UPLINK MULTIUSER SCHEDULING TECHNIQUES FOR SPECTRUM SHARING SYSTEMS

A Thesis

by

MARWA KHALID QARAQE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2012

Major Subject: Electrical Engineering

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ABSTRACT

Uplink Multiuser Scheduling Techniques

for Spectrum Sharing Systems. (August 2012)

Marwa Khalid Qaraqe, B.S., Texas A&M University at Qatar

Co–Chairs of Advisory Committee: Dr. Erchin Serpedin
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This thesis focuses on the development of multiuser access schemes for spectrum sharing systems whereby secondary users that are randomly positioned over the coverage area are allowed to share the spectrum with primary users under the condition that the interference observed at the primary receiver is below a predetermined threshold. In particular, two scheduling schemes are proposed for selecting a user among those that satisfy the interference constraints and achieve an acceptable signal-to-noise ratio level above a predetermined signal-to-noise threshold at the secondary base station. The first scheme selects the user that reports the best channel quality. In order to alleviate the high feedback load required by the first scheme, a second scheme is proposed that is based on the concept of switched diversity where the base station scans the users in a sequential manner until an acceptable user is found. In addition, the proposed scheduling schemes operate under two power adaptive settings at the secondary users that are based on the amount of interference available at the secondary transmitter. In the On/Off power setting, users are allowed to transmit based on whether the interference constraint is met or not, while in the full power adaptive setting, users are allowed to vary their transmission power to satisfy the interference constraint. A special case of the proposed schemes is also analyzed whereby all the users are assumed to be at the same position, thus operating under the influence of independent and identically distributed Rayleigh fading channels. Finally, several numerical results are illustrated for the proposed algorithms where the trade-off between the average spectral efficiency and average feedback load of both schemes are shown.

To my beloved father and mother

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CHAPTER I

INTRODUCTION

The wireless communications industry has seen an explosive growth in the past decade due to various new applications and network services that have emerged, such as wireless local area networks (WLAN), third generation (3G) and beyond wireless cellular systems, wireless metropolitan area networks (WMAN), and worldwide interoperability for microwave access (WiMAX) networks. A common goal of these emerging wireless technologies and services is to support simultaneous access of multiple users while improving user throughput, decreasing power consumption, and increasing the coverage area.

Recent studies conducted by the United States Federal Communications Commission (FCC) indicate that the wireless spectrum is largely underutilized, and the temporal and geographical variation in the utilization of the assigned spectrum ranges from 15% to 85% [1]. The fixed spectrum assignment policy served well in the past; however, the recent need for anytime-anywhere service access over the wireless network has created an urgent demand for wireless radio resources [2]. This demand, as well as the underutilization of the spectrum, gave the concept of cognitive radio a greater importance. First introduced by Mitola and Maguire [3], the basic idea of a cognitive radio is that it allows the primary (licensed) user (PU) and secondary (unlicensed) user (SU) to coexist in the same frequency spectrum.

The cognitive radio technology is the key technology that enables NeXt Generation Networks to use the spectrum in a dynamic manner [3]. Dynamic Spectrum Access Networks (DSANs) facilitates cognitive radio (CR) devices to analyze the spec-

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trum bands and access them if unoccupied until the incumbent transmitter arrives [2]. In underlay cognitive radio systems, also known as spectrum sharing systems, primary and secondary users can simultaneously transmit information as long as the interference of the secondary to the primary stays below a predetermined threshold, called the interference constraint [3].

In this thesis, we focus on the problem of uplink user scheduling for multiuser spectrum sharing systems. For conventional wireless networks, multiuser scheduling schemes have been extensively studied in multiuser communication systems whereby a base station (BS) serves a number of users that are competing for uplink channel access in a time division multiplexed access (TDMA) setting. In such systems, multiuser diversity can be exploited by serving the user with the best channel quality [4]. However, such schemes suffer from high feedback loads between the users and BS. In order to alleviate this problem, multiuser switched diversity schemes have been developed where the BS switches between users in an attempt to find an acceptable user rather than the best user for transmission [5]. A signal-to-noise (SNR) switching threshold dictates when the BS switches between the available users, as well as ensures a reliable secondary communication.

A set of uplink user scheduling schemes based on multiuser switched diversity in an underlay cognitive setting are presented in this thesis. In these spectrum sharing systems, secondary users are permitted to share the spectrum with primary users as long as they do not exceed an interference constraint with the primary. The two scheduling schemes presented in this paper are referred to as the selection combining (SC) and scan-and-wait (SW) schemes. In both scheduling schemes, it is necessary that a user satisfy both the interference constraint with the primary as well as the SNR switching threshold to be considered for transmission by the BS. In the selection combining scheme, the BS serves the user with the strongest channel and that simultaneously meets the interference constraint with the primary and the SNR threshold. This scheme yields the best average spectral efficiency (ASE), but comes at the expense of a high feedback load, (defined as the number of users probed before channel access). In an attempt to simplify the selection procedure and reduce the feedback load, the scan-and-wait transmission (SWT) scheme is analyzed. In this scheme, the BS executes a sequential search of the users and selects the first acceptable user that meets the interference and SNR constraints instead of the best user.

In practical systems, the secondary users' positions are assumed to be randomly distributed over the coverage area, and therefore, their SNRs are not identically distributed (average SNRs are not equal). In an attempt to increase fairness between the users, the secondary system must adapt its parameters so that all users operate with equal average secondary SNR. Thus, the two scheduling schemes are analyzed in two different power adaptive settings. In the first setting, the system operates in an On/Off power adaptive mode where users adapt their power so that all users operate with equal average secondary SNR. Furthermore, the BS does not consider any user that does not satisfy the interference constraint for transmission, thus these users set their transmit power to zero. In the second setting, the system operates in a full power adaptive mode in which case all the users adapt their power so that they do not exceed the interference constraint with the primary. The users then adapt their parameters so that they all meet a predetermined average secondary SNR. The performance of both scheduling schemes operating in the On/Off power mode and the full power mode are analyzed in order to evaluate the spectral efficiencies of the systems, the trade-off between throughput and feedback, and the delay that each system exhibits.

As a special case, the selection combining and scan-and-wait multiuser scheduling schemes are analyzed under the assumption of independent and identically distributed (i.i.d.) Rayleigh fading channels, which creates i.i.d. user SNRs. The i.i.d. case greatly simplifies the analysis of the On/Off and full power adaptive settings. Numerical examples are given in order to evaluate the performances of both scheduling schemes.

The remainder of the thesis is organized as follows. Chapter II briefly discusses the concept of fading channels and gives an overview of multiuser systems and multiuser diversity. Chapter III introduces the concept of cognitive radios and explains how their importance has increased throughout the years. Our system model introduced in Chapter IV where the channel model, adaptive modulation, and average spectral efficiency and bit-error rate analysis are discussed. In Chapter V, the two scheduling schemes are discussed and analyzed in detail. Chapters VI and VII conduct the performance analysis of both scheduling scheme in the On/Off power adaptive setting and the full power adaptive setting, respectively. Chapter VIII offers several numerical examples in order to demonstrate the performances of the discussed schemes. The special case of i.i.d Rayleigh fading channels is introduced and analyzed in Chapter IX, and finally, in Chapter X, we make some concluding remarks and briefly explain future work related to the work done in this thesis.

CHAPTER II

BACKGROUND

The primary goal of this chapter is to introduce models, terminology, and notations which will be used throughout the thesis. Therefore, we briefly review the basic characteristics of fading channels and introduce the basic structure of multiuser systems, multiuser diversity techniques, and briefly discuss scheduling schemes for multiuser systems.

A. Fading Channels

The unique nature of the wireless channel presents many challenges as well as opportunities to system designers. For instance, the wireless channel undergoes severe fading conditions of different scales which greatly corrupts the received signal and degrades system performance if left untreated. There are several basic factors that impact signal propagation in a mobile communication system. Among these are reflection, diffraction, and scattering, which are discussed in detail in [6] and [7].

Enabling mobility, which is the fundamental principle in designing wireless systems, presents itself as the most fundamental challenge. Due to the mobility of users and their surrounding environment, wireless channels are generally time-varying. Signal reflection, diffraction, and scattering from man-made or natural objects force the electromagnetic waveforms transmitted by a BS or by a mobile user to reach the intended receiver via multiple reflected paths, as shown in Fig 1. This phenomenon is known as multipath propagation and can cause fluctuations in the received signal's amplitude, phase, and angle of arrival, giving rise to the notion of multipath fading. The effect of multipath fading can lead to both constructive and destructive interference and phase shifting of the signal. Additionally, since the length of each path may be different, the received signal exhibits a wide fluctuation in its power profile, thus complicating the design of spectrally efficient systems.

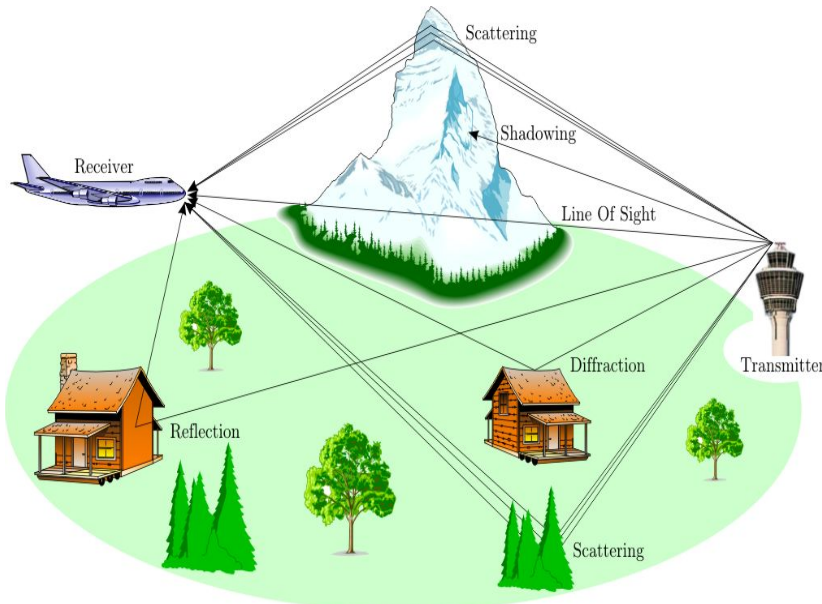

Fig. 1. Multipath propagation

There are two main types of fading effects that characterize mobile communication, namely, large-scale and small scale fading [8]. Large scale fading, also known as shadowing, represents the average signal power attenuation or path loss due to motion over a large area and is affected by protruding terrain contours such as large hills, forests, billboards, buildings, etc., that are located between the transmitter and receiver. Small scale fading establishes itself via two mechanisms, namely, time-spreading of the signal (signal dispersion) and the time-variant behavior of the channel. In mobile radio applications, the channel is time-variant because the motion between the transmitter and receiver lead to propagation path changes. Small scale fading is also referred to as Rayleigh fading. This is because if the multiple incoming reflective paths are large in number, with no line-of-sight signal component received, the envelope of the received signal is statically descried by a Rayleigh probability density function (PDF) [8].

