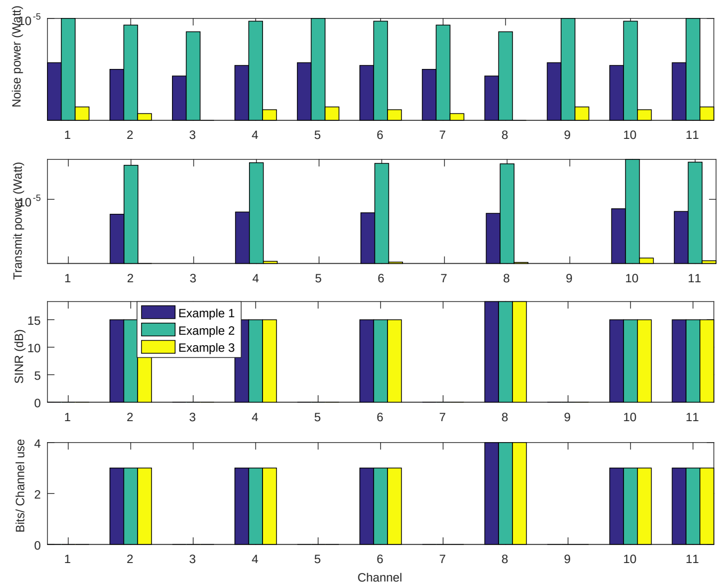

Figure 4.26: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 7 for different noise levels.

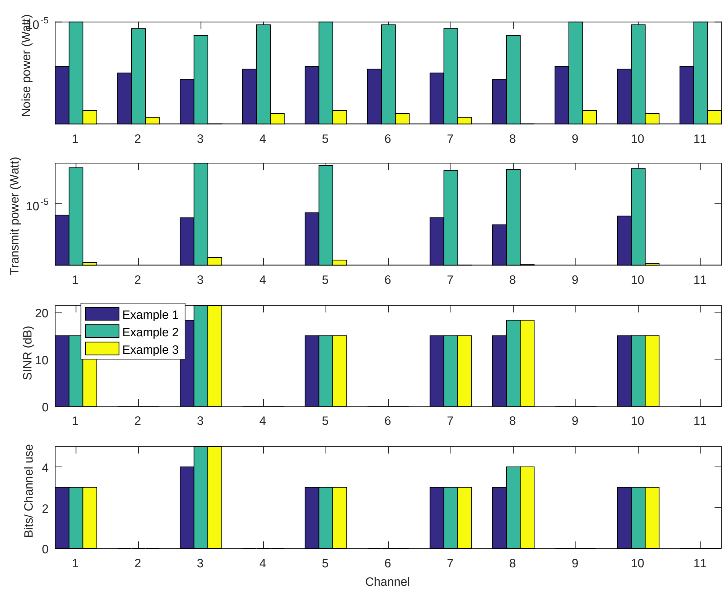

Figure 4.27: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 8 for different noise levels.

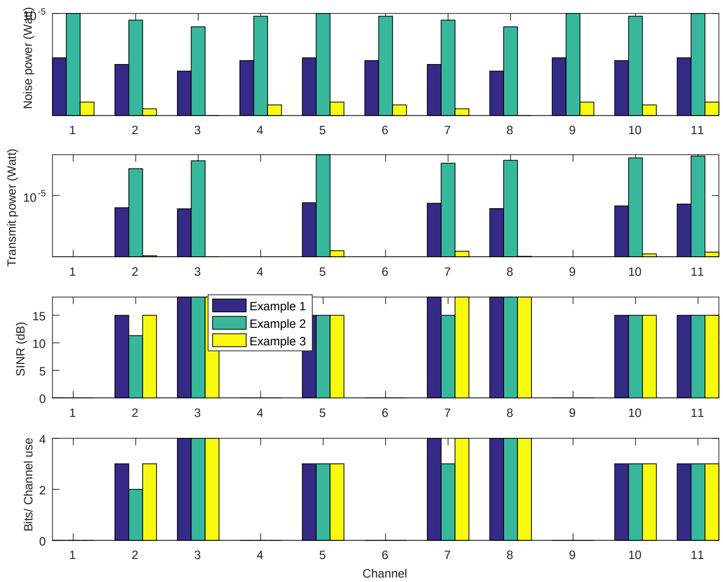

Figure 4.28: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 9 for different noise levels.

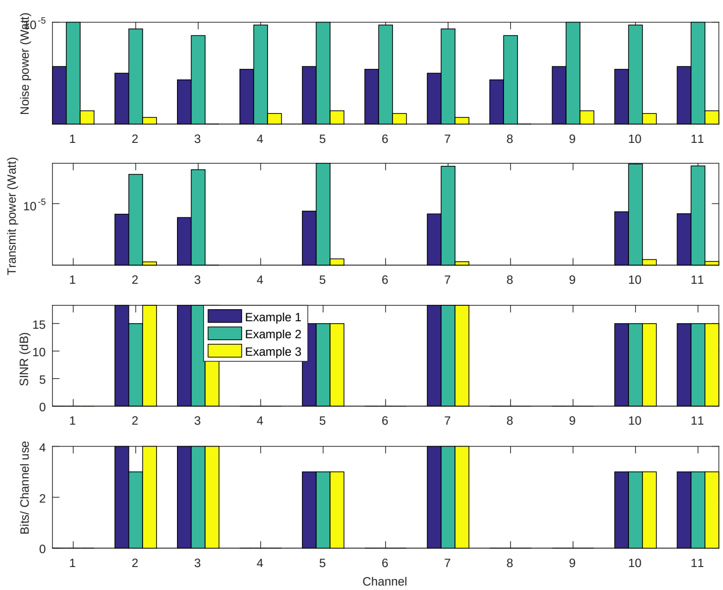

Figure 4.29: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 10 for different noise levels.

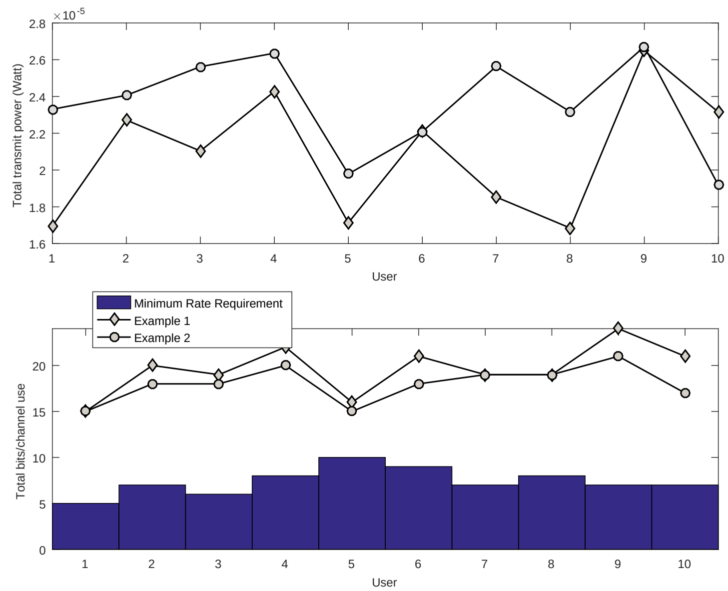

Figure 4.30: Allocation of total transmit power and total bits/channel use across users for different BER threshold.

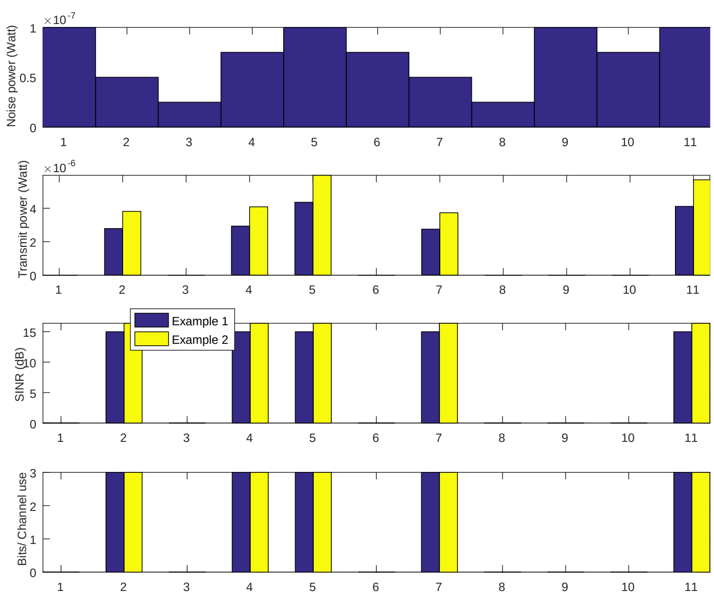

Figure 4.31: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 1 for different BER threshold.

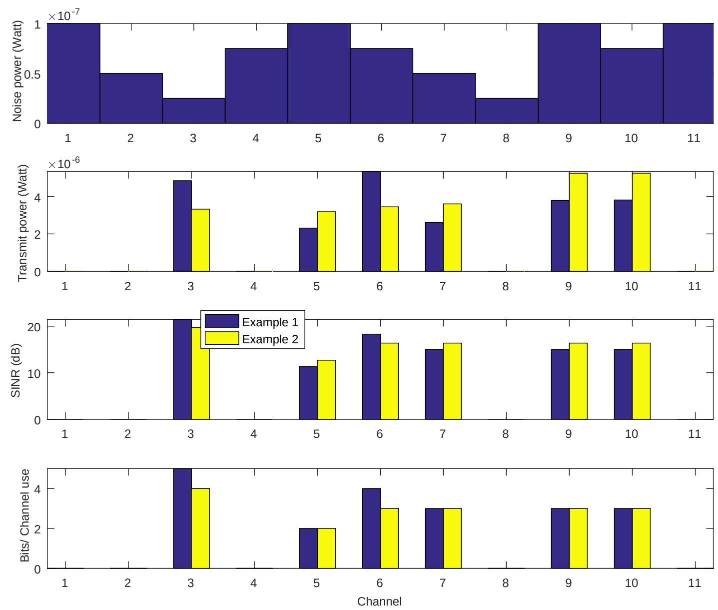

Figure 4.32: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 2 for different BER threshold.

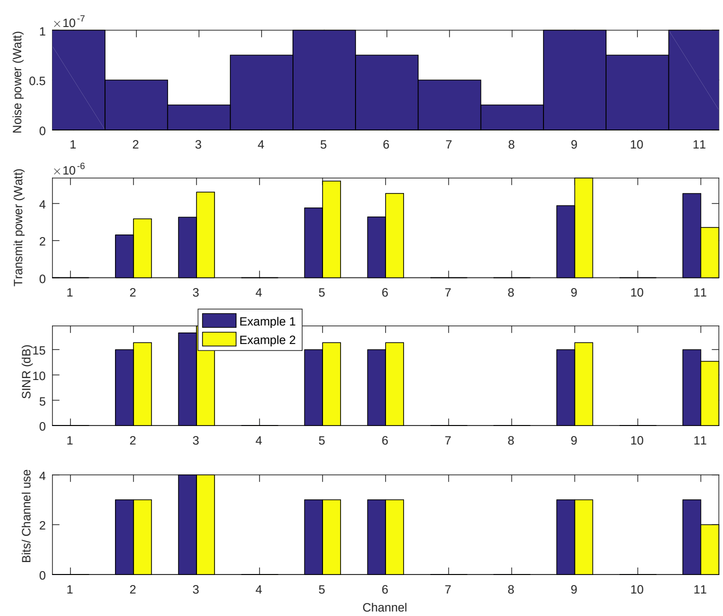

Figure 4.33: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 3 for different BER threshold.

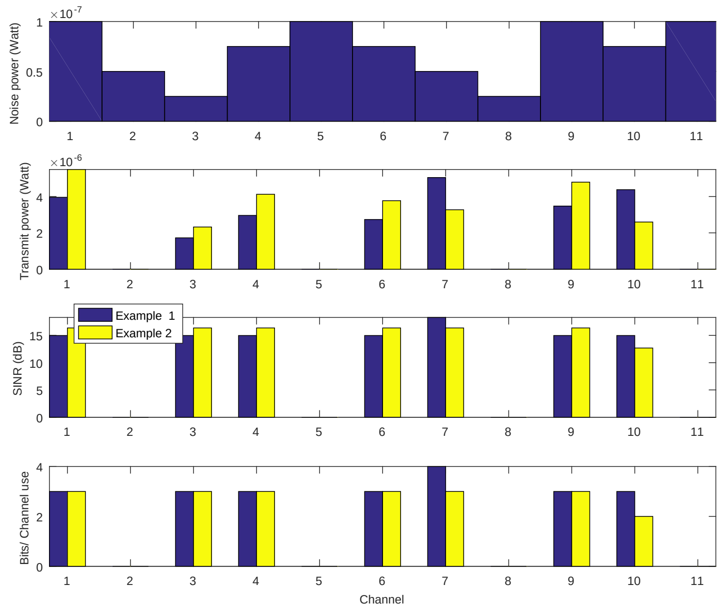

Figure 4.34: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 4 for different BER threshold.

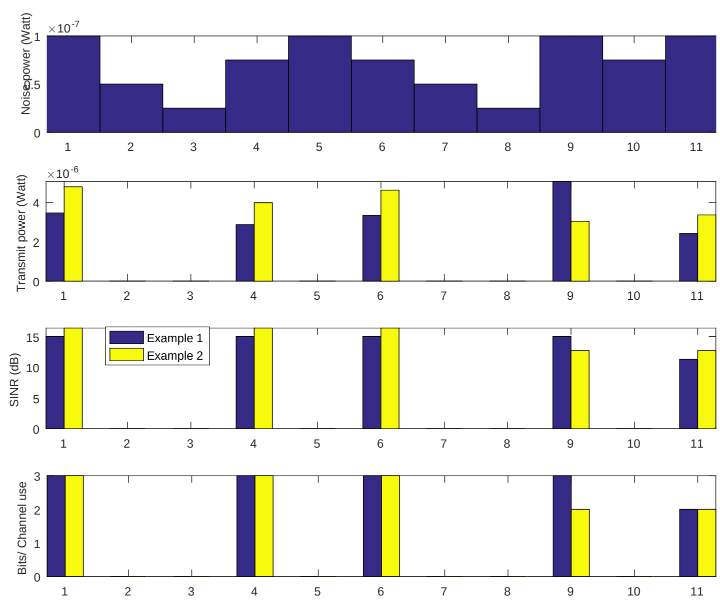

Figure 4.35: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 5 for different BER threshold.

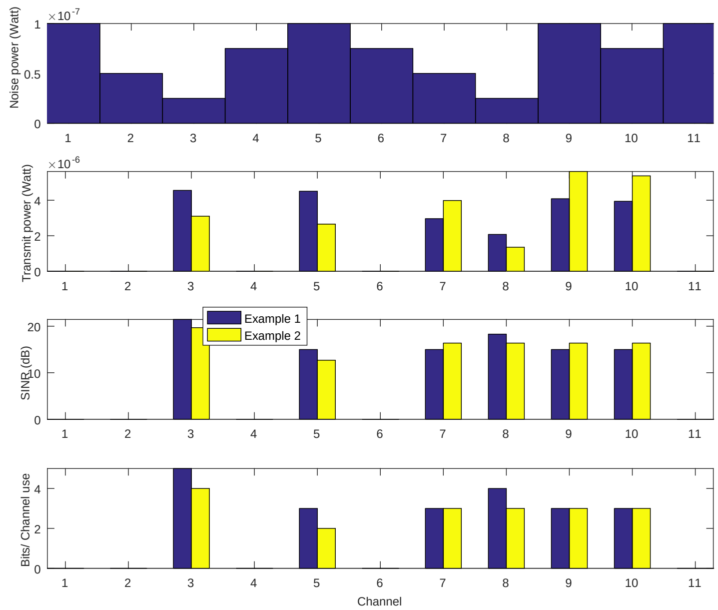

Figure 4.36: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 6 for different BER threshold.