With respect to the time-variant manifestation, the fading can be categorized as fast-fading or slow-fading. As for signal dispersion, the degradation types of small-scale fading is categorized into two types, namely, frequency-selective and frequency-nonselective (flat) fading [9], [8]-[10]. Channels are considered to be fast fading if the channel coherence time (T_c) is less than the time duration of a transmission symbol. Specifically, fast fading describes a condition where the time duration in which the channel behaves in a correlated manner is short compared to the time duration of a symbol. As a result, the fading characteristic of the channel changes several times while a symbol is propagating, leading to a distorted baseband pulse shape. A slow-fading channel is a channel whose channel coherence time is greater than the time duration of a transmission symbol, and therefore, the duration that the channel behaves in a correlated manner is long compared to the time duration of a transmissions symbol. As a result, the channel state essentially remains unchanged during the time interval in which a symbol is transmitted.

A channel is referred to as frequency-selective if the bandwidth of the transmission symbol is greater than the coherence bandwidth of the channel. This characteristic gives rise to frequency-selective fading distortion, in which case the signal's spectral components are not all affected equally by the channel. Specifically, the signal's spectral components that fall outside the coherence bandwidth are affected differently (independently) than the components that lie within the coherence bandwidth. This phenomenon is referred to as inter symbol interference (ISI). This is the opposite scenario for frequency-nonselective or flat-fading channels. In flat-fading channels, the coherence bandwidth of the channel is greater than the bandwidth of the transmission symbol and therefore, all of the signal's spectral components are affected by the channel in a similar manner. Although no ISI distortion is present in flat-fading channels, a performance degradation is still expected due to loss in the SNR whenever the signal is fading.

B. Block Fading Channels

The block fading channel model, described in [9] and [11], is especially suitable for wireless communication systems with slow flat-fading channels. In this model, the fading process is constant over a block of N channel symbols, but is statistically independent between the blocks. It is assumed that the fading process occurs in blocks during which N symbols are transmitted and the fading level is a sequence of random variables (RVs) which are generally independent and identically distributed (i.i.d) between blocks but constant within the block itself. The distribution of the random fading coefficients may assume any fading model such as Rayleigh, Rice, or Nakagami-m.

C. Multiuser Communication Systems

The wireless channel is a shared resource in which multiple users in the same geographical location have to compete for the common spectral resource. Thus, many wireless communication systems are multiuser systems, whereby the system resources are divided among users. In centralized systems, multiple users communicate with a central node or BS by two primary communication links, namely uplink and downlink. The uplink refers to the information flow from the users to the BS and is an example of a classical multiuser channel or may be looked upon as a many-to-one communication setting. In this thesis, we focus on the uplink of multiuser communication. The downlink refers to the flow of information from the BS to the user, as is a typical example of a broadcast channel or a one-to-many communication setting

[12].

In order to allow meaningful and resource efficient communication among the users, all participating users must agree on a common protocol. This protocol should enable fair access to the wireless channel for all users. The technique of allocating channels to specific users is referred to as resource allocation technique and it divides the total available signaling dimension (time, frequency, code, and sector) into channels and then assigns them to different users. The most common multiple access techniques divide the signaling space along the time, frequency, and code dimensions. This thesis focuses on time-division multiple access (TDMA) channelization method.

In TDMA, the systems dimensions are divided along the time axis into non-overlapping channels. Each user is assigned a different cyclically-repeating timeslot, as shown in Fig. 2. In general, TDMA channels occupy the entire system bandwidth. The cyclically repeating timeslots imply that transmission is not continuous for one user; thus, digital transmission techniques that allow for buffering are required [13].

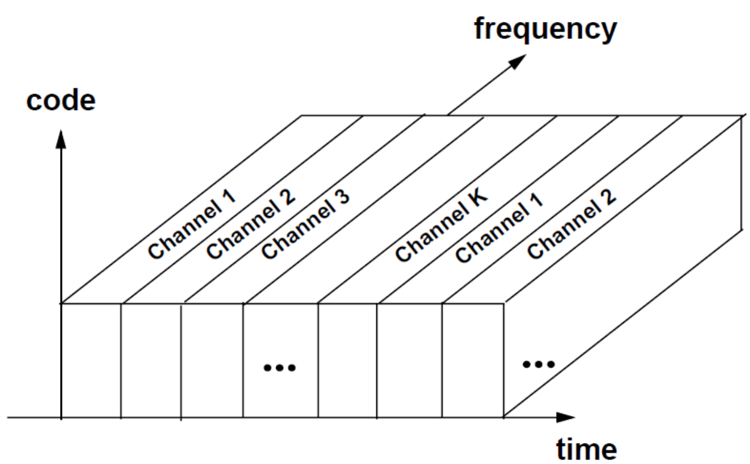

Fig. 2. TDMA [13]

D. Multiuser Diversity

There are two main classes of channel resource allocation schemes. The first class is called channel independent resource allocation (CIRA), whereby users are assigned channel resources in a predetermined fashion, irrespective of the fading channel condition they experience. The second class of resource allocation schemes is called channel aware resource allocation (CARA). In CARA, the channel allocation process is dependent on the users channel conditions. In other words, users that exhibit better channel conditions have priority in being assigned channel resources versus users that exhibit poor channel quality. CARA has the advantage of providing larger capacity in multiuser wireless communication systems by taking advantage of multiuser diversity [14].

Many of the current and emerging wireless communication system use diversity techniques to combat the effects of fading. Diversity techniques have proven to be effective in improving the performance of radio links by skillfully combining two or more copies of the same information bearing signal in order to increase the overall SNR. Diversity can be obtained over time, frequency, and space. The essence of diversity combining consists of i) receiving multiple copies of the same information bearing signal over two or more fading channels and then ii) combining these copies at the receiver in order to increase the overall received SNR. Multiple replicas can be obtained through various diversity schemes such as space diversity in which multiple receiver antennas are implemented at the receiver, frequency diversity in which multiple frequency channels are separated by at least the coherence bandwidth of the channel, and the recent transmit diversity in which multiple transmit antennas are implemented at the transmitter.

The preceding diversity modes pertain to a point-to-point link. Recent results, such as in [12], discuss another form of diversity called *multiuser diversity*. Multiuser diversity (MuD) is inherent in all multiuser systems that are characterized by fading channels and it arises from the fact that in a system with many independent users, it becomes likely that there is a user with a very good channel quality. Tracking the individual user channel quality between the transmitter and receiver, and serving the user with the largest channel gain is shown to greatly improve channel capacity.

An example of MuD is given in [12] and [15] for an uplink channel in a single cell with multiple users communicating to the BS via time-varying channels. The channel is assumed to be tracked at the BS and the channel state information (CSI) is fed back to the users. It was shown that the optimal strategy to maximize the total information-theoretic capacity is to schedule, at any one time, only the user with the best channel to transmit to the BS. As a result, the overall system throughput is maximized by allocating at any time the common channel resource to the user that best exploits it.

Accordingly, one of the most important tasks in multiuser systems is *multiuser scheduling*. Multiuser scheduling pertains to the problem of how and when to assign/schedule the available multiuser channel resources to available users. In general, multiuser scheduling algorithms aim at meeting the following objectives: (1) they must satisfy an individual user's required quality of service (i.e., throughput, BER, etc.), (2) provide maximal combined throughput for all users, and (3) other system restraints and considerations (i.e., power constraints, fairness requirements, etc.).

Multiuser scheduling is a cross-layer design problem because it must balance the requirements of different layers in terms of QoS, capacity, power constraint, as well as other system constraints. Furthermore, the scheduling scheme that always serves the strongest user may cause channel access fairness issues because users with stronger average channel strengths, such as close proximity to the BS, may dominate the channel access resources. In this thesis, we evaluate the performances of two multiuser scheduling schemes, which will be discussed in detail in Chapter V.

CHAPTER III

COGNITIVE RADIO

The focus of this chapter is to introduce the concept of cognitive radio, explain how it gained importance, and discuss various cognitive radio applications that pertain to this thesis.

A. The Licensed and Unlicensed Spectrum

Wireless networks are mainly regulated by a fixed spectrum assignment policy, often referred to as command-and-control, where government agencies oversee the regulation of the limited spectrum and its allocation to licensed users on a long term basis for large geographical regions. These licensed users pay a fee in order to maintain the privilege to have exclusive spectrum usage. Exclusive access rights have the advantage of preventing potential interference, which creates reliable communication links [16].

The access to the unlicensed spectrum is open, but its utilization is strictly regulated. An unlimited number of users, who satisfy certain technical rules and standards in order to mitigate potential interference, share the same unlicensed spectrum. However, the success of the unlicensed spectrum has been greatly restricted as severe QoS constraints imposed by recent multimedia applications cannot be fulfilled with today's means for coexistence [16]. In addition, in many deployment scenarios, such as WLANs, unlicensed spectrum usage is a victim of its own success. Specifically, too many parties and different technologies use the same unlicensed spectrum such that the spectrum becomes over used, and therefore, not functional for all.

B. The Crowded Spectrum

Recent studies conducted by the United States Federal Communications Commission (FCC) indicate that the wireless spectrum is largely underutilized, and temporal and geographical variation in the utilization of the assigned spectrum ranges from 15% to 85% [17]. Since the radio spectrum is a finite natural resource, the demand for spectrum access increases with time. The term 'radio spectrum' refers to the frequencies between 3kHz and 300GHz [18].

The radio spectrum is highly congested and therefore most of todays radio communication systems require rigorous protection against interference from other radio systems. Such protection from interference is generally guaranteed in licensing the radio spectrum for exclusive usage. As a result, most of the radio spectrum is licensed to traditional communication systems and services as indicated in Fig. 3 [18].

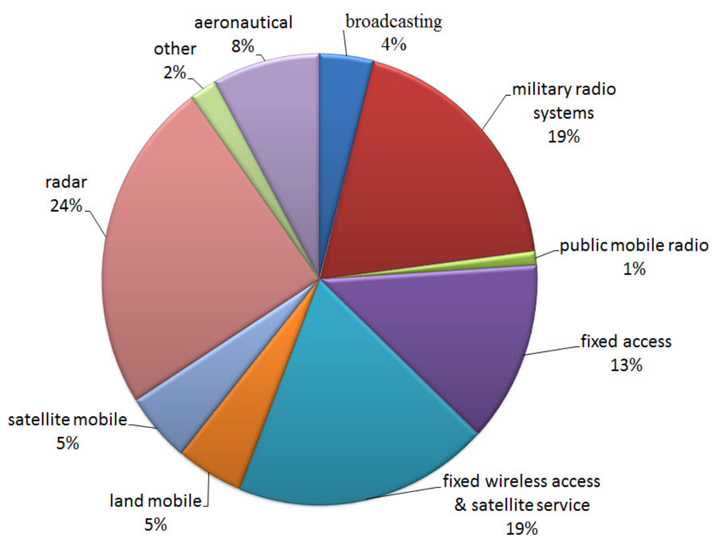

Fig. 3. Radio spectrum usage [18]

This traditional fixed spectrum assignment policy is not optimal since research shows that spectrum resources are underutilized for various reasons. One such reason is due to possible economic failure of licensed radio services that result in unused spectrum. For example, in the past, WiMAX appeared to be commercially unsuccessful. The WiMAX spectrum was allocated and licensed in many countries; however, the spectrum appeared not to be utilized by nationwide network operators until recently [18]. As a result, the WiMAX spectrum was considered to have been wasted.

Secondly, many licensed users, such as public safety and military radio, do not use the spectrum at all times. These users access the spectrum occasionally, leaving a large amount of unused spectrum [18]. Furthermore, technological advances in communication systems, such as the digitalization of television broadcasting, improve the spectrum efficiency of the existing licensed spectrum system, decreasing the amount of spectrum needed for the same service. However, regardless of the decreased need for the total allocated spectrum, many services do not utilize the total licensed spectrum available to them [18]. As a result of these observable trends, a major part of the radio spectrum is unused.

Therefore, if we were to scan portions of the radio spectrum, we would find that some frequency bands in the spectrum are largely unoccupied most of the time, while other bands are only partially occupied, and the remaining bands are heavily used. Fig. 4 depicts the assigned spectrum and illustrates how a large portion of the spectrum is used sporadically, where the signal strength distribution over a large portion of the wireless spectrum is shown. It is noted that spectrum usage is concentrated on certain portions of the spectrum, leaving a significant amount of the spectrum underutilized [17].

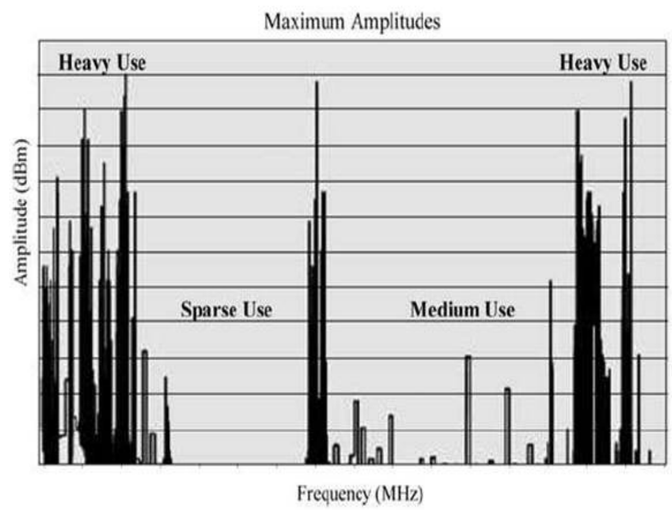

Fig. 4. Spectrum utilization [17]

C. Rise of the Cognitive Radio

The fixed spectrum assignment policy served well in the past; however, the recent need for anytime-anywhere service access over the wireless network has created an urgent demand for wireless radio resources. This demand as well as the underutilization of the spectrum gave the concept of cognitive radio a greater importance. First introduced by Mitola and Maguire [19], the basic idea of a cognitive radio (CR) is to allow the primary (licensed) user and secondary (unlicensed) user to coexist in the same frequency spectrum. Haykin defines the CR in [20] as:

> *"an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to earn form the environment and adapt its internal states to statistical variation in the incoming RF stimuli by making corresponding changes in certain operation parameters (e.g., transmit power, carrier frequency, and modulation strategy) in real-time, with two*

> *primary objects in mind, namely highly reliable communication whenever and wherever needed, and efficient utilization of the radio spectrum."*

From this definition, we are able to divide the tasks of the CR into three main categories [20]:

1. Radio Scene Analysis, which comprises the following sub-tasks:
    - estimation of the interference temperature of the radio environment
    - detection of spectrum holes
2. Channel identification, which encompasses the following sub-tasks:
    - estimation of the channel-state information (CSI)
    - prediction of channel capacity for use by the transmitter
3. Transmit power control and dynamic spectrum management.

Tasks 1 and 2 are carried out in the receiver while task 3 is executed in the transmitter. From the preceding discussion, it is apparent that the cognitive module in the transmitter works in a harmonious manner with the cognitive module in the receiver. As a result, a feedback channel connecting the receiver and transmitter is needed to convey information on the performance of the system, and the CR can be viewed as a typical example of a feedback communication system [20]. The discussion of this feedback will be of great importance in the performance analysis of various transmission schemes that will be discussed in this thesis.

The main importance of the CR is that it allows secondary systems to utilize the licensed band of the primary system as long as the licensee's operation is not compromised [21]. Thus, the cognitive radio technology is the key technology that enables

NeXt Generation Networks to use the spectrum in a dynamic manner. Dynamic Spectrum Access Networks (DSANs) facilitates CR devices to analyze the spectrum bands and access them if unoccupied until the incumbent transmitter arrives.

D. Types of Cognitive Radio Networks

1. Interweave/ Opportunistic Networks

The underutilization of the electromagnetic spectrum calls for the term *spectrum holes*. Spectrum holes are defined by Haykin in [20] as:

> *"a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user".*

In opportunistic/interweave cognitive radio networks, secondary users are permitted to occupy the unused licensed bands (the spectrum holes). Because these spectrum holes change with time and geographic location, secondary transmitters operating in this mode need to have the real-time functionality for monitoring the spectrum and detecting available spectrum holes. Several spectrum sensing techniques are discussed in [22] and [23].

2. Overlay Networks

In overlay cognitive radio networks, secondary users are able to use under-utilized spectrum alongside of the primary users. Because CRs use flexible spectrum access techniques to identify under-utilized spectrum, they offer secondary users the ability to simultaneously share the unlicensed or licensed spectrum. In overlay systems, secondary users have knowledge of the primary's communication link and therefore, can increase the quality of its link by adapting to the sensed primary information and help the primary user decode its information.

3. Underlay Networks

In underlay cognitive radio systems, also known as spectrum sharing systems, primary and secondary users can transmit simultaneously using the same spectrum as long as the interference of the secondary to the primary stays below a predefined threshold. This threshold is commonly referred to as the *interference temperature* and has been introduced to determine a tolerable interference level that a primary receiver can tolerate without jeopardizing the quality of its communication link. If a secondary user is unable to stay below the interference threshold with the primary, the transmission is then considered to be harmful to the incumbent user, and thus, the secondary user will not be allowed to share the spectrum with the primary users. In spectrum sharing systems, the cognitive system does not have any knowledge of the primary communication link, other than the threshold value. In this thesis, all systems operate only in underlay cognitive radio networks.

CHAPTER IV

SYSTEM MODEL AND ADAPTIVE MODULATION

In this chapter, the system and channel models adopted in this work are described. Also, the details behind the adaptive transmission system of our study are outlined, and the general analysis of the average spectral efficiency (ASE) and bit-error-rate (BER) are evaluated.

A. General System Model

In this thesis, we consider a multiuser system operating in an underlay cognitive radio network. This multiuser system allows its secondary users to simultaneously transmit information alongside primary users as long as the interference of the secondary users to the primary user stays below a predetermined threshold. The interference threshold, also known as the interference constraint, will be referred to as the *Peak Interference Constraint* (PIC), denoted by Q, and it represents the maximum allowable interference power level that a primary user will accept from the secondary cognitive users.

In our multiuser setting, a BS serves a number of users competing for uplink channel access in a TDMA setting. These users compete for channel access based on two characteristics, namely, whether or not they are below the interference threshold with the primary, and whether they exceed the minimum modulation threshold. In detail, a time division multiplexed (TDM) system is assumed where only one user is allowed to have channel access per time-slot for uplink transmission. A single time-slot is divided into two regions, a guard time and an information transmission time, as shown in Fig. 5. During the guard time, the BS probes the users to find a user that will be given access to the channel in the succeeding information transmission time. The guard time is assumed to be fixed and equal to the amount of time that is needed to probe all users. The time duration of a single time-slot is assumed to be roughly equal to the channel coherence time. Under the assumption of frequency flat-fading, a block-fading model is used, where each data burst experiences the same fading conditions as the preceding guard period.