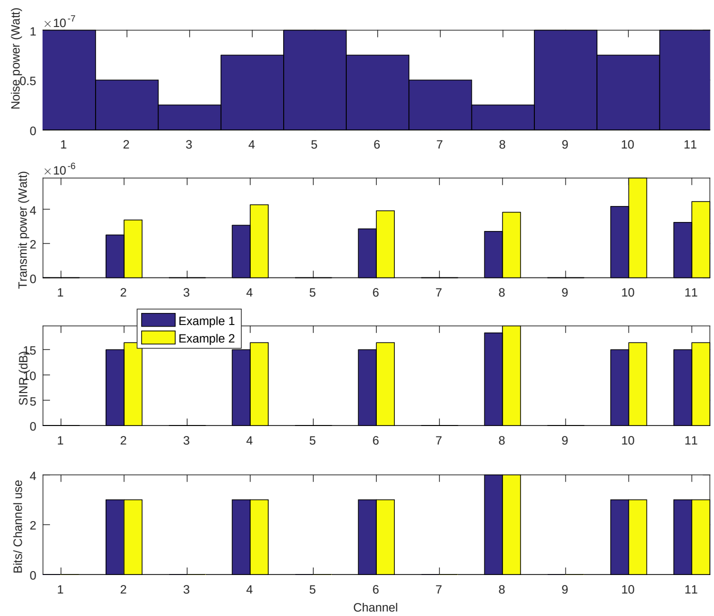

Figure 4.37: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 7 for different BER threshold.

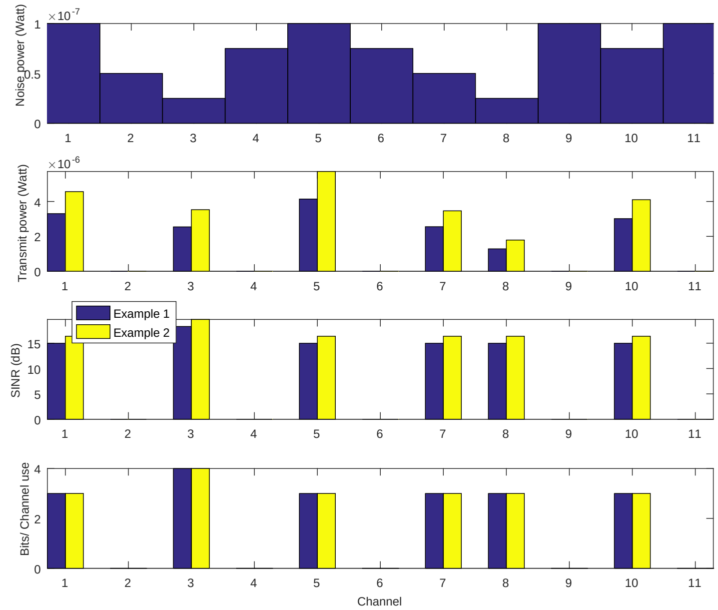

Figure 4.38: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 8 for different BER threshold.

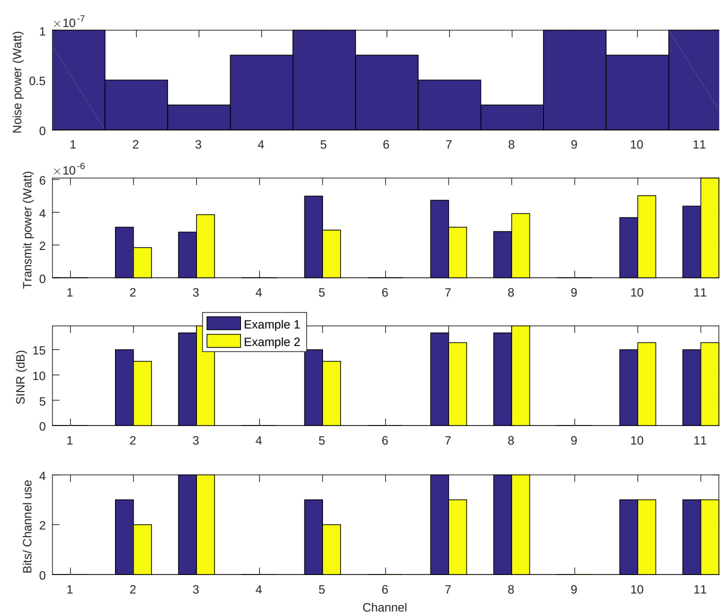

Figure 4.39: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 9 for different BER threshold.

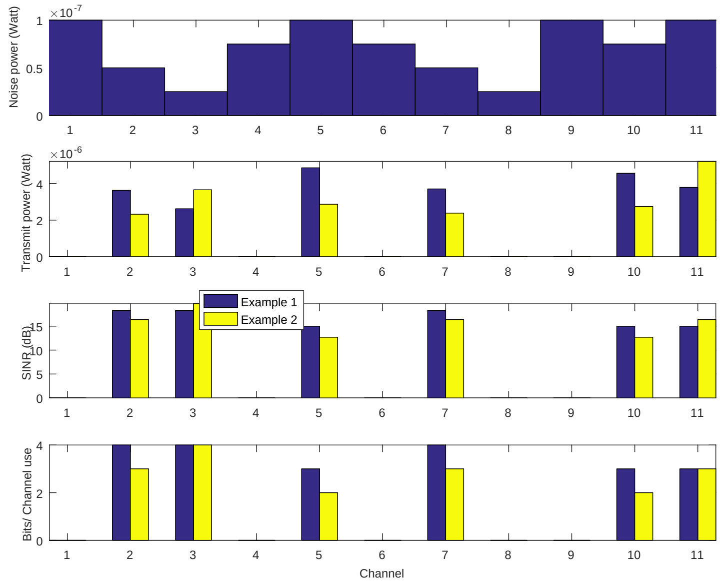

Figure 4.40: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 10 for different BER threshold.

4.2.3 Effect of Users' Minimum Bits/Channel use Requirements

Figure 4.41 illustrates the total transmit power and bits/channel use allocation across users for three different sets of users' minimum bits/channel requirement. Here also, we consider three example cases. In example 1, the users' minimum bits/channel use requirement are set as in Table 4.3, in example 2, the users' minimum bits/channel use requirement are set as in Table 4.8, and in example 3, the users' minimum bits/channel use requirement are set as in Table 4.9. Here, rest of the system parameters are kept same as in Sec. 4.1 for all examples. In Fig. 4.41 the users' minimum bits/channel use requirement for three examples are shown as bar. Figure 4.41 illustrates that in all three example cases, the transmit power distribution profile are almost identical. However, our proposed optimization framework is successful in satisfying the minimum bits/channel use requirement for all users for all three example cases. Figure

4.42 depicts the allocation of transmit power and bits/channel use across channels (assuming scalarization parameters τ_1 and τ_2 to 0.5) for user 1 for three example cases. The resulting SINR are also shown in the figure. Figure 4.42 also shows that the allocation of transmit power and bits/channel use across channels are identical for user 1 for all three example cases. Almost similar pattern on allocation of transmit power and bits/channel use are also observed for rest of the nine users and shown in Figs 4.43-4.51 for example 1, 2 and 3.

User, i	1	2	3	4	5	6	7	8	9	10
R_i^l	10	14	12	16	20	18	14	16	14	14

Table 4.8: Minimum bits/channel use requirement of users for example 2.

User, i	1	2	3	4	5	6	7	8	9	10
R_i^l	12.5	17.5	15	20	25	22.5	17.5	20	17.5	17.5

Table 4.9: Minimum bits/channel use requirement of users for example 3.

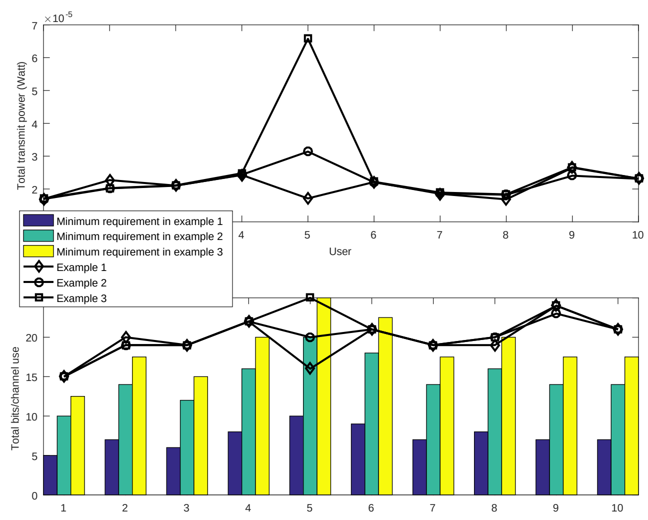

Figure 4.41: Allocation of total transmit power and total bits/channel use across users for different minimum bits/channel use requirement.

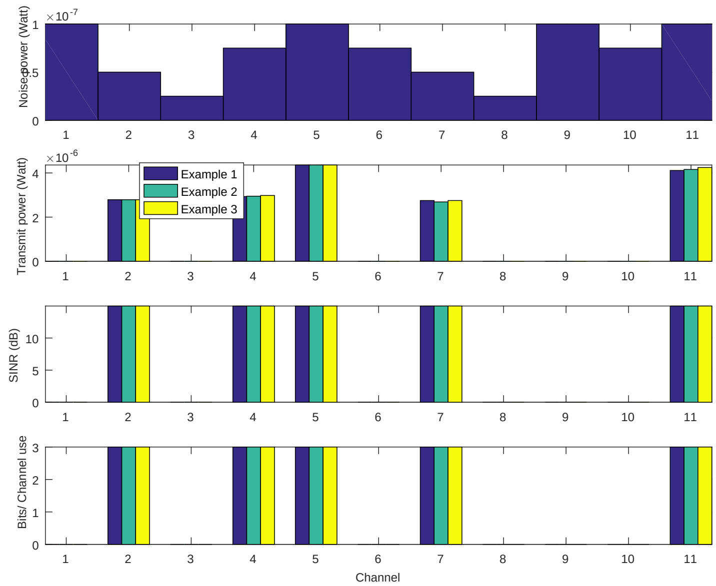

Figure 4.42: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 1 for different minimum bits/channel use requirement.

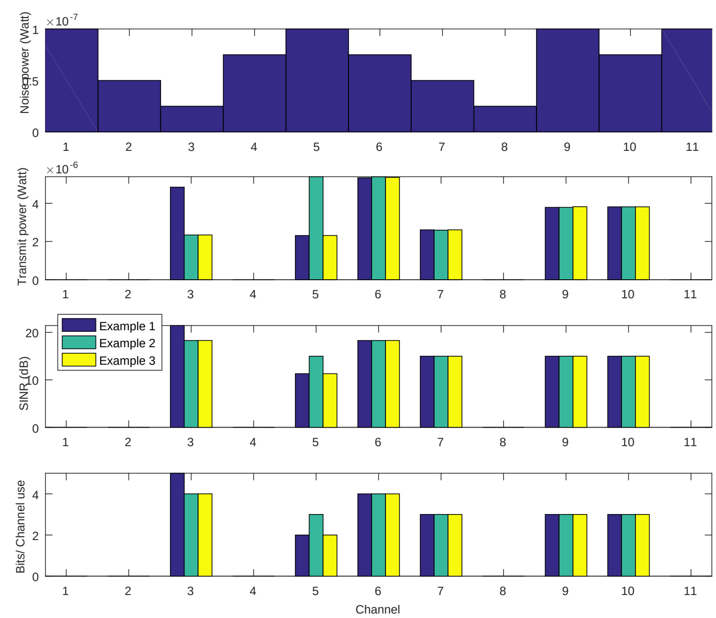

Figure 4.43: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 2 for different minimum bits/channel use requirement.

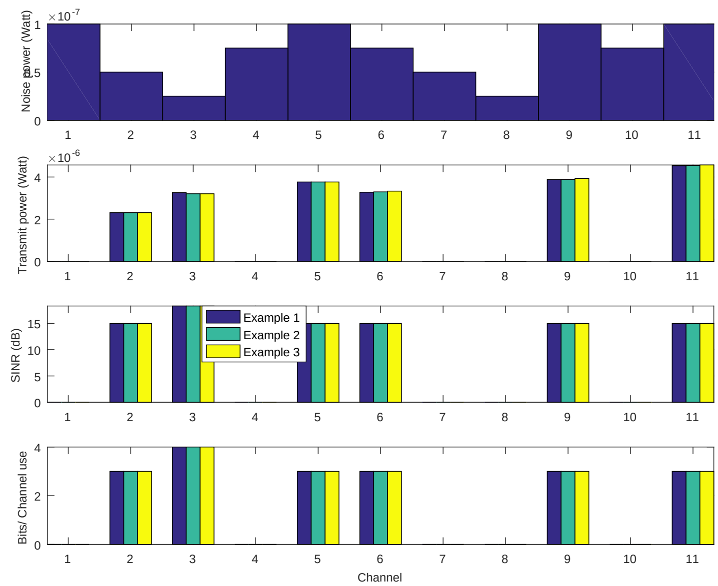

Figure 4.44: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 3 for different minimum bits/channel use requirement.

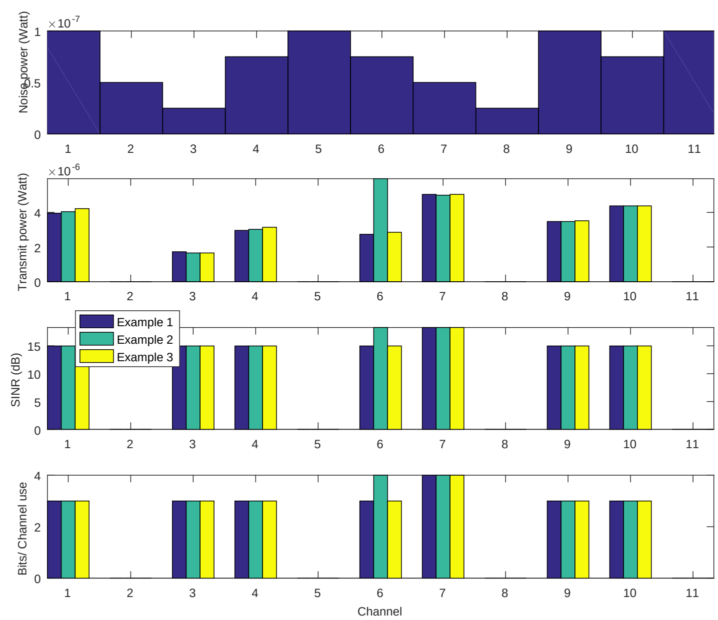

Figure 4.45: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 4 for different minimum bits/channel use requirement.

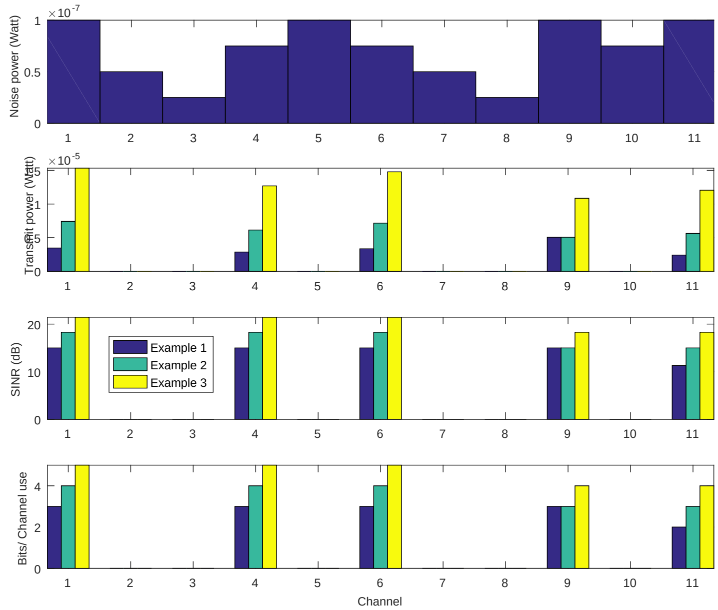

Figure 4.46: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 5 for different minimum bits/channel use requirement.

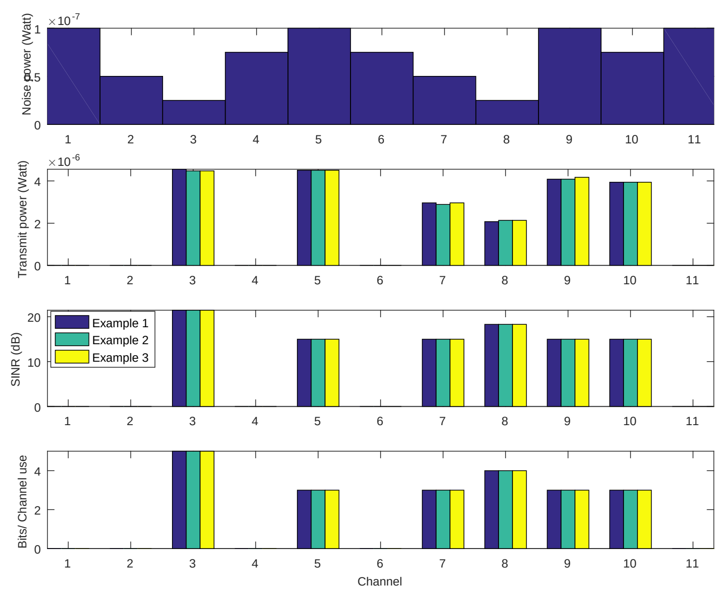

Figure 4.47: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 6 for different minimum bits/channel use requirement.