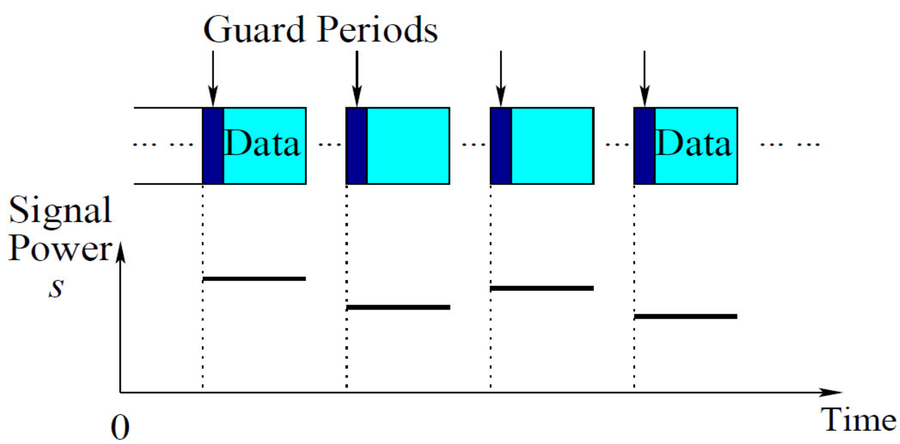

Fig. 5. Block fading channel model

For simplicity, each individual user and the BS are equipped with a single antenna, and perfect channel state information (CSI) is assumed available at both the BS and the users. Initially, independent but not necessarily identically distributed Rayleigh fading channels across the different users are assumed. However, Chapter IX analyzes the special case when users are associated with independent and identically distributed (i.i.d) Rayleigh fading channels.

B. User Random Location Model

In practical systems, users are likely to be distributed randomly over the coverage area, and therefore, their average SNRs are not equal. Moreover, the trade-off between multiuser selection diversity gain and scheduling fairness among all users is a more prominent issue when the channels of different users are statistically non-identical. As a result, when users are randomly distributed across the coverage area, their average SNRs can be quite disparate, resulting in independent but not necessarily identical Rayleigh fading channels among the users and non-identical average user SNRs.

Let d_{I_i} denote the distance between the i^{th} user and the PR and let d_{s_i} be the distance between the i^{th} user and the BS. In determining these distances, a random location model similar to [24] is adopted, as shown in Fig. 6. It is assumed that the cell shape is approximated by a circle of radius R_s, where the secondary BS is the center of the circle, and all users are assumed to be mutually independent and uniformly distributed in their cell. Thus, the PDF of the users' polar coordinates (r, θ) relative to the secondary BS are given by

$$f_r(r) = \frac{2(r - R_o)}{(R_s - R_o)^2}, \qquad R_o \leq r \leq R_s \tag{4.1}$$

$$f_\theta(\theta) = \frac{1}{2\pi}, \qquad 0 \leq \theta \leq 2\pi, \tag{4.2}$$

where R_o represents the closest distance a user can be from the BS. We also define D_{PS} to be the distance between the primary receiver (PR) and the secondary BS.

C. Channel Model

Let h_{I_i} denote the channel coefficient between the i^{th} user and primary receiver (PR) and let h_{s_i} denote the channel coefficient between the i^{th} user and the BS. It is assumed that h_I and h_s are zero-mean complex Gaussian random variables with variances $\sigma^2_{I_i}$ and $\sigma^2_{s_i}$, respectively. We also let $|h_{I_i}|^2$ and $|h_{s_i}|^2$ denote the instantaneous channel gains from the i^{th} secondary user to the PR and from the i^{th} secondary user to the BS, respectively. Both interference and secondary channel gains are exponentially

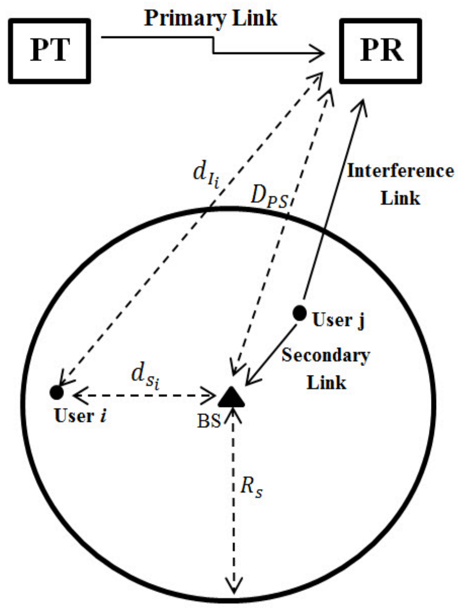

Fig. 6. User random location model

distributed with means $\sigma^2_{I_i}$ and $\sigma^2_{s_i}$, respectively. Fig. 7 illustrates the channel model of a single secondary user, where PT represents the primary transmitter, PR stands for the primary receiver, U_i denotes the i^{th} user, and BS is the base station the secondary user is connected to.

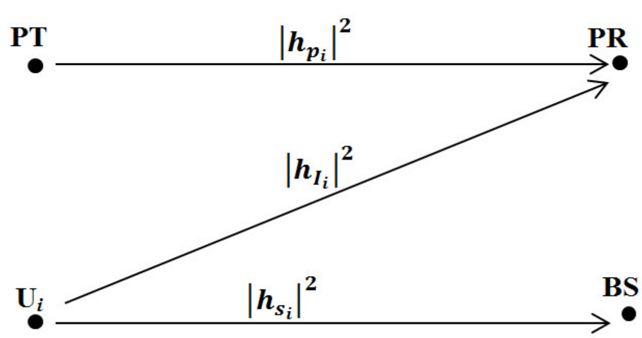

Fig. 7. Single user channel model

Assuming a transmit power of P_t and Gaussian noise with zero mean and variance

N_o at both the secondary and interference channels, the received interference SNR with the primary and the received instantaneous secondary SNR at the BS are found to be

$$\gamma_{I_i} = \frac{P_{t_i} |h_{I_i}|^2}{N_o} \tag{4.3}$$

and

$$\gamma_{s_i} = \frac{P_{t_i} |h_{s_i}|^2}{N_o}. \tag{4.4}$$

Furthermore, it is well known that signal propagation in a mobile radio environment is affected by a deterministic path-loss variation with distance. As a result, we adopt the simplified path-loss model [13] to evaluate the average received power as a function of the distance. According to this model, the average received signal power is given by

$$P_r = P_t \, \tau \left(\frac{d_o}{d}\right)^{\alpha}, \tag{4.5}$$

where τ is a unitless constant that depends on the antenna characteristics and average channel attenuation, d_o stands for the reference distance, d denotes the distance between the user and the BS, and α is the path-loss exponent. The path-loss exponent is a function of carrier frequency, environment, obstructions, etc., and typically ranges from 2 to 4.

Defining the average SNR as the ratio of received signal average power and noise average power, the average interference SNR and average secondary SNR are given respectively by

$$\bar{\gamma}_{I_i} = \frac{P_{t_i} \, \tau \left(\frac{d_o}{d_{I_i}}\right)^{\alpha}}{N_o} \tag{4.6}$$

and

$$\bar{\gamma}_{s_i} = \frac{P_{t_i} \, \tau \left(\frac{d_o}{d_{s_i}}\right)^{\alpha}}{N_o}, \tag{4.7}$$

where d_{I_i} is the distance between the i-th user and the PR and d_{s_i} denotes the distance between the i^{th} user and the secondary BS.

An alternative way the average SNR can be calculated is by taking the average of the instantaneous SNR. Specifically, the average interference SNR is expressed as follows:

$$\bar{\gamma}_{I_i} = E[\gamma_{I_i}] = \left[\frac{P_{t_i}\ |h_{I_i}|^2}{N_o}\right] = \frac{P_{t_i}\ E\left[|h_{I_i}|^2\right]}{N_o} = \frac{P_{t_i}\ \sigma_{I_i}^2}{N_o}, \tag{4.8}$$

where $E[\cdot]$ is the expected value operator and $\sigma_{I_i}^2 = \tau\left(\frac{d_o}{d_{I_i}}\right)^{\alpha}$. Similarly,

$$\bar{\gamma}_{s_i} = E[\gamma_{s_i}] = \left[\frac{P_{t_i}\ |h_{s_i}|^2}{N_o}\right] = \frac{P_{t_i}\ E\left[|h_{s_i}|^2\right]}{N_o} = \frac{P_{t_i}\ \sigma_{s_i}^2}{N_o}, \tag{4.9}$$

where $\sigma_{s_i}^2 = \tau\left(\frac{d_o}{d_{s_i}}\right)^{\alpha}$.

As mentioned in Sections A and C, independent but not identically distributed Rayleigh fading channels are observed across the users. We also mentioned that the interference and secondary channel gains are exponentially distributed. As a result, the cumulative distribution function (CDF) of the received SNR from the i^{th} user at the PR and at the BS are given by

$$F_{\gamma_{I_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{I_i}}\right), \quad x \geq 0 \tag{4.10}$$

and

$$F_{\gamma_{s_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{s_i}}\right), \quad x \geq 0, \tag{4.11}$$

respectively, where $\bar{\gamma}_{I_i}$ and $\bar{\gamma}_{s_i}$ are given by (4.6) and (4.7).

D. Adaptive Modulation

Adaptive modulation schemes have become very popular due to their ability to achieve high spectral efficiency when compared to the traditional constant modulation schemes. The basic concept of adaptive transmission is real link budget through adaptive variation of the transmitted power level, constellation coding rate, symbol transmission rate, scheme, or any combination of these parameters. As a result, adaptive modulation schemes are able to provide a higher average link spectral efficiency by taking advantage of the time-varying nature of the wireless channel, transmitting at high speeds under favorable channel conditions and responding to channel degradation through a smooth reduction of data throughput. It is also important to note that since the outage probability of such adaptive schemes can be quite high, especially for channels with low average SNR, buffering of the data may be required, and therefore adaptive systems are best suited for application without stringent delay constraints [25].

In general, the basic idea of rate-adaptive transmission is to track and exploit the time varying characteristic of the wireless channel to transmit data with a high information rate when the channel quality is good, and to lower the information rate when the channel quality is low. As a result, a feedback channel is required in all rate-adaptive modulation schemes whereby the receiver reports the CSI to the transmitter. Based on the reported CSI, the transmitter can make a decision on which rate to employ for the following transmission period.

In our system, rate-adaptation is dependent on a secondary user's SNR received at the BS. Specifically, a constant-power, variable-rate, uncoded M-ary quadrature amplitude modulation (QAM) is considered as the adaptive modulation system for our proposed schemes. With this adaptive modulation, the SNR range is divided into $N+1$ fading regions and the constellation size $M = 2^n$ (where $n = 0, 1, \ldots, N$ denotes the number of bits per symbol) is assigned to the n-th region. The rate adaption is achieved by dividing the SNR range into $N+1$ regions which are defined by the constellation SNR thresholds $\{\gamma_n\}_{n=1}^{N}$. A data rate of $\mathrm{R_n} = \mathrm{n}$ bits/sec/Hz is used if the i^{th} user's reported received secondary SNR (γ_{s_i}) of the chosen user satisfies the following inequality: $\gamma_n \leq \gamma_{s_i} < \gamma_{n+1}$.

We note that the lower limit, γ_n, of each fading region is equal to the lowest SNR which guarantees that the predefined target BER is achieved by code n. Any user whose secondary SNR falls into the interval $[0, \gamma_1)$ is associated with a data rate of zero (no transmission). This interval is referred to as the outage interval. The BER of a 2^n−QAM constellation with an SNR of γ is given in [26] and can be expressed as:

$$P_{b_n}(\gamma) = \frac{1}{5}\exp\left(\frac{-3\gamma}{2(2^n-1)}\right). \tag{4.12}$$

Given a target BER equal to BER_o, the region boundaries for n = 0, 1, ..., N are given by [2]

$$\gamma_n = -\frac{2}{3}\ln(5\text{BER}_\text{o})(2^\text{n}-1). \tag{4.13}$$

In our system, we define a minimum modulation threshold, which we refer to as the SNR threshold, γ_T. The SNR threshold ensures that the quality of the secondary's communication link does not fall below a desired value. All secondary users are expected to at least meet the SNR threshold to be considered for scheduling by the BS.

E. ASE and BER Analysis

The ASE of the systems in this section is conditioned on a set of given secondary user positions (d_s), and is obtained as a sum of the spectral efficiencies $\{\text{R}_n\}_{n=1}^{N} = \{1, 2, \ldots, N\}$ for the individual codes weighted by the probability P_n that code n is used or equivalently,

$$\text{ASE} = \sum_{n=1}^{N} \text{R}_n P_n \tag{4.14}$$

where

$$P_n = \int_{\gamma_n}^{\gamma_{n+1}} f_{\gamma_{BS}}(x)\, dx. \tag{4.15}$$

The function $f_{\gamma_{BS}}(x)$ denotes the PDF of the received SNR at the BS, where the distribution of the PDF depends on the mode of operation of the selected multiuser access scheme. Simplifying the ASE expression further, we obtain

$$\text{ASE} = \sum_{n=1}^{N} \text{R}_\text{n} P_n = \sum_{n=1}^{N} \text{R}_\text{n} \left[F_{\gamma_s}(\gamma_{n+1}) - F_{\gamma_s}(\gamma_n)\right] = N - \sum_{n=1}^{N} F_{\gamma_s}(\gamma_n). \tag{4.16}$$

The system's BER conditioned on a set of given user positions is given as the average number of erroneous bits divided by the average number of bits transmitted

$$\overline{\text{BER}} = \frac{\sum_{n=1}^{N} R_n \overline{\text{BER}}_n}{\text{ASE}}, \tag{4.17}$$

where $\overline{\text{BER}}_n$ is the average BER for constellation size n and is given by [2]

$$\overline{\text{BER}}_n = \int_{\gamma_n}^{\gamma_{n+1}} \text{BER}(x) f_{\gamma_{BS}}(x)\, dx. \tag{4.18}$$

Assuming that a total of K secondary user are connected to the BS, integrating ASE and $\overline{\text{BER}}$ over the users position PDF, given by (4.1), yields the exact analytical value of ASE and $\overline{\text{BER}}$ averaged over the random positions of the secondary users,

$$\begin{aligned} \langle ASE \rangle \;=\; & \sum_{n=0}^{N} R_n \int_{R_o}^{R_s} \int_{R_o}^{R_s} \cdots \int_{R_o}^{R_s} \left[F_{\gamma_s}(\gamma_{n+1}) - F_{\gamma_s}(\gamma_n)\right] f_r(d_{s_1}) f_s(d_{s_2}) \cdots f_s(d_{s_K}) \\ & \times d(d_{s_1}) d(d_{s_2}) \cdots d(d_{s_K}) \end{aligned} \tag{4.19}$$

and

$$\begin{aligned} \langle BER \rangle \;=\; & \sum_{n=0}^{N} R_n \int_{R_o}^{R_s} \int_{R_o}^{R_s} \cdots \int_{R_o}^{R_s} \left(\frac{\overline{BER}_n}{ASE} \right) f_r(d_{s_1}) f_s(d_{s_2}) \cdots f_s(d_{s_K}) \\ & \times\, d(d_{s_1}) d(d_{s_2}) \cdots d(d_{s_K}). \end{aligned} \tag{4.20}$$

CHAPTER V

MULTIUSER SCHEDULING SCHEMES

This chapter offers an in depth view of the two multiuser scheduling schemes that are adopted and analyzed in this thesis, namely the selection combining scheme and the scan-and-wait scheme. In order to understand the system model better as well as the subsequent discussion, the channel model of a single user is depicted in Fig. 8, where γ_{s_i} is the secondary SNR of user i and γ_{I_i} is the interference SNR with the primary.

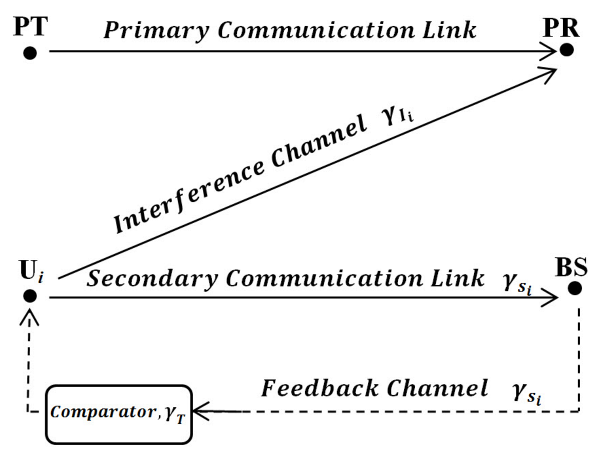

Fig. 8. Complete channel model of a single secondary user

A. Selection Combining Transmission Scheme

The selection combining transmission scheme, denoted as SCT or SC for short, relies on always serving the user with the strongest channel (user with the highest received SNR at the BS). Because the secondary system operates in an underlay cognitive setting, all users must first ensure that their transmission does not interfere with the primary user's communication link beyond a certain threshold. As a result, all secondary users must first guarantee they stay below the PIC. Users who exceed the

PIC are not considered for scheduling. The users that meet the interference constraint must then ensure they at least meet the minimum SNR threshold. Those users whose secondary received SNR is below the SNR threshold, γ_T, are also not considered for scheduling. As a result, the BS selects the users with the best channel quality (or highest SNR value) among the user who satisfy both the PIC and SNR threshold.

Assuming that there are a total of K users connected to the BS, the SCT scheme is examined as follows. During the guard period, the BS probes all users and selects those users that meet the PIC with the primary ($\gamma_{I_i} \leq Q$), (users receiving an acknowledgment from the PR in an ACK/NACK signaling system). These users are referred to as “feedback users” since they contribute to the feedback load of the system. Next, the BS probes the feedback users, requesting their SNR and determining which user meets the SNR threshold ($\gamma_{s_i} \geq \gamma_T$).

It is assumed that the secondary SNR information is sent back to the transmitting users via an error-free direct feedback channel. The time delay in this feedback is assumed to be negligible compared to the rate of the channel variation. Of the users that exceed the SNR threshold and meet the PIC, the BS selects the user with the best channel quality (user with the largest γ_s). If all K users fail to meet the PIC or SNR threshold, the last user is picked (for simplicity); however, the selected user is not allowed to transmit anything in the subsequent transmission time. In essence, the users who are not allowed to transmit set their transmit power to zero. The BS starts a new search after waiting a period equivalent to the channel coherence time.

The SC schemes yields the best ASE since it always serves the user with the highest secondary SNR. However, the SC scheme comes at the expense of a high feedback load. In essence, the feedback load can be viewed as the number of users that are requested to send their secondary SNR information to the BS.

B. Scan-and-Wait Transmission Scheme

In an attempt to simplify the selection procedure and decrease the feedback load of the SC scheme, the scan-and-wait transmission (SWT/SW) scheme is analyzed. In this scheme, the BS is no longer looking for the best user, but rather an acceptable user that meets both the PIC and SNR threshold. Simply put, the BS executes a sequential search of the users and selects the first acceptable user that meets both the PIC and SNR threshold.

The mode of operation of the SWT scheme is described as follows: during the guard period, the BS initiates a sequential search of the users, requesting the SNR (γ_{s_i}) of each user while simultaneously comparing it with the ACK or NACK that is received from the PR. If the i^{th} user receives an ACK from the PR and $\gamma_{s_i} \geq \gamma_T$, then that user is given access to the channel during the following transmission period. If the i^{th} user fails to meet both or one of the conditions, the BS switches to the next user to examine it. This switching and probing process continues until either a user is found that satisfies both constraints (this user is selected for the subsequent transmission time) or all K users fail to meet one or both constraints, in which case the BS simply picks the last user but does not allow it to transmit. Once again the BS waits a period equivalent to the channel coherence time before it starts a new sequential search. In this scheme, the BS always begins the sequential search from the user that was last given channel access. The mode of operation of the SW scheme is illustrated in the flow diagram shown in Fig. 9.