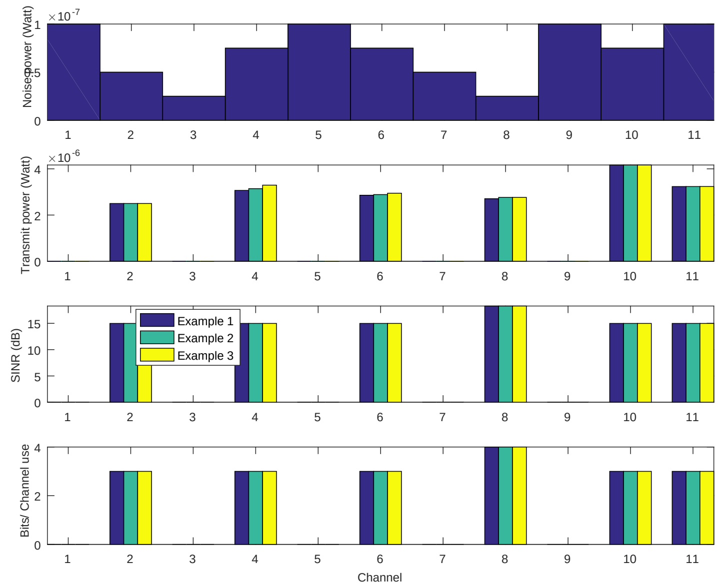

Figure 4.48: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 7 for different minimum bits/channel use requirement.

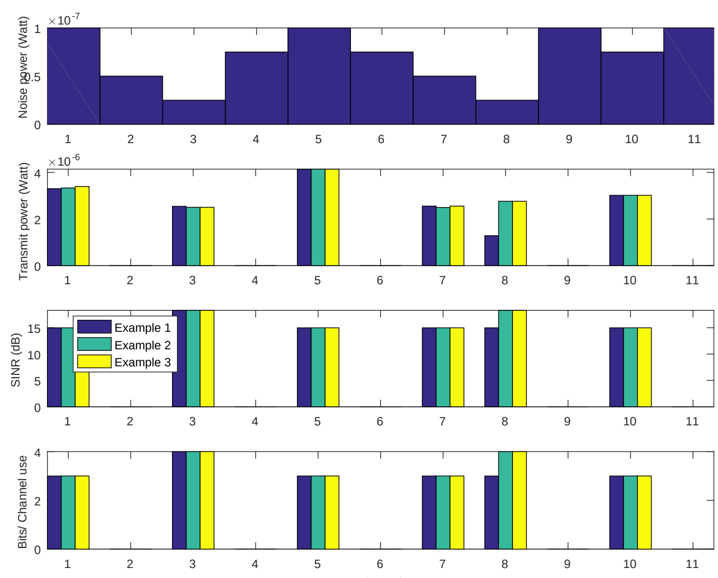

Figure 4.49: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 8 for different minimum bits/channel use requirement.

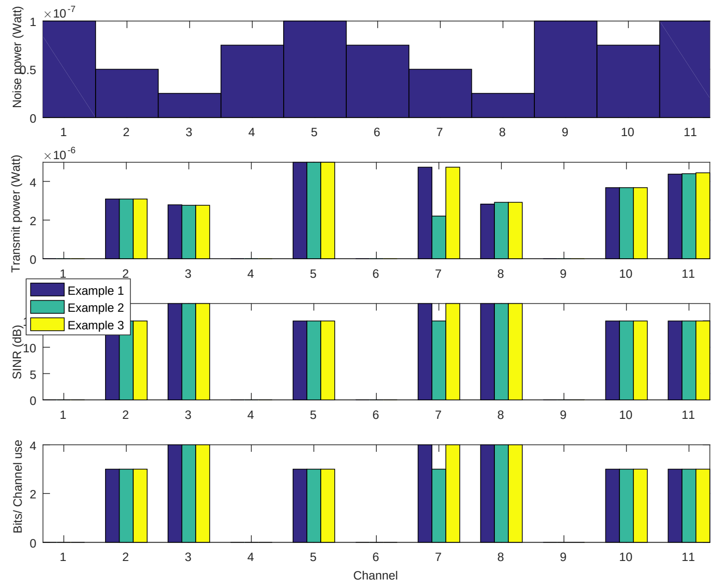

Figure 4.50: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 9 for different minimum bits/channel use requirement.

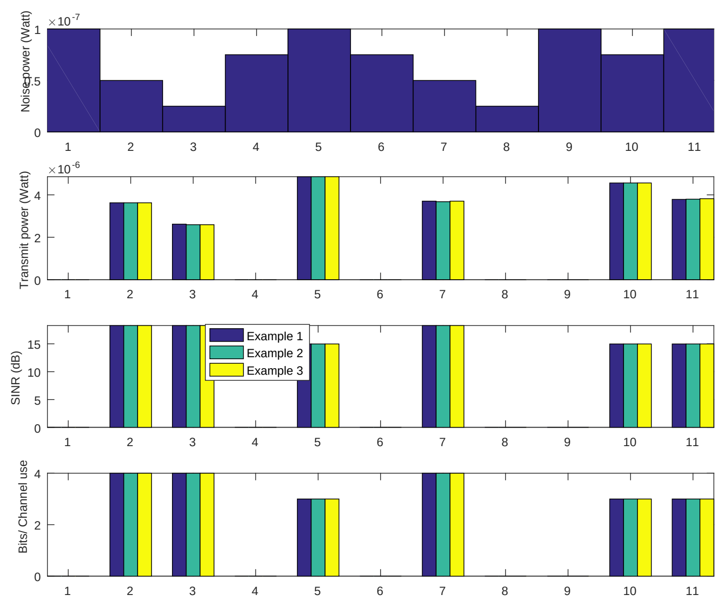

Figure 4.51: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 10 for different minimum bits/channel use requirement.

4.2.4 Effect Of Users' Power Budget

Now, we observe the impact of higher users' power budget on the performance of the proposed optimization framework. 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 kept same as in Sec. 4.1 in both examples. Figure 4.52 shows the allocation of total transmit power and total bits/channel use across users for examples 1 and 2. User's minimum bits/channel use requirement for all the users is also depicted in this figure as a bar. Figure 4.52 shows that the total transmit power and total bits/channel use allocation profile for both examples are same. Hence, in this case users' increased power budget have not any significant impact on the performance on the proposed framework. Similar result is observed for allocation of transmit power and bits/channel use across channels (assuming scalarization parameters τ_1 and τ_2 to 0.5) for user 1 for both examples in Fig. 4.53. The resulting SINR are also shown in the figure. The similar pattern on allocation of transmit power and bits/channel use for three different noise levels are also observed for rest of the nine users and shown in Figs 4.54-4.62.

User, i	1	2	3	4	5	6	7	8	9	10
p_i^{max}(Watt)	7.5	10.5	9	12	15	13.5	10.5	12	10.5	10.5

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

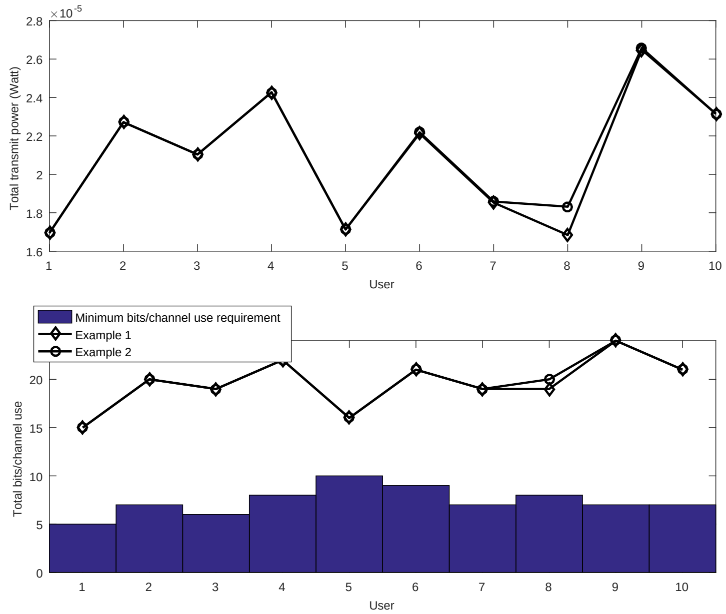

Figure 4.52: Allocation of total transmit power and total bits/channel use across users for different users' power budget.

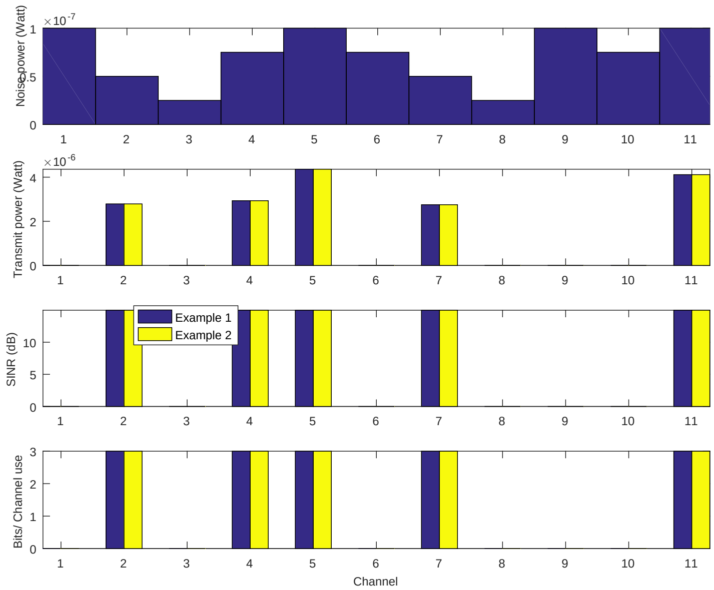

Figure 4.53: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 1 for different users' power budget.

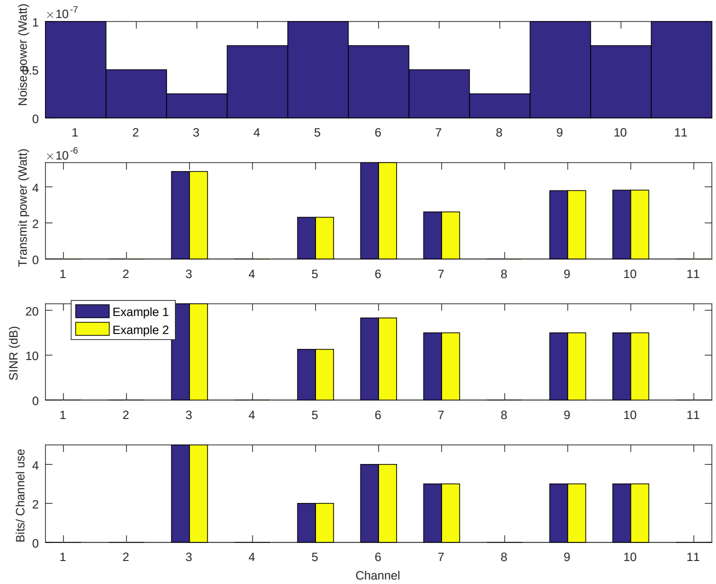

Figure 4.54: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 2 for different users' power budget.

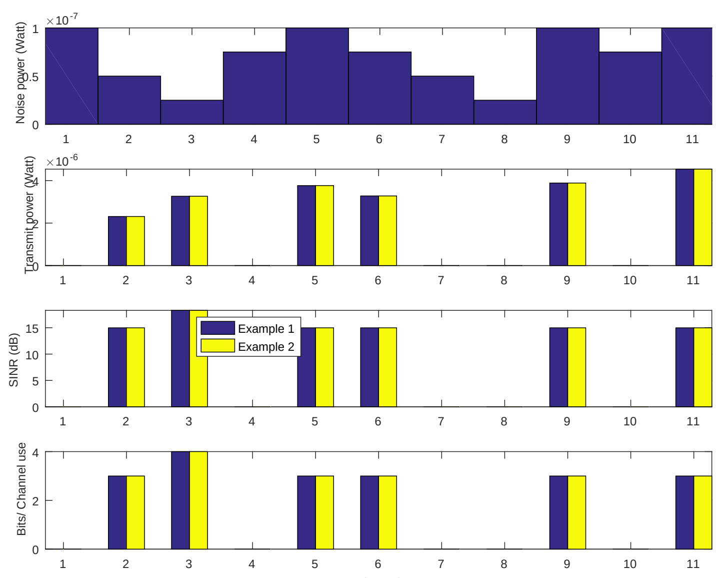

Figure 4.55: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 3 for different users' power budget.

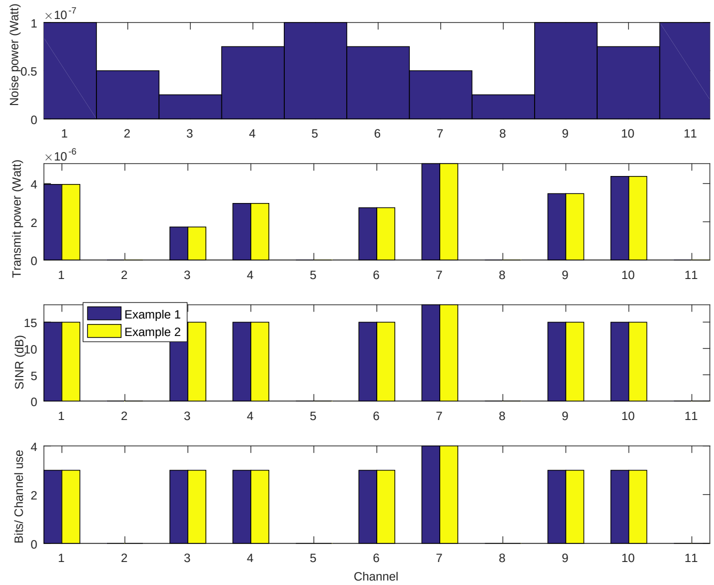

Figure 4.56: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 4 for different users' power budget.

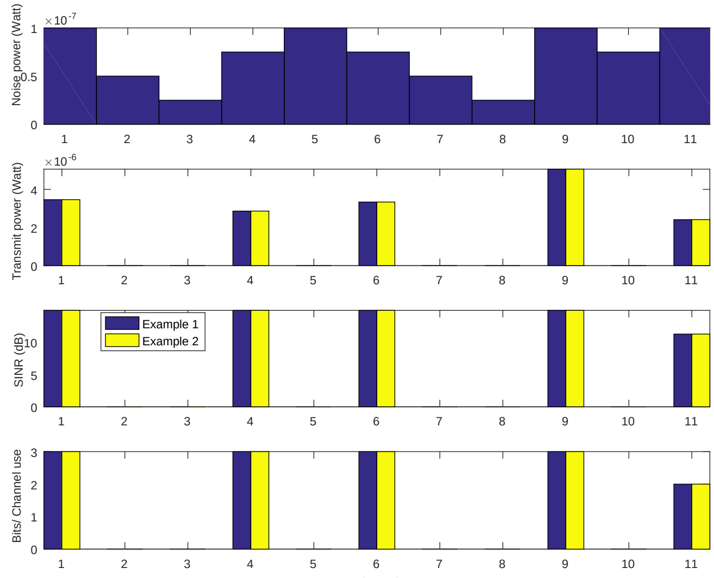

Figure 4.57: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 5 for different users' power budget.

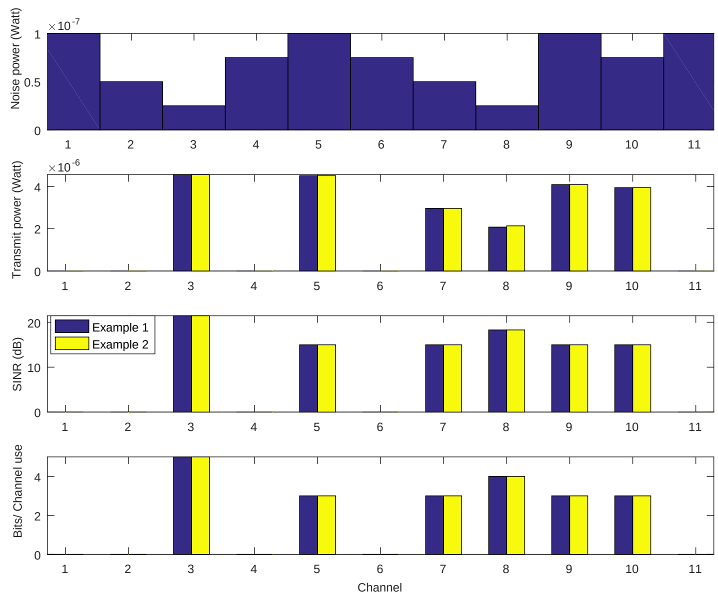

Figure 4.58: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 6 for different users' power budget.

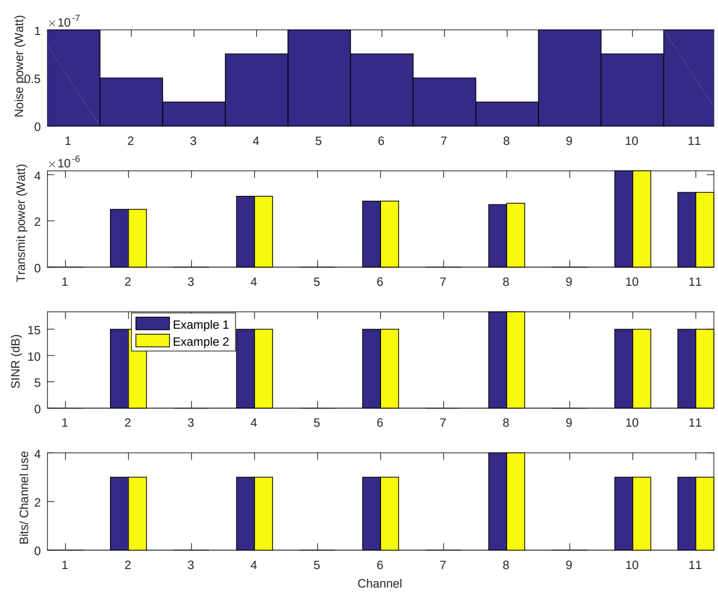

Figure 4.59: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 7 for different users' power budget.

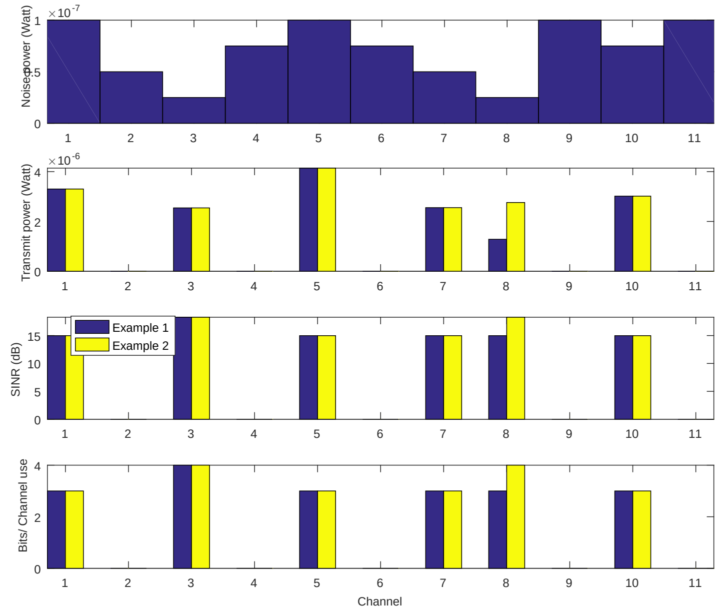

Figure 4.60: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 8 for different users' power budget.

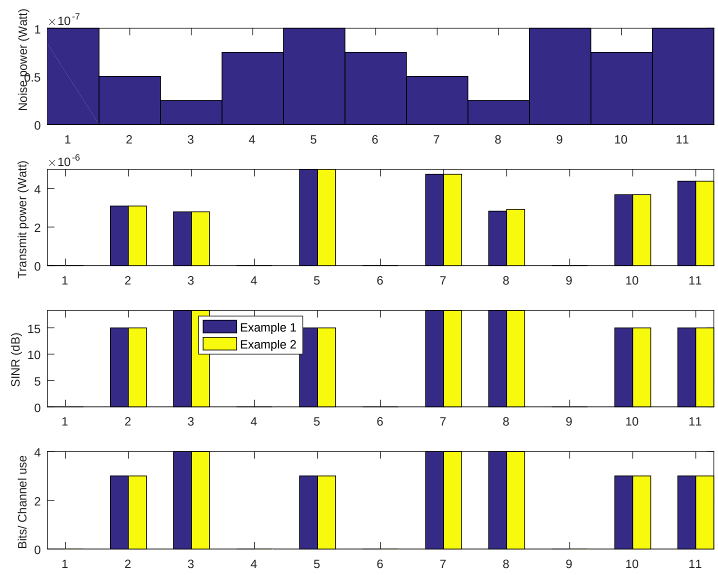

Figure 4.61: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 9 for different users' power budget.

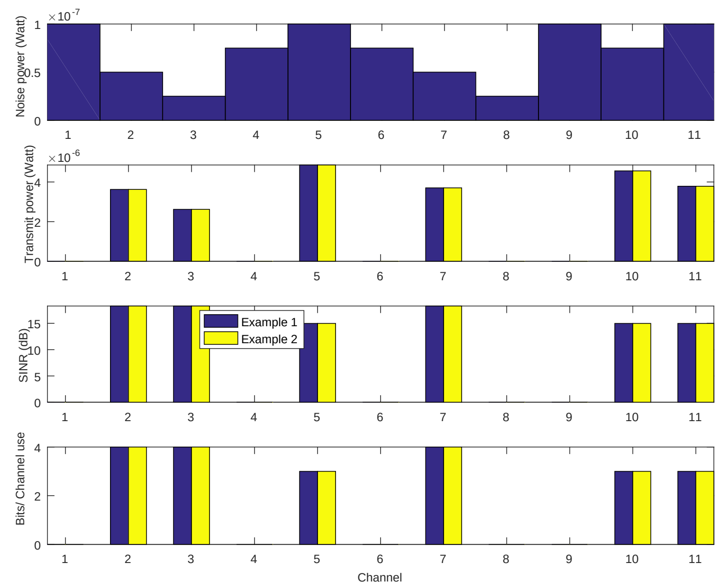

Figure 4.62: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 10 for different users' power budget.

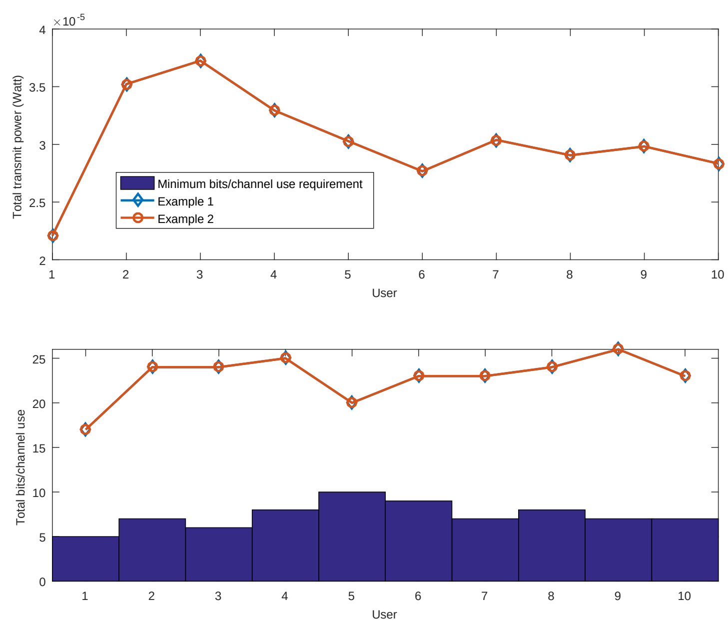

Figure 4.63: Allocation of total transmit power and total bits/channel use across users for different users' power budget with $\rho_{j,i} = 0$.

Now, for the same example cases, Fig. 4.63 depicts the allocation of total transmit power and total bits/channel use across users considering orthogonality factor, $\rho_{j,i} = 0$. Minimum bits/channel use requirement for all the users are also depicted in this figure as bar. Figure 4.63 shows that in both cases the our proposed optimization framework is successful in meeting the minimum bits/channel use requirements. Here, in this figure, the allocation profile for both cases are exactly same, which means the results are optimal. In a convex problem, it is expected to get same allocation profile if the QoS parameters are kept as same as they were. So, considering $\rho_{j,i} = 0$, the proposed optimization problem turns in to a complete convex problem, hence results optimal solution as we have mentioned in Sec. 3.2.

4.2.5 Effect of Users' Upper Bound on Bits/Channel use

Figure 4.64 presents the allocation of total transmit power and total bits/channel use across users for two different Users' upper bound on bits/channel use ($b_i^{max}(k)$) values, i.e., example 1 and example 2. Minimum bits/channel use requirement for all the users are also depicted in Fig. 4.30 as bar. Here, for example 1, $b_i^{max}(k)$ is set to 6 and for example 2, $b_i^{max}(k)$ is set to 8. The value of C_{qarg} is computed following the method discussed earlier in Sec 4.1 and $C_{qarg} = 4.37$ is set to guarantee a BER that is less than or equal to 10^{-3} with $b_i^{max}(k) = 8$. The rest of the system parameters are kept same as in Sec. 4.1 in both examples. Figure 4.64 shows that the total transmit power and bits/channel use allocation profile for both examples are similar. Figure 4.65 illustrates the allocation of transmit power and bits/channel use across channels (assuming scalarization parameters τ_1 and τ_2 to 0.5) for user 1 for examples 1 and 2. The resulting SINR are also shown in the figure. In this figure also, it can be observed again that the allocation of transmit power and bits/channel use are identical for both example cases. The similar pattern on allocation of transmit power and bits/channel use for three different noise levels are also observed for rest of the nine users and shown in Figs 4.66-4.74.

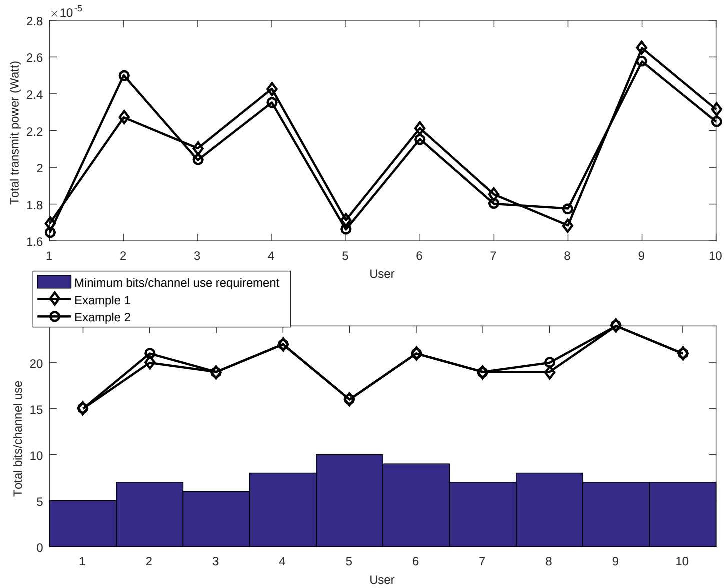

Figure 4.64: Allocation of total transmit power and total bits/channel use across users for different users' upper bound on bits/channel use.

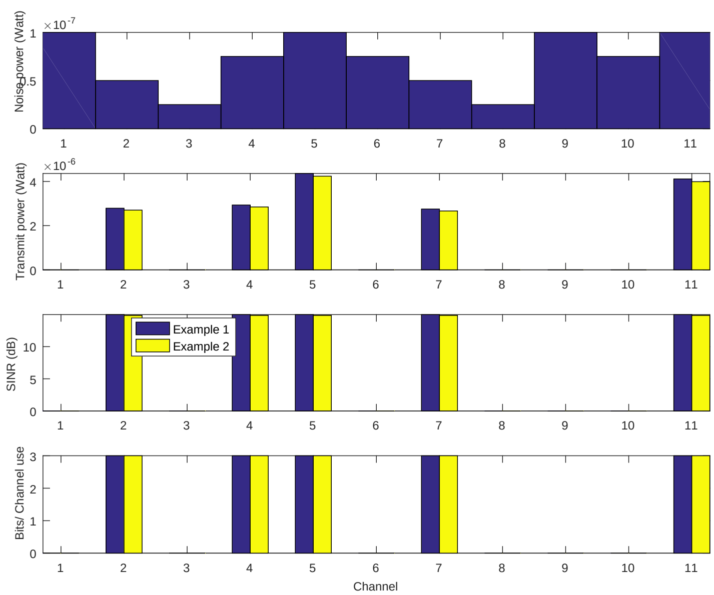

Figure 4.65: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 1 for different users' upper bound on bits/channel use.

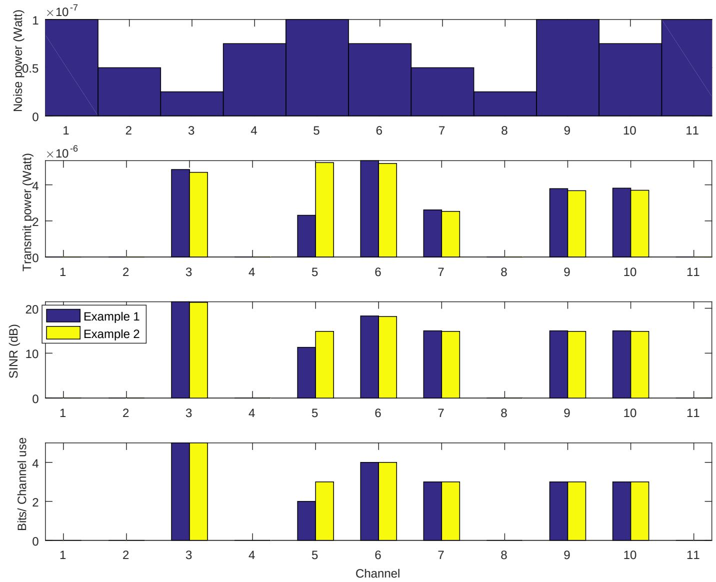

Figure 4.66: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 2 for different users' upper bound on bits/channel use.

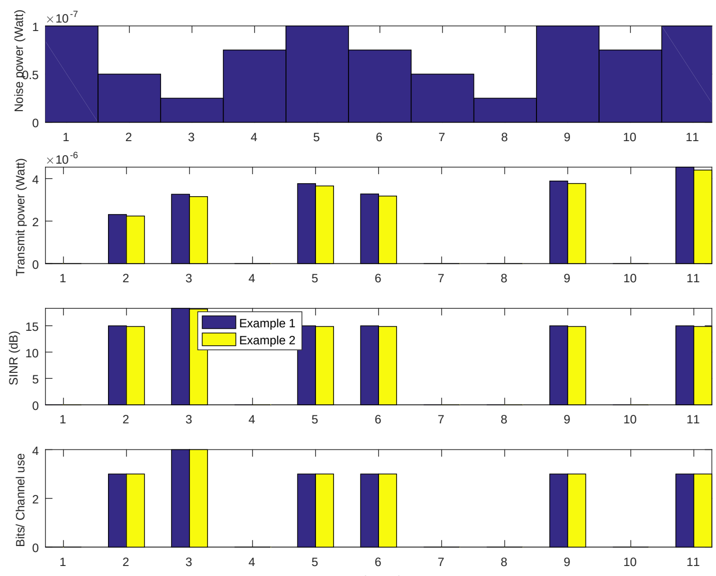

Figure 4.67: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 3 for different users' upper bound on bits/channel use.