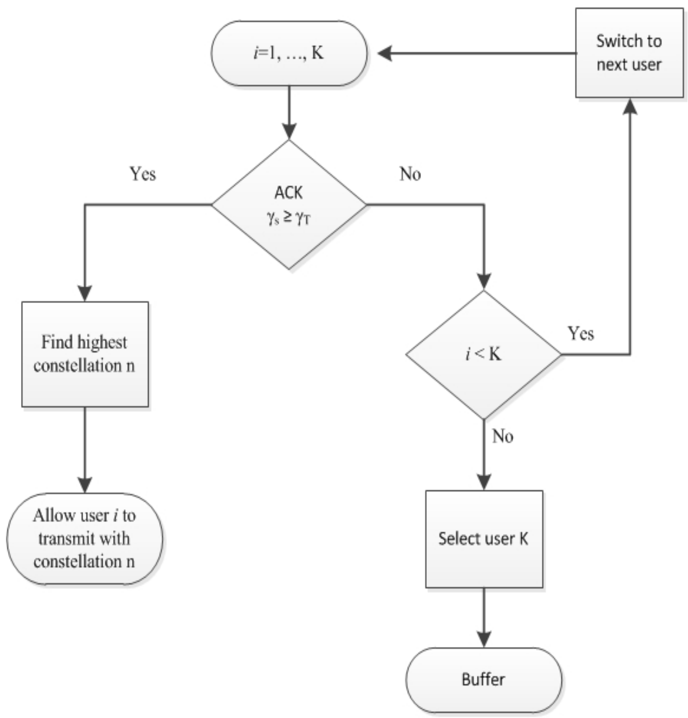

Fig. 9. Scan-and-Wait transmission scheme

CHAPTER VI

PERFORMANCE ANALYSIS OF THE ON/OFF POWER ADAPTIVE MULTIUSER ACCESS SCHEMES

In this chapter, the performance measures of the SCT and SWT schemes in the On/Off power adaptive mode are derived and analyzed in terms of the ASE, average feedback load, and average delay, where all performance measures are conditioned on a set of given user distances for simplicity.

A. On/Off Power Adaptive Setting

In chapter IV, we defined the fading characteristics of our system. Because our secondary users are randomly distributed with various distances from the BS, their average secondary SNRs are unequal. This feature causes a dilemma in terms of fairness of scheduling the users. In particular, the user with the highest average secondary SNR value will predominantly be chosen by the BS. In order to increase fairness between the users, each user adapts its transmit power in such a way that its average secondary SNR is set to a predetermined, required value, which we denote by $\bar{\gamma}_{req}$. Thus, the transmit power of the i^{th} user is defined by

$$P_{t_i} = \frac{\bar{\gamma}_{req}\ N_o}{\sigma^2_{s_i}}, \tag{6.1}$$

where $\sigma^2_{s_i} = \tau \left(\frac{d_o}{d_{s_i}}\right)^{\alpha}$.

In this scenario, the interference channels follow a Rayleigh fading distribution with independent but not necessarily identically distributed channel coefficients, resulting in exponentially distributed interference SNRs (γ_I) with unequal average interference SNRs ($\bar{\gamma}_{I_i} \neq \bar{\gamma}_{I_j}$ for $i \neq j$). Meanwhile, the secondary channels follow an i.i.d Rayleigh fading distribution with exponentially distributed secondary SNRs and $\bar{\gamma}_{s_i} = \bar{\gamma}_{req}$ for all $i = 1, 2, \ldots, K$. The CDF of received SNR from the i^{th} user at the PR and at the BS are then given by

$$F_{\gamma_{I_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{I_i}}\right), \quad x \geq 0 \tag{6.2}$$

and

$$F_{\gamma_{s_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{req}}\right), \quad x \geq 0. \tag{6.3}$$

The user that is selected by the BS is allowed to transmit its information using the transmit power given in (6.1), while users who are not permitted to transmit must set their transmit power to zero, thus giving rise to the term "On/Off power adaptation".

The probability that a single user fails to meet the PIC (i.e., $\gamma_{I_i} > Q$) is found as follows:

$$P(\gamma_{I_i} > Q) = 1 - P(\gamma_{I_i} \leq Q) = 1 - F_{\gamma_{I_i}}(Q), \tag{6.4}$$

where i denotes the i^{th} user. Similarly, the probability that a user fails to meet the SNR threshold (i.e. $\gamma_{s_i} < \gamma_T$) is shown to be

$$P(\gamma_{s_i} < \gamma_T) = F_{\gamma_{s_i}}(\gamma_T). \tag{6.5}$$

Analyzing the probability that a single user meets both the PIC and SNR threshold and the probability that a user is unable to meet either or both conditions, the probability of success and failure of the i^{th} user are given by

$$P_{S_i} = F_{\gamma_{I_i}}(Q)[1 - F_{\gamma_s}(\gamma_T)] \tag{6.6}$$

and

$$P_{F_i} = 1 - P_{S_i}. \tag{6.7}$$

The probability that all K users are unable to meet one or both constraints in both the SCT and SWT scheme is referred to as the probability of no transmission since the system must "buffer" the transmission for that time-slot. The probability of no transmission can be expressed as

$$P_{no} = \prod_{i=1}^{K} P_{F_i}. \tag{6.8}$$

B. Performance of the SCT Scheme

Analyzing the mode of operation of the SC scheme, we derive the CDF of the received SNR at the BS. For simplicity, we let γ_s^* denote the received secondary SNR at the BS post scheduling, and therefore the CDF of γ_s^* *per-time-slot* when $x \geq \gamma_T$ is computed as follows:

$$\begin{aligned}
F_{\gamma_s^*}^{SC}(x) \;=\; & \prod_{n=1}^{K}\left[1 - F_{\gamma_{I_i}}(Q)\right] + \left[\sum_{a_1}^{K} F_{\gamma_{I_{a_1}}}(Q) \prod_{\substack{k=1\\k\neq a_1}}^{K}\left(1 - F_{\gamma_{I_k}}(Q)\right)\right] \\
& \times \left[\sum_{j=0}^{1}\binom{1}{j}\left(F_{\gamma_s}(\gamma_T)\right)^{1-j}\left(F_{\gamma_s}(x) - F_{\gamma_s}(\gamma_T)\right)^{j}\right] \\
& + \left[\sum_{a_1=1}^{K}\sum_{a_2=a_1+1}^{K} F_{\gamma_{I_{a_1}}}(Q)F_{\gamma_{I_{a_2}}}(Q) \prod_{\substack{k=1\\k\neq\{a_1,a_2\}}}^{K}\left(1 - F_{\gamma_{I_k}}(Q)\right)\right] \\
& \times \left[\sum_{j=0}^{2}\binom{2}{j}\left(F_{\gamma_s}(\gamma_T)\right)^{2-j}\left(F_{\gamma_s}(x) - F_{\gamma_s}(\gamma_T)\right)^{j}\right] \\
& + \\
& \vdots \\
& + \left[\sum_{a_1=1}^{K}\cdots\sum_{a_{K-1}=a_{K-2}+1}^{K}\left(\prod_{m=1}^{K-1} F_{\gamma_{I_{a_m}}}(Q)\right) \prod_{\substack{k=1\\k\neq\{a_1,\ldots,a_{K-1}\}}}^{K}\left(1 - F_{\gamma_{I_k}}(Q)\right)\right] \\
& \times \left[\sum_{j=0}^{K-1}\binom{K-1}{j}\left(F_{\gamma_s}(\gamma_T)\right)^{K-1-j}\left(F_{\gamma_s}(x) - F_{\gamma_s}(\gamma_T)\right)^{j}\right]
\end{aligned}$$

$$+\prod_{n=1}^{K} F_{\gamma_{I_n}}(Q)\left[\sum_{j=0}^{K}\binom{K}{j}\left(F_{\gamma_s}(\gamma_T)\right)^{K-j}\left(F_{\gamma_s}(x)-F_{\gamma_s}(\gamma_T)\right)^{j}\right], \qquad (6.9)$$

where $a_0 = 0$. Simplifying the above expression yields

$$\begin{aligned} F_{\gamma_s^*}^{SC}(x) &= \prod_{n=1}^{K}\left[1-F_{\gamma_{I_n}}(Q)\right]+\sum_{i=1}^{K}\left[\prod_{j=1}^{i}\left(\sum_{a_j=a_{j-1}+1}^{K}\right)\prod_{m=1}^{i}F_{\gamma_{I_{a_m}}}(Q)\prod_{\substack{k=1\\ k\neq\{a_1,\cdots,a_i\}}}^{K}\left(1-F_{\gamma_{I_k}}(Q)\right)\right] \\ &\quad\times\sum_{l=0}^{i}\binom{i}{l}\left(F_{\gamma_s}(\gamma_T)\right)^{i-l}\left[F_{\gamma_s}(x)-F_{\gamma_s}(\gamma_T)\right]^{l} \\ &\quad+\prod_{n=1}^{K}F_{\gamma_{I_n}}(Q)\left[\sum_{l=0}^{K}\binom{K}{l}\left(F_{\gamma_s}(\gamma_T)\right)^{K-l}\left[F_{\gamma_s}(x)-F_{\gamma_s}(\gamma_T)\right]^{l}\right]. \qquad (6.10)\end{aligned}$$

The operation of selecting a user but not transmitting anything in the case when all K users fail to be selected by the BS ensures that the probability of not exceeding γ_T will be different from zero. Since no user is allowed to transmit information if all fail to be selected, the correct ASE and BER expressions are obtained by letting $\{\mathrm{R_n}\}_{n=1}^{N} = 0$ when $x < \gamma_T$. For the case when $x < \gamma_T$, the CDF is equal to the probability that all users fail to be selected and the last selected user's SNR at the BS is below x, and is given by $F_{\gamma_s^*}^{SC}(x) = P_{no}$.

Replacing $F_{\gamma_s}(x)$ in (4.19) with $F_{\gamma_s^*}^{SC}(x)$ yields the ASE of SCT scheme. We define the feedback load as the number of *feedback users* (users that meet the PIC) that the BS must probe until a user is given channel access. In other words, feedback is generated every time the BS requests a user to send its secondary SNR information, where the BS must then return this value to the user via the feedback channel. We let U_F denote the amount of feedback generated per-time-slot, where the value of U_F can range from zero to K, depending on the number of users that meet the PIC.

Thus, U_F is found as follows:

$$\begin{aligned} U_F &= K\left[\prod_{j=1}^{K} F_{\gamma_{I_i}}(Q)\right] + (K-1)\left[\sum_{a_1=1}^{K}(1-F_{\gamma_{I_{a_1}}}(Q))\prod_{\substack{j=1\\ j\neq a_1}}^{K} F_{\gamma_{I_{a_1}}}(Q)\right] \\ &\quad +(K-2)\left[\sum_{a_1=1}^{K}\sum_{a_2=a_1+1}^{K}(1-F_{\gamma_{a_1}}(Q))(1-F_{\gamma_{a_2}}(Q))\prod_{\substack{j=1\\ j\neq\{a_1,a_2\}}}^{K} F_{\gamma_{I_j}}(Q)\right] \\ &\quad + \\ &\quad \vdots \\ &\quad +(1)\left[\sum_{a_1=1}^{K}\cdots\sum_{a_{K-1}=a_{K-2}+1}^{K}\left\{\prod_{i=1}^{K-1}(1-F_{\gamma_{a_i}}(Q))\right\}\prod_{\substack{j=1\\ j\neq\{a_1,\cdots,a_{K-1}\}}}^{K} F_{\gamma_{I_j}}(Q)\right]. \end{aligned} \tag{6.11}$$

The average feedback load (AFL) of the SC scheme is then given by:

$$AFL_{SC} = \sum_{m=0}^{+\infty} U_F\,(P_{no})^m = \frac{U_F}{1-P_{no}}. \tag{6.12}$$

If no user is able to satisfy both the SNR threshold and the inference constraint, the system has to delay transmission until an acceptable user is found. Letting D denote the number of time-slots that the system does not transmit until a successful transmission, we notice that the delay may range from zero to infinity (which means the system is constantly buffering data due to unacceptable user characteristics). Thus, the average number of delays can be expressed as:

$$\bar{D}^{SC} = \sum_{m=0}^{+\infty} mP(D=m) = \sum_{m=0}^{+\infty} m(P_{no})^m(1-P_{no}) = \frac{P_{no}}{1-P_{no}}. \tag{6.13}$$

C. Performance of the SWT Scheme

The SWT scheme is based on a sequential search of an acceptable user, thus the CDF of the received SNR is quiet different than that of the SCT scheme. Analyzing the mode of operation of the SWT scheme, the CDF of the received SNR at the BS (${\gamma_s}^*$) of the SWT scheme (*per-time-slot*) when $x \geq \gamma_T$ takes the expression:

$$F^{SW}_{\gamma_s^*}(x) = P(\gamma_s^* \leq x). \tag{6.14}$$

Using the law of total probability, we obtain

$$\begin{aligned} F^{SW}_{\gamma_s^*}(x) &= \sum_{i=1}^{K} P(\gamma_{s_i} \leq \gamma_s^* \mid \gamma_s^* = \gamma_{s_i}) P(\gamma_s^* = \gamma_{s_i}) \\ &= \frac{1}{K} \sum_{i=1}^{K} P(\gamma_{s_i} \leq \gamma_s^* \mid \gamma_s^* = \gamma_{s_i}), \end{aligned} \tag{6.15}$$

where $P(\gamma_s^* = \gamma_{s_i}) = \frac{1}{K}$ because each user has equal probability of being chosen. Considering all events that select successfully a user, it follows that:

$$\begin{aligned} F^{SW}_{\gamma_s^*}(x) = P_{no} &+ (S_1 + P_{F_K} S_1 + P_{F_{K-1}} P_{F_K} S_1 + \cdots + P_{F_2} P_{F_3} \cdots P_{F_K} S_1) \\ &+ (S_2 + P_{F_1} S_2 + P_{F_K} P_{F_1} S_2 + \cdots + P_{F_3} P_{F_4} \cdots P_{F_K} P_{F_1} S_2) \\ &+ \cdots + (S_K + P_{F_{K-1}} S_K + P_{F_{K-2}} P_{F_{K-1}} S_K + \cdots + P_{F_1} P_{F_2} \cdots P_{F_{K-1}} S_K) \end{aligned} \tag{6.16}$$

where S_i is the probability of success of the i^{th} user and is given by

$$S_i = F_{\gamma_{I_i}}(Q) \left[F_{\gamma_s}(x) - F_{\gamma_s}(\gamma_T) \right] \tag{6.17}$$

and P_{F_j} is the probability that the j^{th} user fails and is given in (9.16). Rewriting this expression in a more compact fashion yields

$$F^{SW}_{\gamma_s^*}(x) = \frac{1}{K} \sum_{i=1}^{K} \left\{ S_i \left[1 + \sum_{l=0}^{K-2} \prod_{n=1}^{l+1} P_{F_{x[\langle n-i \rangle_K]}} \right] \right\} + P_{no} \tag{6.18}$$

where $\langle \cdot \rangle$ denotes the modulo operator and $\langle a \rangle_b$ represents a modulo b. The term $x[\langle n-i \rangle_K]$ represents the index i (i^{th} user) in P_{F_i} and is given by

$$x[r] = \begin{bmatrix} K \\ K-1 \\ \vdots \\ 2 \\ 1 \end{bmatrix}, \quad r = 0, 1, \cdots, K-1 \tag{6.19}$$

where $x[0] = K,\ x[1] = K-1,\ \cdots,\ x[K-1] = 1$. The mathematics of the CDF are specifically set up in this fashion in order to mimic the circular shift phenomenon of the SW scheme. The CDF of the received SNR at the BS when $x < \gamma_T$ is given by $F^{SW}_{\gamma_s^*}(x) = P_{no}$.

Replacing $F_{\gamma_s}(x)$ in (4.19) with $F^{SW}_{\gamma_s^*}(x)$ yields the ASE of SWT scheme. The average feedback of the SWT scheme depends on the number of users that the BS probes before channel access, thus the feedback can range from 1 to infinity if no users are ever able to satisfy both the PIC and SNR threshold. The derivation of the average feedback load of the SW scheme is as follows. First, we let

$$\begin{aligned}
X_1 &= \frac{1}{K}(P_{S_1} + P_{S_2} + \cdots + P_{S_K}) \\
X_2 &= \frac{1}{K}(P_{F_K}P_{S_1} + P_{F_1}P_{S_2} + \cdots + P_{F_{K-1}}P_{S_K}) \\
X_3 &= \frac{1}{K}(P_{F_{K-1}}P_{F_K}P_{S_1} + P_{F_K}P_{F_1}P_{S_2} + \cdots + P_{F_{K-2}}P_{F_{K-1}}P_{S_K}) \\
&\vdots \\
X_K &= \frac{1}{K}(P_{F_2}P_{F_3}\cdots P_{F_K}P_{S_1} + P_{F_3}P_{F_4}\cdots P_{F_K}P_{F_1}P_{S_2} + \cdots P_{F_1}P_{F_2}\cdots P_{F_{K-1}}P_{S_K})
\end{aligned} \tag{6.20}$$

Writing out all the possible values that the AFL can take, we obtain

$$\begin{aligned}
AFL_{SW} &= (X_1 + 2X_2 + \cdots + KX_K) + P_{no}\left[(1+K)X_1 + (2+K)X_2 + \cdots + (K+K)X_K\right] \\
&\quad + (P_{no})^2\left[(1+K2)X_1 + (2+2K)X_2 + \cdots + (K+2K)X_K\right] + \cdots
\end{aligned}$$

$$= \sum_{j=0}^{+\infty} (P_{no})^j \left[(1+jK)X_1 + (2+jK)X_2 + \cdots + (K{+}jK)X_K\right]$$
$$= \sum_{j=0}^{+\infty} (P_{no})^j (X_1 + 2X_2 + \cdots + KX_K) + K \sum_{j=0}^{+\infty} j(P_{no})^j (X_1 + X_2 + \cdots + X_K)$$
$$= \frac{(X_1 + 2X_2 + \cdots + KX_K)}{1 + P_{no}} + \frac{K(X_1 + X_2 + \cdots + X_K)P_{no}}{(1-P_{no})^2} \qquad (6.21)$$

Rewriting (6.21) in a more compact manner

$$AFL_{SW} = \frac{V_1}{1-P_{no}} + K\frac{P_{no}\,V_2}{(1-P_{no})^2} \qquad (6.22)$$

where $V_1 = (X_1 + 2X_2 + \cdots + KX_K)$ and $V_2 = (X_1 + X_2 + \cdots + X_K)$. The average delay of the SWT scheme is equivalent to (6.13).

CHAPTER VII

PERFORMANCE ANALYSIS OF THE FULL POWER ADAPTIVE MULTIUSER ACCESS SCHEMES

In this chapter, the performance of the SCT and SWT schemes in the full power adaptive setting are derived and analyzed in terms of the ASE, average feedback load, and average delay, where for simplicity, all performance measures are conditioned on a set of given user distances.