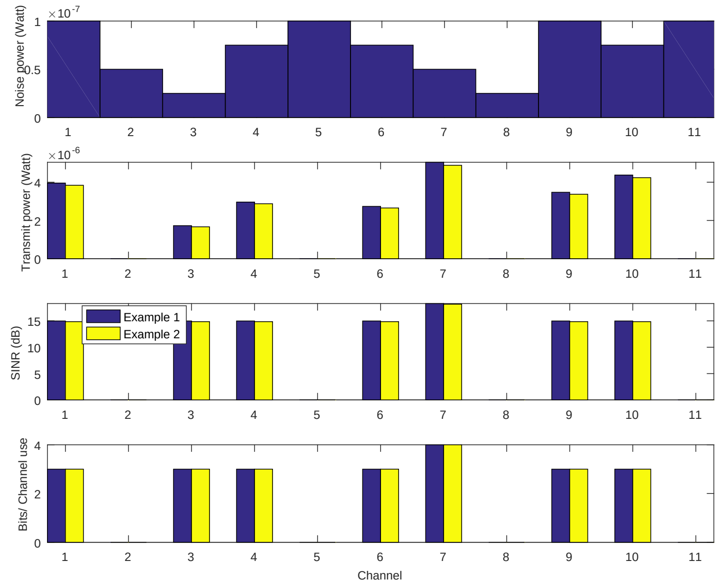

Figure 4.68: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 4 for different users' upper bound on bits/channel use.

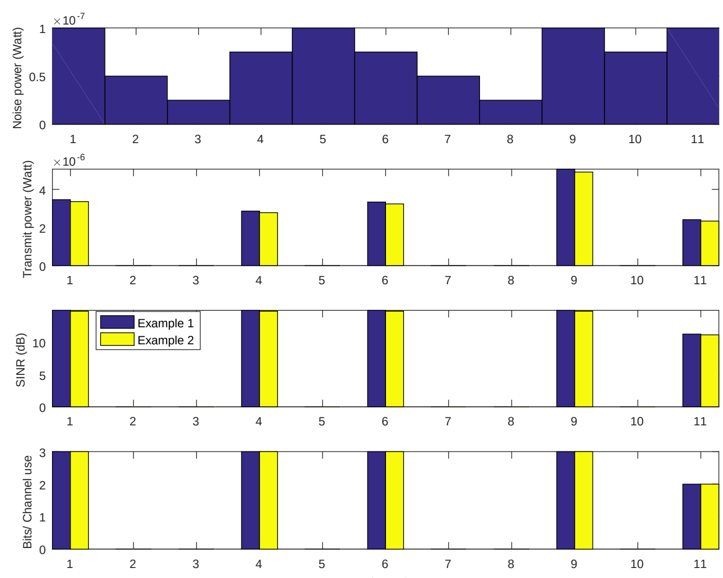

Figure 4.69: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 5 for different users' upper bound on bits/channel use.

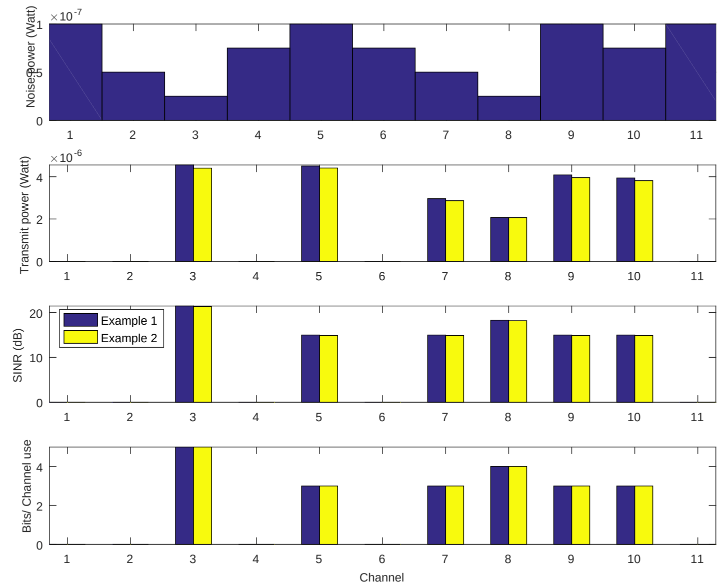

Figure 4.70: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 6 for different users' upper bound on bits/channel use.

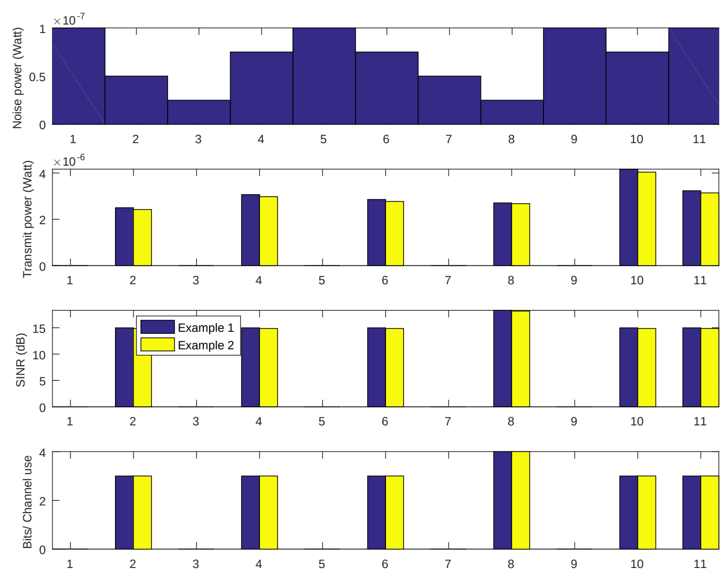

Figure 4.71: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 7 for different users' upper bound on bits/channel use.

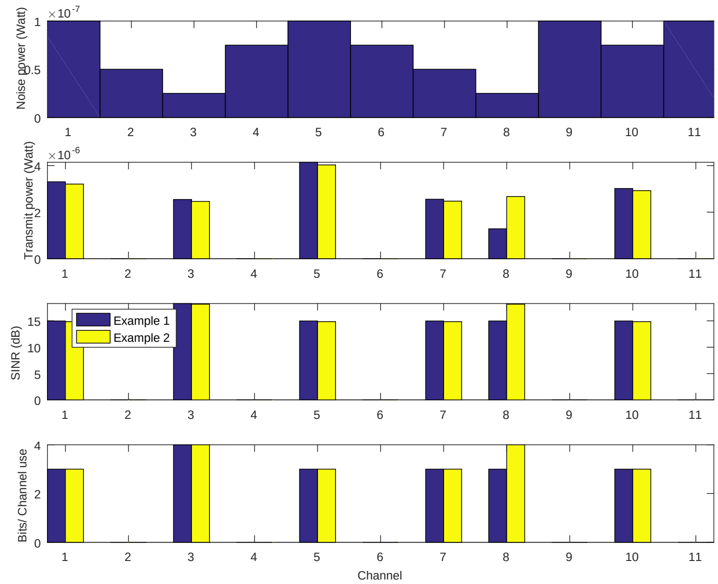

Figure 4.72: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 8 for different users' upper bound on bits/channel use.

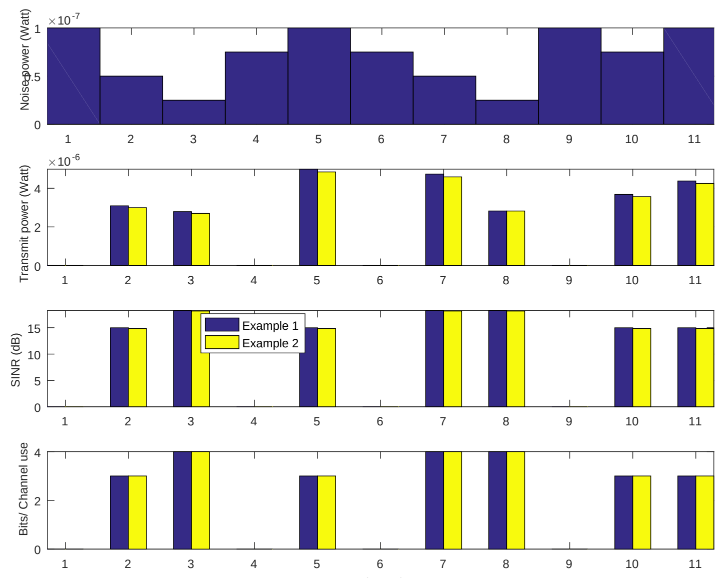

Figure 4.73: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 9 for different users' upper bound on bits/channel use.

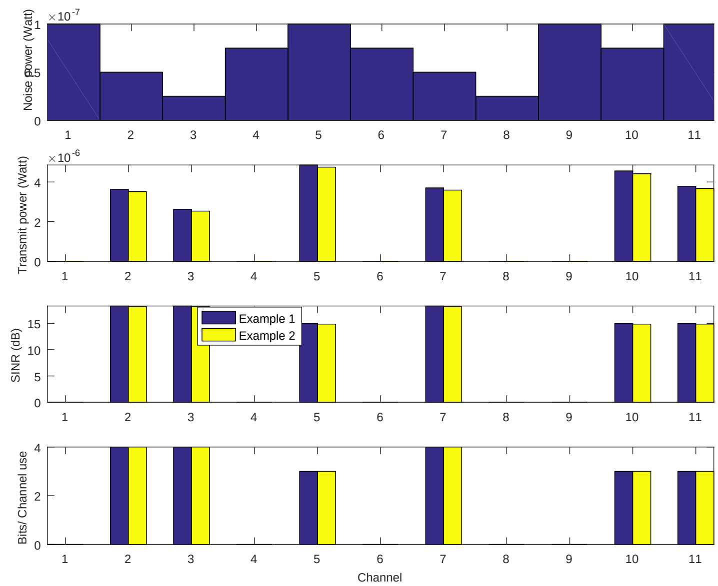

Figure 4.74: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 10 for different users' upper bound on bits/channel use.

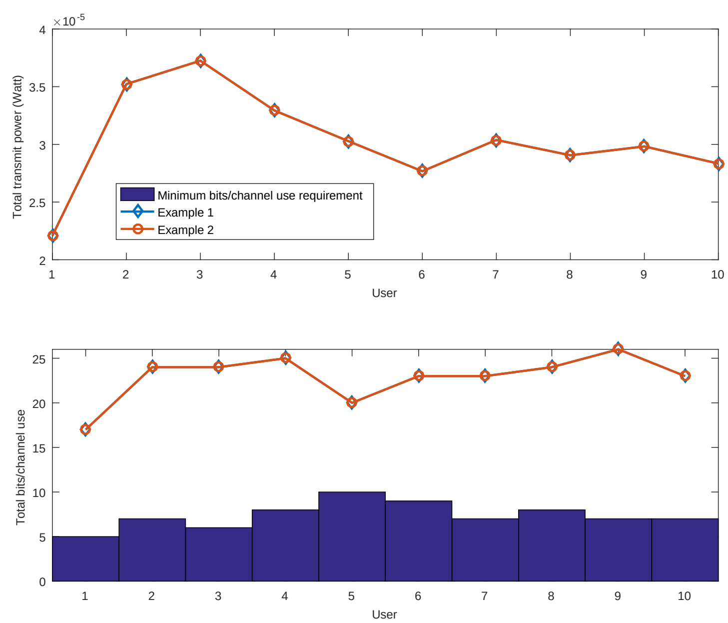

Figure 4.75: Allocation of total transmit power and total bits/channel use across users for different users' upper bound on bits/channel use with $\rho_{j,i} = 0$.

Now, Fig. 4.75 depicts the allocation of total transmit power and total bits/channel use across users considering orthogonality factor, $\rho_{j,i} = 0$ for the same example cases. Minimum bits/channel use requirement for all the users are also depicted in this figure as bar. Here, the allocation profile for both cases successfully satisfies the minimum bits/channel use requirements for all users. The results for the both cases are exactly same, hence the results are optimal.

4.3 Summary

In this chapter, the proposed optimization problem is solved in a centralized manner. The simulation results illustrate that the allocation of transmit power is proportional to noise level of the channel. Also, optimal bits/channel use allocation follows the SINR. Finally, our proposed framework is seen to be more successful in providing solution with higher user's bits/channel use requirement in better quality channels, which is a beneficial side. Therefore, wider solution space is obtained with our proposed framework.

Chapter 5

Distributed Solution of Proposed Resource Allocation Optimization Framework

In Chapter 3, we state an optimization framework to compute the best choice of transmit power and bits/channel use to SUs in a competitive CRN and in Chapter 4, we solve the proposed optimization problem in a centralized manner. The centralized solution requires extensive control signaling and is difficult to implement in practice as the central controller needs to know all the information about all users and channels. On the contrary, in distributed CRN, no central controller is required to coordinate the spectrum access. Spectrum access decisions are taken based on the local information. Hence, in this chapter, we solve the proposed resource allocation problem in a user-based distributed approach. Game theory is used to obtain the user-based resource allocation algorithm. Specifically, we develop a non-cooperative game where all the SUs are considered as selfish players who try to maximize their own utilities, which are formulated later in this chapter. Moreover, the existence of Nash Equilibrium (NE) for the game is studied.

The rest of the chapter is organized as follows. Section 5.1 describes the game formulation of the proposed framework. Section 5.2 presents the analysis of the proposed game. Numerical results are illustrated in Sec. 5.3. Finally, Sec. 5.4

summarizes the chapter.

5.1 Game Formulation of the Proposed Optimization Framework

Game theory plays a central role in modeling interactions of rational decision makers in the decision-making process. To formulate a game, game theory studies that each player has a strategy space of possible strategies from where a player takes an action at every point in the game and also player has a payoff or utility function, which represents the relative desirability of a player from his action (chosen from his strategy or action space) in combination with actions from the rest of the players (chosen from their strategy or action space) [11]. Players are said to play rationally if they continuously seek for an action to maximize their utility functions. A strategic non cooperative game Γ is expressed as $\Gamma = \{\Omega,\ A,\ U\}$ and consists of following components:

1. Player set $\Omega :\ \Omega = 1,\ 2,\ \ldots,\ M$, where M is the number of rational players.

2. Action set $A :\ \mathbf{a} \in A = \prod_{i=1}^{M} A_i = A_1 \times A_2 \times \ldots A_M$, where each component, a_i, of the action vector $\mathbf{a}$ belongs to the set A_i, the action set of player i. Action vector is also denoted as $\mathbf{a} = (a_i, \mathbf{a}_{-i})$, where a_i is player i's action and $\mathbf{a}_{-i}$ denotes the actions of rest $(M-1)$ players. $A_{-i} = \prod_{j=1, j \neq i}^{M} A_j$ is the action set of all players other than player i. If A_i is continuous then the game would be also continuous.

3. Utility U: $U_i :\ A \to \mathcal{R}$ is the utility (payoff) function of player i, which depends on the strategy of player i, as well as strategies of all other players and $U = (U_1, \ldots, U_M) :\ A \to \mathcal{R}^M$ denotes the utility vector of utility functions.

Various kind of action properties have been studied to figure out equilibrium point of the game. The most familiar is the Nash Equilibrium (NE) [11]. Typically, NE is an action vector that coincides to the effective response for all the players. NE gives no chance to players to get benefit by individual deviation.

Theorem 2. *(Nash Equilibrium) An action vector* $\hat{\mathbf{a}}$ *is a NE if, for every player* i *and every action vector* $\mathbf{a}$

$$U_i(\hat{a}_i, \hat{\mathbf{a}}_{-i}) \geq U_i(a_i, \hat{\mathbf{a}}_{-i}). \tag{5.1.1}$$

A game is called non-cooperative, where player acts in his self-interest. In a "non-cooperative" CRN, to evaluate SU's power and bits/channel use, each SU is interested in minimizing its own power and also maximizing its own bits/channel use while maintaining QoS.

Let $G = \{\Omega,\ \mathcal{P},\ \mathcal{B},\ \{u_i(.)\}\}$ denote the non-cooperative power and bits/channel use control game (NPRG) according to the resource allocation framework (3.2.11). $\Omega = 1,\ 2,\ \ldots,\ M$ is the set of players according to M SUs; $P = \mathcal{P}_1 \times \mathcal{P}_2 \times \ldots$ is the action space for power, $\mathcal{P}_i$ defines the action set for power of player i; $B = \mathcal{B}_1 \times \mathcal{B}_2 \times \ldots$ is the action space for bits/channel use, $\mathcal{B}_i$ defines the action set for bits/channel use of player i. Each SU selects a power vector $\mathbf{p}_i \in \mathcal{P}_i$ and a bits/channel use vector $\mathbf{b}_i \in \mathcal{B}_i$. For ease in presentation, we define the action for user i as $\mathbf{y}_i = [\mathbf{p}_i^T\ \mathbf{b}_i^T]^T$, where, ($\mathbf{p}_i = [p_i(1)\ p_i(2) \ldots p_i(L)]^T$ and $\mathbf{b}_i = [b_i(1)\ b_i(2) \ldots b_i(L)]^T$). We consider utility function of user i as

$$u_i(\mathbf{y}_i, \mathbf{y}_{-i}) = -\tau_1 \sum_{k=1}^{L} p_i(k) + \tau_2 \sum_{k=1}^{L} b_i(k), \tag{5.1.2}$$

where, $\mathbf{y}_{-i}$ is the union set of all other users actions and $\mathbf{y}_{-i} \triangleq [\mathbf{y}_1^T \ldots \mathbf{y}_{i-1}^T\, \mathbf{y}_{i+1}^T \ldots \mathbf{y}_M^T]^T$. The "noncooperative" game formulation to determine transmit power and bits/channel use can be formally represented as

$$
\begin{aligned}
\text{Determine} \quad & \mathbf{y}_i \\
\text{To Maximize} \quad & u_i(\mathbf{y}_i, \mathbf{y}_{-i}) \\
\text{subject to} \quad & \\
& CG1: \ 0 \le p_i(k) \le p_i^{gmax}(k), \ \forall \ i, \ k \\
& CG2: \ 1 \le b_i(k) \le b_i^{gmax}(k), \ \forall \ i, \ k \\
& CG3: \ \sum_{k=1}^{L} b_i(k) \ge R_i^l, \ \forall \ i, \\
& CG4: -\gamma_i(k) \le -C_{qarg}(2^{b_i(k)} - 1), \\
& \forall \ i, \ k.
\end{aligned} \tag{5.1.3}
$$

It is important to know, how the system constraint type $C4$ in the proposed resource allocation framework (3.2.11) is controlled in the formulated "non-cooperative" game. We take it in a simple way to satisfy those constraints in the game formulation. We consider the total interference (constraint type $C4$) caused by all SUs in a channel is partitioned equally across all SUs in that channel. This approach results in imposing maximum limit on transmit power for each SU in each channel. In (5.1.3), this is captured in constraint $CG1$. In the game G, maximum limit on power $p_i^{gmax}(k)$ is set as the minimum of maximum usual limit on power $p_i^{max}(k)$ and the upper bound obtained from dividing interference temperature threshold $I_t(k)$ by the product of channel power gain at some location m ($h_{i,m}(k)$) and possible number of users at next time instant $\widetilde{N}_s(k)$ (i.e., obtained bound corresponds to $I_t(k)/(h_{i,m}(k)\widetilde{N}_s(k))$). $p_i^{max}(k)$ is determined from constraint type $C2$ by diving p_i^{max} by the number of channels that user i is going to utilize in next transmission. $b_i^{gmax}(k)$ is obtained following the concept in [49] as

$$b_i^{gmax}(k) = \frac{1}{2} log_2 \left(1 + \frac{\sum_{i=1}^{\widetilde{N}_s(k)} p_i^{gmax}(k) h_{i,i}(k)}{\sigma^2(k)} \right).$$

In summary, based on local information such as possible number of users at next time instant $\widetilde{N}_s(k)$, $\forall k$, we formulate a game to determine optimal distribution of power and bits/channel use that a SU has to employ across the channels in order to minimize total power consumption, maximize total bits/channel use, and maintain QoS.

5.2 Analysis of the Game

The solution concept that is most widely used for game theoretic implementations is the Nash Equilibrium (NE). At a NE point, given the other users power and bits/channel use levels, no user can enhance his/her utility by making individual deviation in his/her power and bits/channel use. The NE solution concept results in a secure and permanent solution of a game where players are combating rationally through self-optimization and reach at a point where no player can deviate individually. According to NE, if there is a solution for above game, then there would be a point that reaches NE. The following theorem shows that a NE solution always exists for the game G in (5.1.3).

Theorem 3. *For a given $p_i^{gmax}(k)$, $b_i^{gmax}(k)$, R_i^l and C_{qarg}, there is at least one NE for the game G in (5.1.3).*

Proof. The game is our setup can be shown to be a concave game if the following two conditions are satisfied:
(1) the action spaces $\mathcal{P}$ and $\mathcal{B}$ are closed and bounded convex set and
(2) the utility function $u_i(\mathbf{y}_i, \mathbf{y}_{-i})$ is concave over its strategy set.
It is very easy to show that the first condition is satisfied by the game G. The utility function $u_i(\mathbf{y}_i, \mathbf{y}_{-i})$ is linear (and hence considered concave) in $p_i(k)$ and $b_i(k)$. As a concave game admits at least one NE [50], the theorem follows immediately. □

Given the existence of NE solution for the above game, next we design an algorithm for SUs to reach the NE. The modeling of algorithm is shown in Algorithm 1. In Algorithm 1, t is the iteration counter. Firstly, each SU measures the interference and noise power (*i.e.*, $\sum_{j=1,\ j\neq i}^{\widetilde{N}_s(k)} p_j(k) h_{j,i}(k) {\rho_{j,i}}^2 + \sigma^2(k)$) across its intended channels.

Each user executes their own optimization problem (5.1.3) to determine power and bits/channel use optimally. Each user continues to do (1) measure the interference and noise power term and (2) solve own optimization problem until a finite number of iterations (t_{max}) is completed or stopped at a point, where Algorithm 1 is confirmed. Finally, each user searches in the neighborhood for the optimal discrete valued $b_i^t(k)$ (denoted as $\mathbf{b}_i^{opt}$) and optimal transmit power $\mathbf{p}_i^{opt}$ corresponds to $\mathbf{b}_i^{opt}$ is recalculated using Eq. (5.1.3). Generally, the stopping criterion threshold ϵ is set to a reasonable small value.

Algorithm 1 Algorithm to reach NE for the game G

Stopping counter, $t = 1$;
while $(t \leq t_{max}$ or $||(\mathbf{p}_i^t - \mathbf{p}_i^{t-1}||/||\mathbf{p}_i^{t-1}|| \leq \epsilon),\ \forall i)$ **do**
  % Execute optimization problem
  for $i = 1,\ 2, \cdots,\ M$ **do**
    for $k = 1,\ 2, \cdots,\ L$ **do**
      Measure the interference and noise power ($i.e.$, $\sum_{j=1,\ j\neq i}^{\widetilde{N}_s(k)} p_j^{t-1}(k) h_{j,i}(k) {\rho_{j,i}}^2 + \sigma^2(k)$) across the intended channels;
    end for
    Solve optimization problem (5.1.3) and obtain $\mathbf{p}_i^t$ and $\mathbf{b}_i^t$;
  end for
  for $i = 1,\ 2, \cdots,\ M$ **do**
    Transmit $\mathbf{p}_i^t$;
  end for
  $t = t + 1$;
end while

The user-based distributed approach is more alluring than centralized scheme in terms of information exchange requirement. In the case of centralized scheme, information of all users and channels in the network are required. The required amount of information exchange in centralized scheme is $O(M^2)$. As a result, it incurs a high communication overhead and poor scalability in CRN with large number of SUs whereas,in the developed user-based distributed approach, each SU requires only local information- (i) possible number of users at next time instant $\widetilde{N}_s(k),\ \forall k$ and (ii) measurement of interference and noise power ($i.e.$, $\sum_{j=1,\ j\neq i}^{\widetilde{N}_s(k)} p_j(k) h_{j,i}(k) {\rho_{j,i}}^2 +$

$\sigma^2(k), \ \forall k)$.

5.3 Numerical Results

In this section, we explore the performance of the game theory based distributed solution of the proposed resource allocation framework. We assume the same simulation setup as in chapter 4.

Figure 5.1 presents the transmit power and bits/channel use allocation across channels for user 1 (assuming scalarization parameters τ_1 and τ_2 to 0.5) from the developed distributed scheme along with centralized scheme Eq. (3.2.11). Along with transmit power and bit/channel use allocation, the channel noise power and resulting SINR are also shown in the figures. From Fig. 5.1 we can see, user 1 is active on channels 2, 3, 5, 7, 8, 10 and 11. Here we can see that user 1 requires more transmit power in poor quality channels. Transmit power is proportional to noise power whereas, bits/channel use is proportional to SINR. The similar pattern on the transmit power and bits/channel allocation for rest of the nine users are observed and shown in Figs. 5.2- 5.10.

Figure 5.2 shows the transmit power and bits/channel use distribution across channels for user 2 from both distributed and centralized scheme. We can see, user 2 is active on channels 3, 5, 6, 7, 9 and 10. Next, the similar power and bits/channel use allocation profile for user 3 is presented in Fig. 5.3, where user 3 is active on channels 2, 3, 5, 6, 9 and 11. Then, Fig. 5.4 illustrates the power and bits/channel use profile for user 4. In this figure we can see, user 4 is present on channels 1, 3, 4, 6, 7, 9 and 10. Now, the transmit power and bits/channel use distribution for user 5 is depicted in Fig. 5.5, where user 5 operates on channels 1, 4, 6, 9 and 11. Figure 5.6 shows the power and bits/channel use distribution for user 6. We can see, user 6 is active on channels 3, 5, 7, 8, 9 and 10. Next, the transmit power and bits/channel use allocation for user 7 is presented in Fig. 5.7, where user 7 is active on channels

2, 4, 6, 8, 10 and 11. Then, Fig. 5.8 illustrates the transmit power and bits/channel use allocation profile for user 8. In this figure, user 8 is present on channels 1, 3, 5, 7, 8 and 10. The transmit power and bits/channel use distribution for user 9 is depicted in Fig. 5.9, where user 9 operates on channels 2, 3, 5, 7, 8, 10 and 11. Lastly, Fig. 5.10 shows the power and bits/channel use allocation for user 10. Here user 10 operates on channels 2, 3, 5, 7, 10 and 11. Thereby, it is seen that the transmit power and bits/channel use distribution across channels for all users in distributed scheme follows the centralized solution closely.

Figures 5.11-5.20 show the obtained BER values for users. Form these figures, we can observe that for all users, the obtained BER values are within the given limit of BER threshold value, $p^t_{e,i}\ \forall\ i = 10^{-3}$.

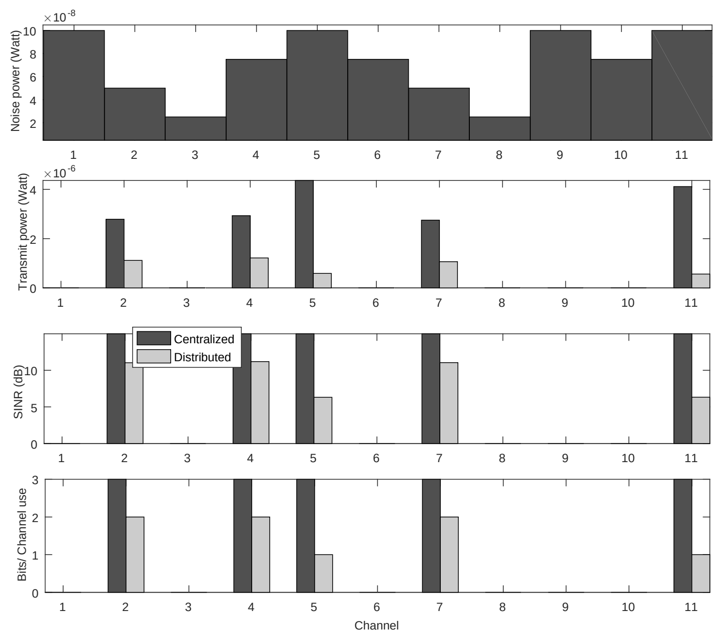

Figure 5.1: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 1.

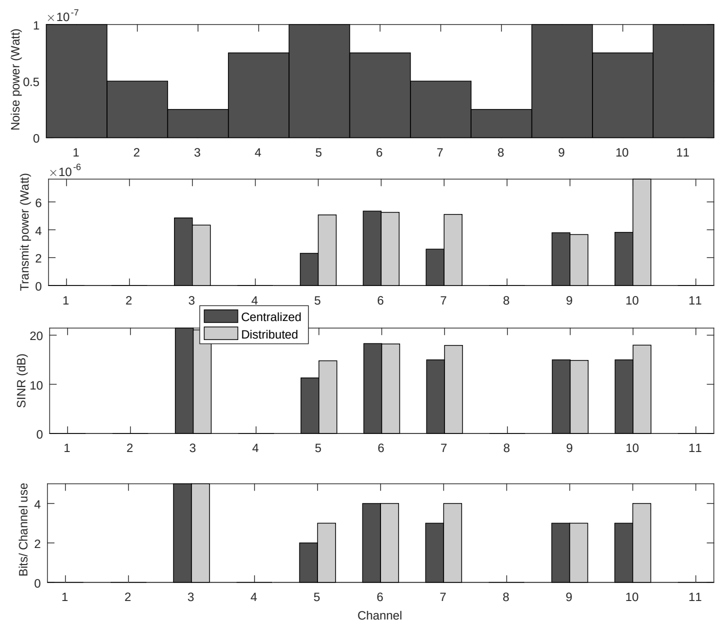

Figure 5.2: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 2.

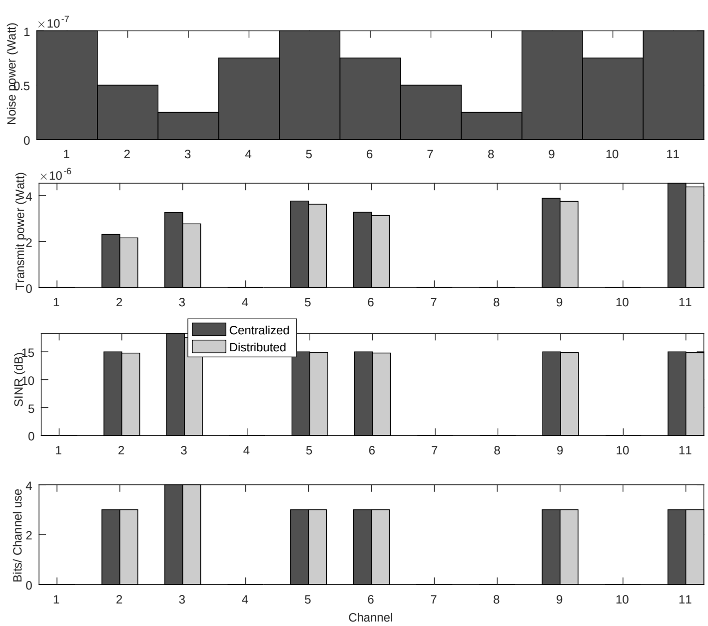

Figure 5.3: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 3.

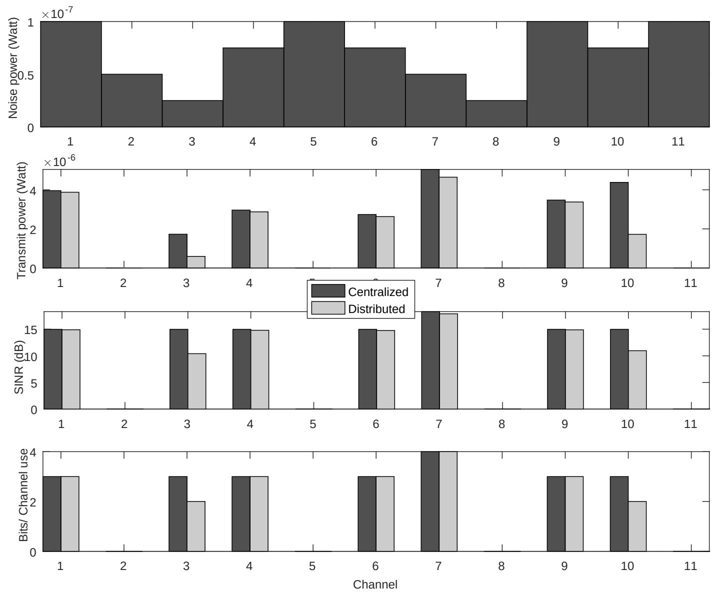

Figure 5.4: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 4.

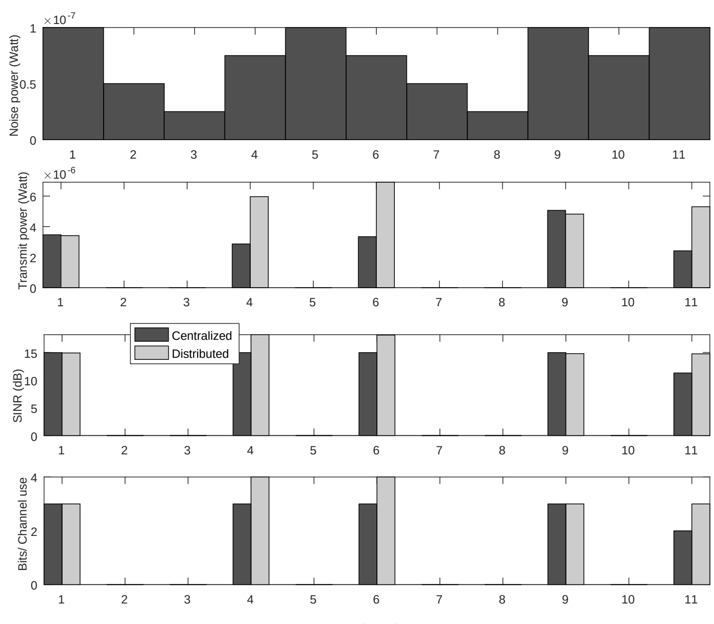

Figure 5.5: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 5.

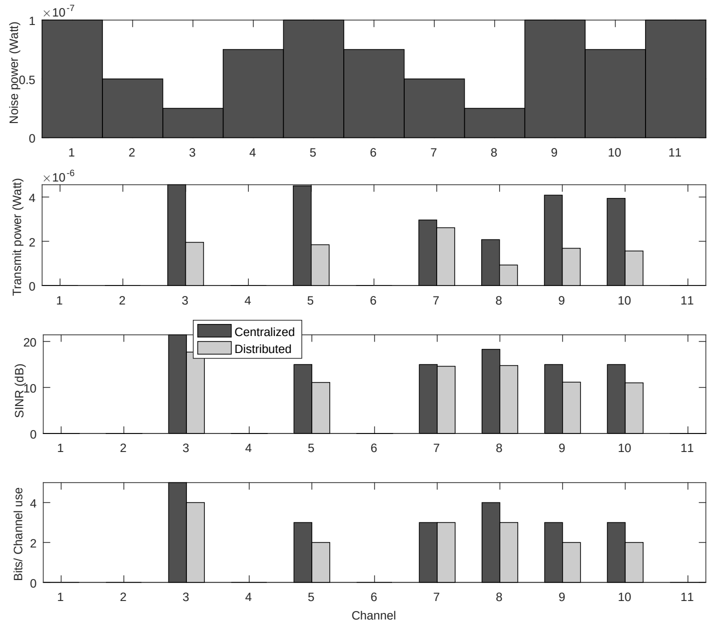

Figure 5.6: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 6.

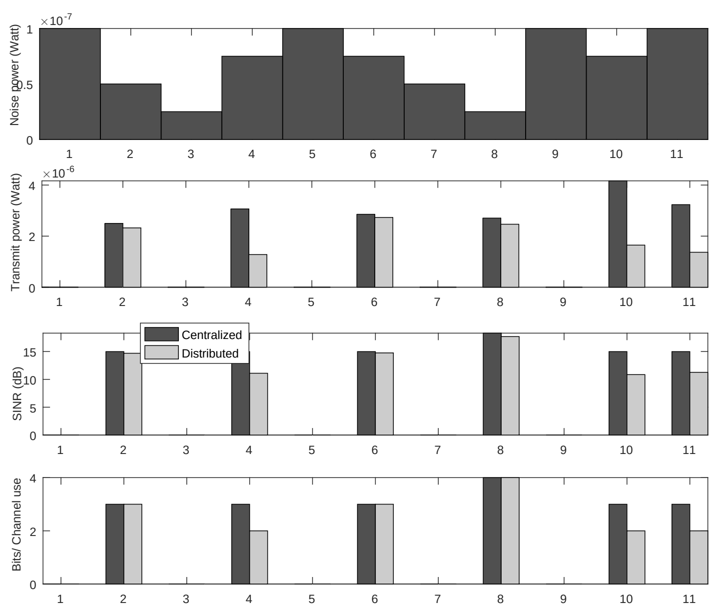

Figure 5.7: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 7.

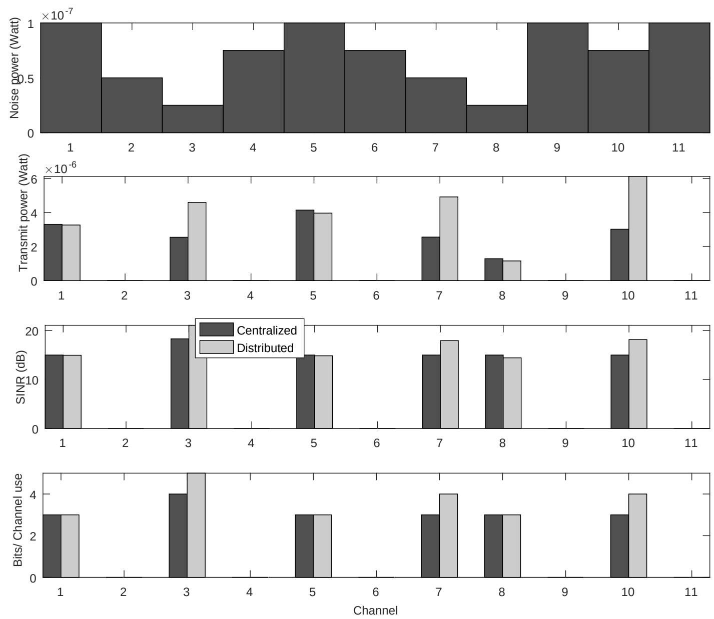

Figure 5.8: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 8.

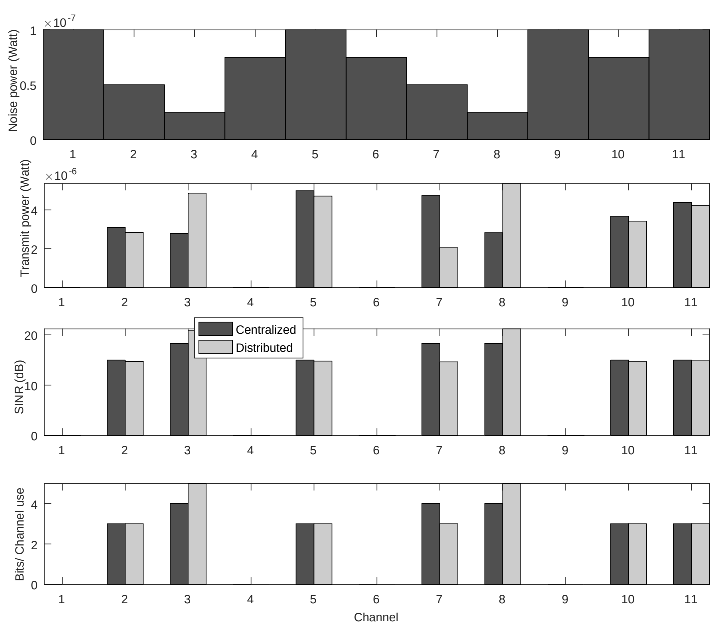

Figure 5.9: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 9.

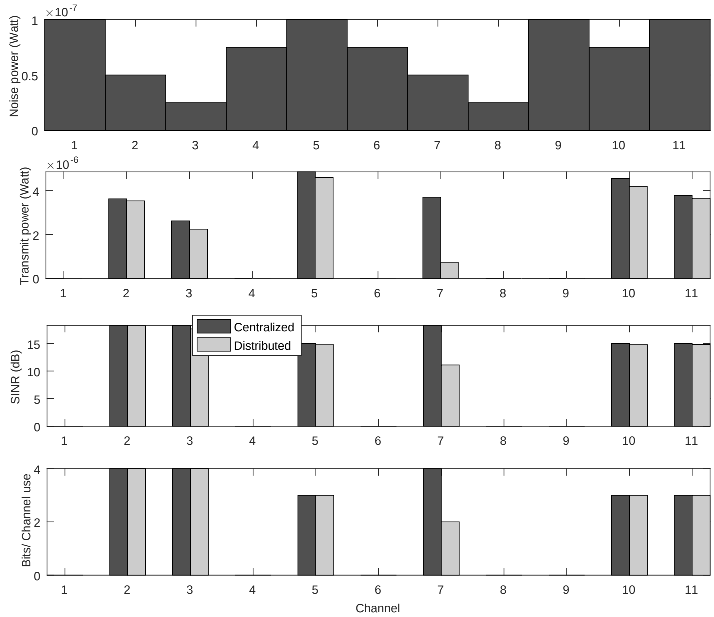

Figure 5.10: Allocation of transmit power and bits/channel use with channel noise power and SINR for user 10.

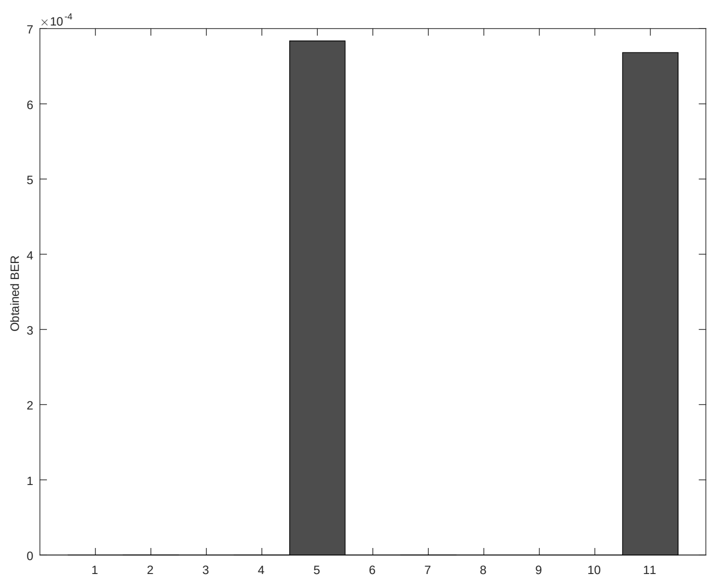

Figure 5.11: The obtained BER for user 1 across channels.

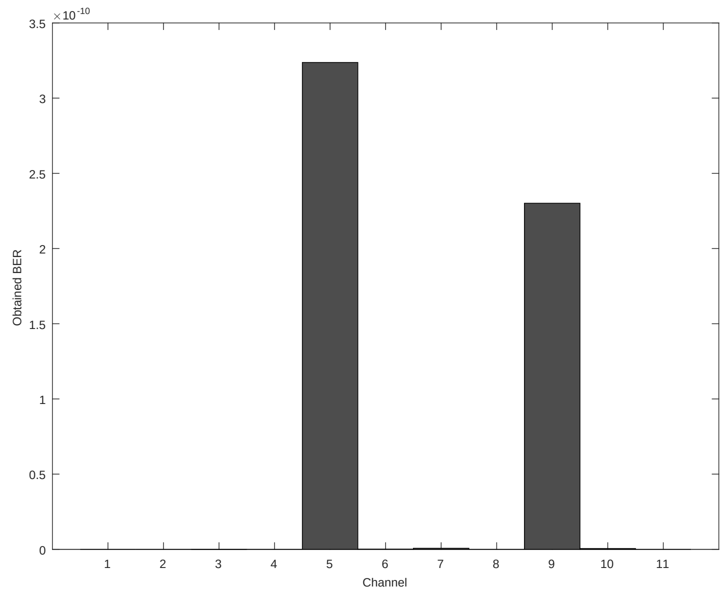

Figure 5.12: The obtained BER for user 2 across channels.

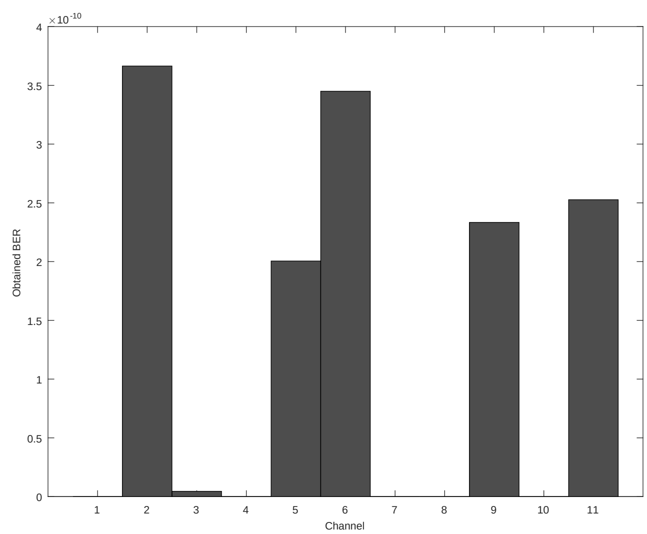

Figure 5.13: The obtained BER for user 3 across channels.

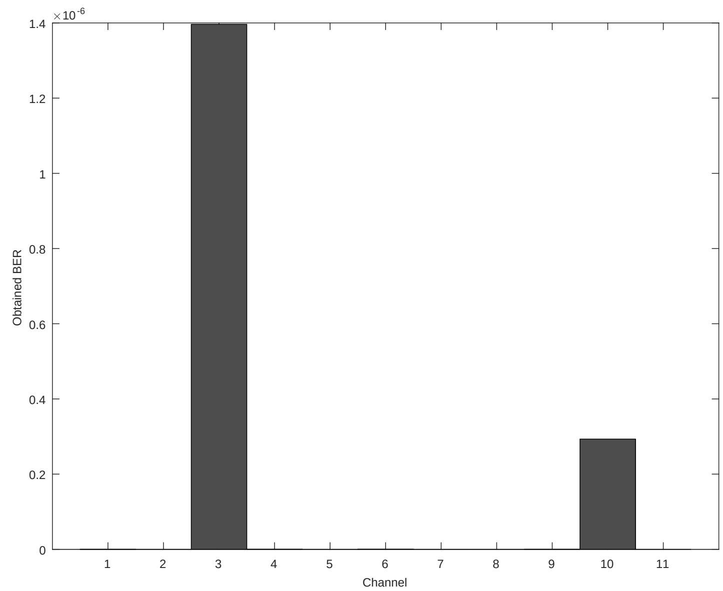

Figure 5.14: The obtained BER for user 4 across channels.

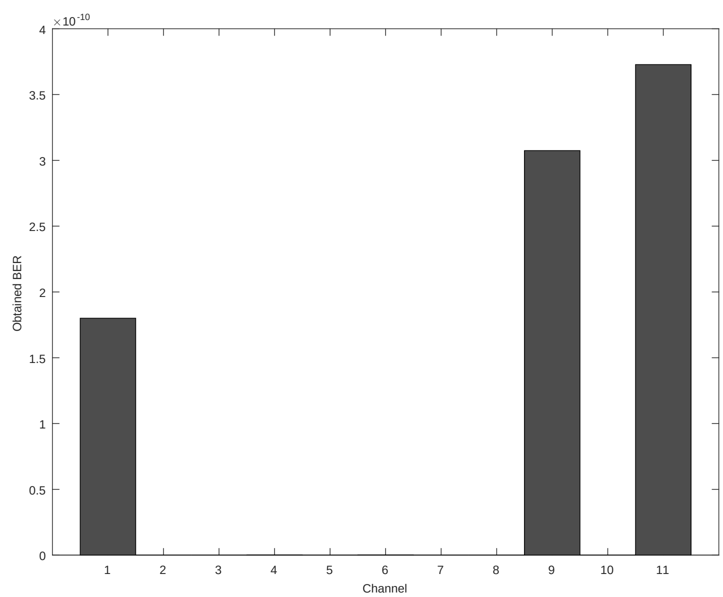

Figure 5.15: The obtained BER for user 5 across channels.

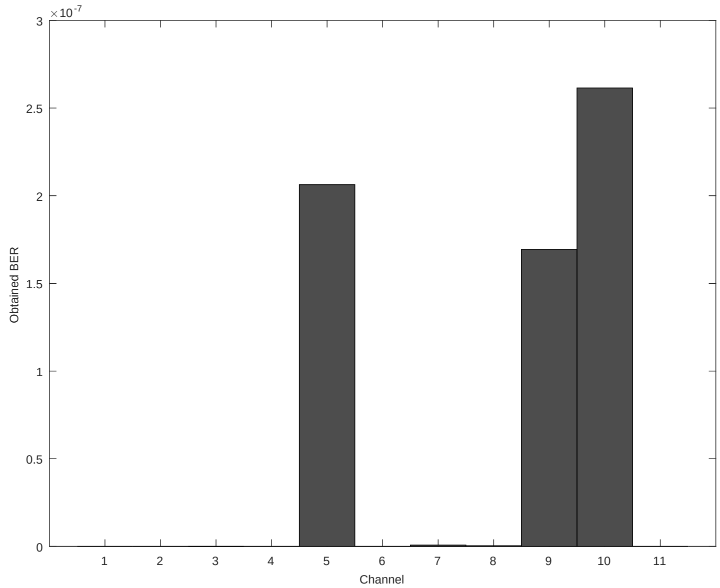

Figure 5.16: The obtained BER for user 6 across channels.

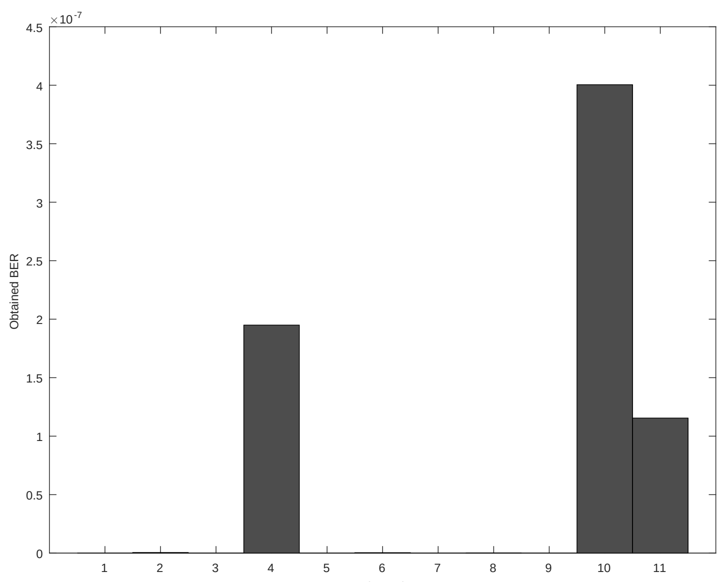

Figure 5.17: The obtained BER for user 7 across channels.

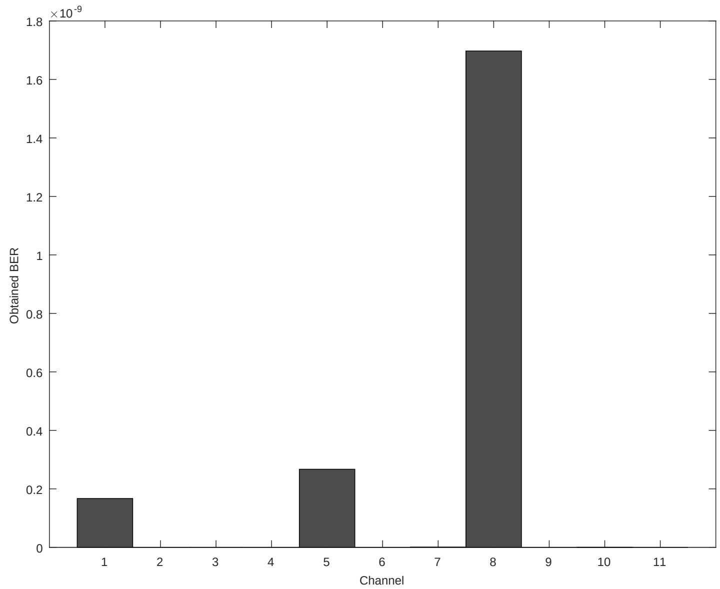

Figure 5.18: The obtained BER for user 8 across channels.

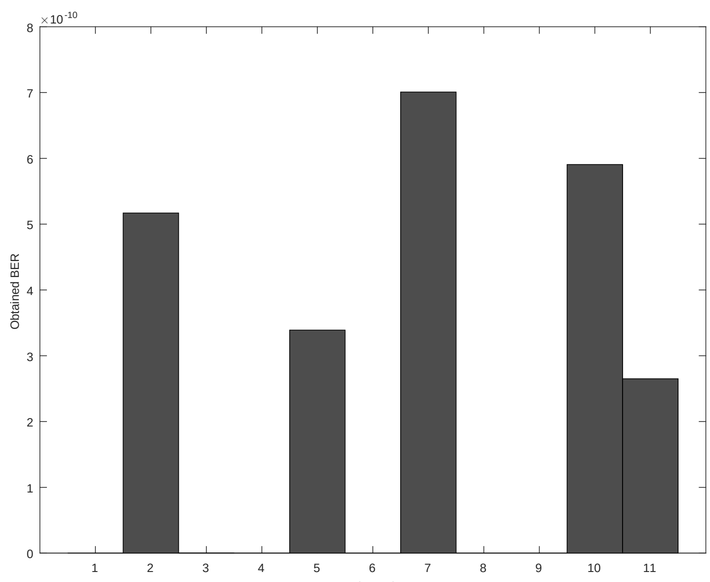

Figure 5.19: The obtained BER for user 9 across channels.

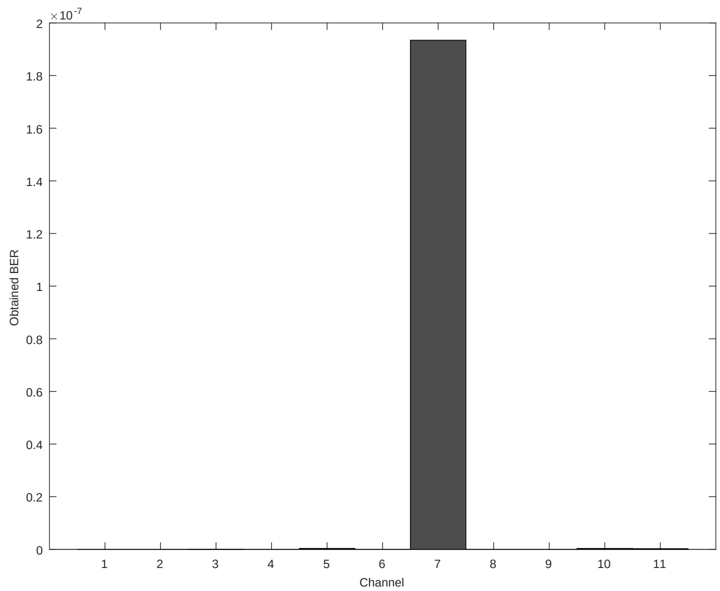

Figure 5.20: The obtained BER for user 10 across channels.

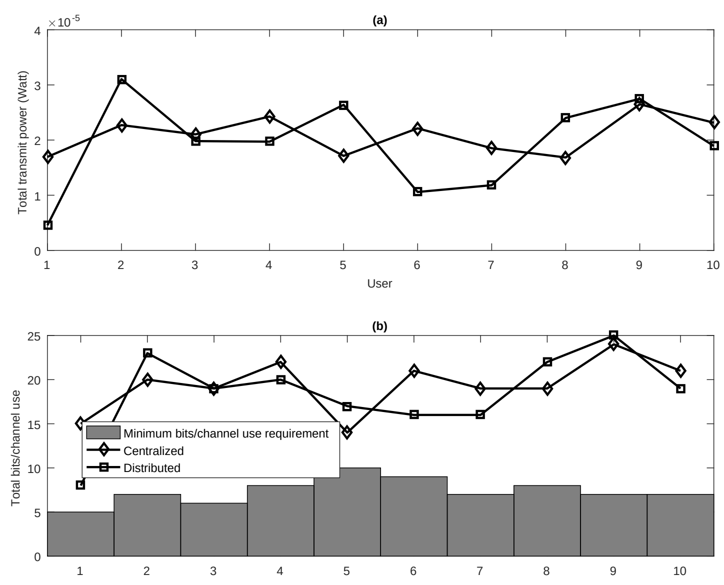

Figure 5.21: Allocation of total transmit power and total bits/channel use across users.

Figure 5.21(a) shows the allocation of total transmit power across users from both centralized Eq. (3.2.11) and distributed schemes, respectively. Figure 5.21(b) shows the allocation of total bits/channel use across users from both centralized Eq. (3.2.11) and distributed schemes, respectively. From Figs. 5.21(a) and 5.21(b) it is seen that both total allocated power and bits/channel use across users in distributed case are comparable to centralized scheme. Additionally, our proposed distributed resource allocation scheme is successful in meeting bits/channel use requirements for all SUs. The reason is obvious from the proposed user-based optimization problem formulation (5.1.3). A user executes its own optimization problem (5.1.3) after checking the feasibility of the optimization problem solution. The feasibility is determined by user minimum bits/channel use requirement (constraint type $CG3$) and the upper bound of bits/channel use (constraint type $CG2$). For each user, if the optimization problem is feasible, the distributed scheme is guaranteed to be successful in meeting the bits/channel use requirements for all SUs.

Figure 5.22 shows the resulting total interference power across channels from distributed scheme along with upper limit. We see from Fig. 5.22 that resulting total interference power across channels does not violate the corresponding upper limit. That is, the conservative approach based on constraint type $CG1$ in the proposed distributed case is successful in satisfying the system constraint type $C4$.

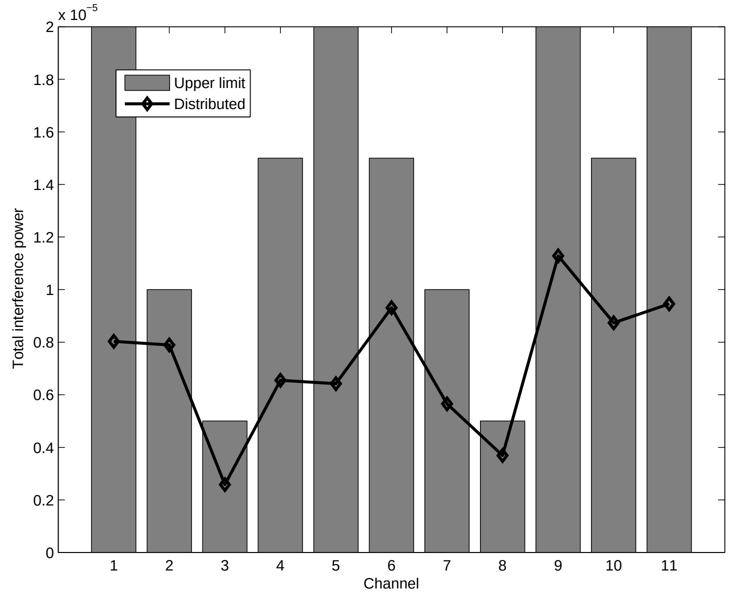

Figure 5.22: Total interference power across channels.

5.4 Summary

In this chapter, we develop a game theory based distributed approach to solve our proposed resource allocation framework that determine the optimal transmit power and bits/channel use that a SU has to employ across the channels in order to minimize total power consumption, maximize over all bits/channel use, and maintain QoS in a competitive CRN. In the game, the users make the decisions individually to maximize their utility function based on the local information. From the simulation results, we can see that the solution obtained from the developed game theory based distributed approach is comparable to the centralized solution closely. The simulation results show that the minimum bits/channel requirements for all SUs are satisfied and the total interference power across channels are within the admissible limit.

Chapter 6

Conclusion

6.1 Conclusion

In this thesis, we have proposed an optimization framework for resource allocation for SUs in a competitive CRN where multiple secondary users may coexist in a single channel and each SU can use multiple channels to satisfy their bits/channel use requirements. In such an environment, our proposed optimization framework intends to jointly determine the optimal allocation of transmit power and bits/channel use to SUs. The main objectives of the optimization framework are: (1) minimize the total transmit power, and (2) maximize the total bits/channel use while satisfying the QoS requirements for all active SUs. We have considered an upper bound on probability of bit error and lower bound on bits/channel use requirement of SUs as QoS. The problem is also constrained by total power budget across channels or users.

Then we have solved the proposed optimization framework in a centralized manner. In a centralized manner, all active SUs convey their channel state information (CSI) in periodic intervals to the central controller. The controller computes power and bits/channel use per SU in each channel based on channel quality and interference threshold. We have also assumed that CSI and allocated power and bits/channel use are exchanged between controller and SUs on a dedicated control channel. From the simulation results, it has been seen that more transmit power is required in a channel with higher noise power and bits/channel use follows the SINR. It has been also seen that our proposed framework is more capable of supporting high bits/channel use requirement compared to other existing framework. Thus the proposed framework achieves wider solution space than other existing framework and is very beneficial in the cases where minimum bits/channel requirement of the SUs is higher.

Finally, we have considered the communication overhead associated with centralized solution of proposed resource allocation framework and designed a user based distributed approach (requiring minimal or no communication overhead relative to centralized scheme). We have formulated a fully distributed approach based on game theory to solve our proposed resource allocation framework. We have studied the existence of Nash Equilibrium (NE) and in this regard we have developed an algorithm. We have simulated the game theory based distributed approach and investigated the transmit power and bits/channel use allocation across users and channels. We have also compared the results with that of the centralized approach. The simulation results have shown that the user based distributed solution also follows centralized solution.

6.2 Scope for the Future Work

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

1. Our proposed optimization framework can be studied for other different M-ary modulation schemes (e.g., M-ary Amplitude Shift Keying (M-ASK), M-ary Phase Shift Keying (M-PSK)).

2. The fairness in resource allocation indicates how equally the available scarce resources are distributed among the SUs in the network. Though our proposed framework is providing optimal resource allocation to SUs, users may not be satisfied with optimal allocation of resources based on instantaneous QoS.

Specifically, when multiple SUs compete for a limited number of available frequency bands in CRNs, fairness among SUs in resource allocation is another important consideration. As an example, when two SUs with different minimum rate requirements are allocated the same rate or when a user is assigned higher average power relative to other users, a dissatisfaction among SUs may arise. Typically dissatisfaction is a feeling that develops over time. Fairness issues in resource allocation has gathered some attention in recent years [24], [25]. The authors in [25] propose a fair random access protocol as well as a Homo Egualis (HE) society model based distributed approach. Hence, to maintain fairness among SUs, ideas from social behavior models [25] can be imposed in our proposed resource allocation framework.

3. In Chapter 5, we have formulated a distributed approach using game theory to solve our proposed resource allocation framework. However, to satisfy the given constraints, we have imposed a maximum limit on transmit power for each SU in each channel, which turns this approach as a conservative approach. In this context, the user based distributed approaches can be developed based on dual decomposition theory [51], [52] for our proposed resource allocation framework.

4. Currently non-orthogonal multiple access (NOMA) scheme has got huge attention and to the best of our knowledge transmit power and bits/channel use (modulation order) allocation in NOMA-based CRNs is not an explored area of research. So the feasibility of our proposed framework can be studied in NOMA-based CRN.

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Appendix A

Active Set Method

In mathematical optimization, a problem is defined using an objective function to minimize or maximize, and a set of constraints

$$g_1(x) \leq 0, ..., g_k(x) \leq 0$$

that define the feasible region, that is, the set of all x to search for the optimal solution. Given a point x in the feasible region, a constraint

$$g_i(x) \leq 0$$

is called active at x if $g_i(x) = 0$ and inactive at x if $g_i(x) > 0$. Equality constraints are always active. The active set at x is made up of those constraints $g_i(x)$ that are active at the current point. Active-set methods are mainly iterative methods that solve a sequence of equality-constrained quadratic subproblems. The goal of the method is to predict the active set, the set of constraints that are satisfied with equality, at the solution of the problem.

The active set is particularly important in optimization theory as it determines which constraints will influence the final result of optimization. For example, in solving the linear programming problem, the active set gives the hyperplanes that intersect at the solution point. In quadratic programming, as the solution is not necessarily on one of the edges of the bounding polygon, an estimation of the active set gives us a subset of inequalities to watch while searching the solution, which reduces the complexity of the search. In general an active set algorithm has the following structure:

Algorithm 2 Find a feasible starting point;

---

repeat until "optimal enough"
solve the equality problem defined by the active set (approximately)
compute the Lagrange multipliers of the active set
remove a subset of the constraints with negative Lagrange multipliers
search for infeasible constraints
end repeat

Methods that can be described as active set methods include:

- Successive linear programming (SLP)
- Sequential quadratic programming (SQP)
- Sequential linear-quadratic programming (SLQP)
- Reduced gradient method (RG)
- Generalized reduced gradient method (GRG)