A. Full Power Adaptive Setting

In all spectrum sharing systems, users that want to transmit data to a target secondary receiver must first ensure that they stay below a maximum interference threshold, Q, that the primary receiver can tolerate. If a user is unable to meet the PIC, it is not considered for transmission. In this chapter, a power adaptive scheme that adapts the secondary user's transmit power P_{t_i} according to $|h_{I_i}|^2$ to satisfy the PIC at the primary receiver is proposed and analyzed. That is, a secondary user allocates its peak power, P_{max}, for transmission if the interference constraint is satisfied with the peak power. Otherwise, it adaptively adjusts its transmit power to the allowable level so that the interference observed at the PR is below the maximum interference level Q. A user meets the PIC if

$$\gamma_{I_i} = \frac{P_{t_i}|h_{I_i}|^2}{N_o} \leq Q. \tag{7.1}$$

Thus, the transmit power, that ensures the PIC is is satisfied, is upper bounded by

$$P_{t_i} \leq \frac{QN_o}{|h_{I_i}|^2}. \tag{7.2}$$

However, for small $|h_{I_i}|^2$, equation (7.2) becomes extremely large, and for $|h_{I_i}|^2 = 0$, the transmit power becomes infinity. As a result, we define the i^{th} user's transmit power that satisfies the PIC as

$$P_{t_i} = min\left(P_{max}, \frac{QN_o}{|h_{I_i}|^2}\right). \tag{7.3}$$

With the defined transmit power, a user's secondary SNR becomes

$$\gamma_{s_i}^{PA} = \frac{min\left(P_{max}, \frac{QN_o}{|h_{I_i}|^2}\right)|h_{s_i}|^2}{N_o}, \tag{7.4}$$

where PA denotes the Full Power Adaptive Setting. The CDF of the secondary SNR is similar to [27] and is given by

$$\begin{aligned} F_{\gamma_{s_i}^{PA}}(x) &= P\left(\gamma_{s_i}^{PA} \leq x\right) \\ &= 1 - \left(1 - \frac{1}{1 + \frac{\sigma_{s_i}^2}{\sigma_{I_i}^2}\frac{Q}{x}} e^{-\frac{QN_o}{\sigma_{I_i}^2 P_{max}}}\right) e^{-\frac{xN_o}{\sigma_{s_i}^2 P_{max}}}. \end{aligned} \tag{7.5}$$

Because the users experience independent but not identically distributed Rayleigh fading channels, to increase fairness in the selection process of the users, the average secondary SNRs are all set to the desired value $\bar{\gamma}_{req}$ by multiplying each user's instantaneous SNR, γ_s^{PA} by a coefficient β such that $\mathrm{E}\left[\beta_i \gamma_{s_i}^{PA}\right] = \bar{\gamma}_{req}$ where E[·] denotes the expected/average value operator. Letting $\gamma_{s_i}^{PA\prime} = \beta_i \gamma_{s_i}^{PA}$, the value of β is found as follows

$$\mathrm{E}\left[\beta_i \gamma_{s_i}^{PA}\right] = \bar{\gamma}_{req}$$

$$\beta_i \mathrm{E}\left[\gamma_{s_i}^{PA}\right] = \beta_i \bar{\gamma}_{s_i}^{PA} = \bar{\gamma}_{req}$$

$$\beta_i = \frac{\bar{\gamma}_{req}}{\overline{\gamma}_{s_i}^{PA}}$$

where $\overline{\gamma}_{s_i}^{PA}$ is the statical mean of the random variable $\gamma_{s_i}^{PA}$.

The CDF of new secondary SNR, $\gamma_{s_i}^{PA'} = \beta_i \gamma_{s_i}^{PA}$, is found through a simple change of variable calculation and is given by

$$\begin{aligned} F_{\gamma_{s_i}^{PA'}}(x) &= P\left(\gamma_{s_i}^{PA'} \leq x\right) \\ &= 1 - \left(1 - \frac{1}{1 + \frac{\sigma_{s_i}^2}{\sigma_{I_i}^2} \frac{Q\beta_i}{x}} e^{-\frac{QN_o}{\sigma_{I_i}^2 P_{max}}}\right) e^{-\frac{xN_o}{\sigma_{s_i}^2 \beta_i P_{max}}}. \end{aligned} \quad (7.6)$$

We note that the secondary SNRs ($\gamma_{s_i}^{PA'}$) are now i.i.d random variables with the above CDF. Due to the additional β factor in the secondary SNR, the previously defined power is changed; however, the number of users that meet the PIC is still deterministic and depends on β. Specifically, if the i^{th} user has $\beta_i \leq 1$, then that user satisfies the PIC and is considered for scheduling (depending on whether or not it meets the SNR threshold).

Furthermore, we define $\Phi = \{\varphi_1, \varphi_2, \cdots, \varphi_m\}$ as the set that contains all the indices of the users that satisfy $\beta \leq 1$, where φ_j represents the index of the j-th user that satisfies $\beta \leq 1$ and $m = 0, 1, \cdots, K$ is the total number of users in the set Φ that meet the PIC. For example, if we have a total of five users and only users 1,3, and 5 meet the PIC (i.e., $\beta_1 \leq 1, \beta_3 \leq 1, \text{and } \beta_5 \leq 1$), then $\Phi = \{1, 3, 5\}$, where $\varphi_1 = 1, \varphi_2 = 3, \text{and } \varphi_3 = 5$.

At this point we emphasis an important characteristic of the full power adaptive setting. Since the m users belonging to the set Φ meet the PIC, the scheduling process of these users becomes dependent only on the SNR threshold, γ_T. From this point forward, the analysis of the SC and SW schemes will be defined for a given set Φ with m users that meet the PIC. Furthermore, the probability of no transmission of the full power adaptive schemes is equivalent to the probability that all m users fail to meet the SNR threshold and is given by

$$P_{no}^{PA} = \left[F_{\gamma_{s_i}^{PA'}}(\gamma_T)\right]^m . \tag{7.7}$$

B. Performance of the SC-PA Scheme

In this section we discuss the mode of operation of the full power adaptive SC (SC-PA) scheme, characterize its received SNR post scheduling, and analyze its performance.

In the SC-PA scheme, the BS starts by asking the m users $(U_{\varphi_1}, U_{\varphi_2}, \cdots, U_{\varphi_m})$ belonging to the set Φ for their secondary SNR and compares them to γ_T. The BS then chooses the user with the maximum $\gamma_s^{PA'}$ among all the users that exceed the SNR threshold. If all m users are unable to meet the SNR threshold, the BS selects the last user in the set; however, it does not allow it to transmit any information in the subsequent transmission time interval.

Analyzing the mode of operation of the SC-PA scheme, the CDF of the received SNR at the BS (γ_s^*) for a given set Φ is similar to (6.10) but now since the scheduling procedure is independent of the PIC, the terms that take into account the PIC are eliminated and therefore the following CDF is obtained for $x \geq \gamma_T$:

$$F_{\gamma_s^*}^{SC-PA}(x) = \sum_{j=0}^{m} \binom{m}{j} \left[F_{\gamma_{s_i}^{PA'}}(x) - F_{\gamma_{s_i}^{PA'}}(\gamma_T)\right]^j \left[F_{\gamma_{s_i}^{PA'}}(\gamma_T)\right]^{m-j} , \tag{7.8}$$

where $F_{\gamma_{s_i}^{PA'}}(\cdot)$ is given in (7.6). For the case when $x < \gamma_T$, the CDF is given by $F_{\gamma_{s_i}^{PA'}}^{SC-PA}(x) = P_{no}^{PA}$.

The ASE_{SC-PA} is obtained by replacing $F_{\gamma_s}(x)$ in (4.19) with (7.8). The average feedback load of the SCT-PA scheme is dependent on the cardinality of Φ and is derived as follows :

$$\begin{aligned} AFL_{SC-PA} &= m(1-P_{no}^{PA}) + 2mP_{no}^{PA}(1-P_{no}^{PA}) + 3mP_{no}^{PA}(1-P_{no}^{PA}) + \cdots \\ &= m(1-P_{no}^{PA})\sum_{j=0}^{+\infty} j(P_{no}^{PA})^{j-1} \\ &= \frac{m}{1-P_{no}^{PA}} \quad for \quad m \neq 0 \end{aligned} \tag{7.9}$$

The average number of coherence times that the system must wait before a successful transmission (average delay) is shown to be

$$\bar{D}^{SC-PA} = \sum_{n=0}^{+\infty} nP(D=n) = \sum_{n=0}^{+\infty} n\left(P_{no}^{PA}\right)^n \left(1-P_{no}^{PA}\right) = \frac{P_{no}^{PA}}{1-P_{no}^{PA}}. \tag{7.10}$$

C. Performance of the SW-PA Scheme

In this section we discuss the mode of operation of the full power adaptive SW (SW-PA) scheme, characterize its received SNR post scheduling, and analyze its performance.

In the SW-PA scheme, the BS starts by asking the first user out of the m users $(U_{\varphi_1}, U_{\varphi_2}, \cdots, U_{\varphi_m})$ belonging to the set Φ for its secondary SNR and compares it to γ_T. If the selected user meets the switching threshold, the BS selects it for transmission. Otherwise, the BS switches to the next user. This probing and switching process continues until either a successful user is found or until all m users have been probed and none was found to meet γ_T. In the latter case, the BS selects the last user but does not allow it to transmit in the subsequent transmission time.

The probability of a user's secondary SNR being less than the SNR threshold is given by

$$P_F^{PA} = P(\gamma_{s_i}^{PA'} < \gamma_T) = F_{\gamma_{s_i}^{PA'}}(\gamma_T), \tag{7.11}$$

and it represents the probability that a user fails to be selected in the SW-PA scheme.

The CDF of the received SNR at the BS for when $x \geq \gamma_T$ is derived as shown below:

$$
\begin{aligned}
F_{\gamma_s^*}^{SW-PA}(x) &= P\left(\gamma_s^* \leq x\right) \quad \text{by definition of the CDF} \\
&= \sum_{i=1}^{K} P\left(\gamma_{s_i}^{PA'} \leq x \mid \gamma_s^* = \gamma_{s_i}^{PA'}\right) P\left(\gamma_s^* = \gamma_{s_i}^{PA'}\right) \quad \text{by total probability theorem} \\
&= \frac{1}{m}\sum_{i=1}^{K} P\left(\gamma_{s_i}^{PA'} \leq x \mid \gamma_s^* = \gamma_{s_i}^{PA'}\right) \quad \text{because users are equiprobable users} \\
&= \frac{m}{m} P\left(\gamma_{s_i}^{PA'} \leq x \mid \gamma_s^* = \gamma_{s_i}^{PA'}\right) \quad \text{because i.i.d SNRs} \\
&= P\left(\gamma_{s_i}^{PA'} \leq x \mid \gamma_s^* = \gamma_{s_i}^{PA'}\right)
\end{aligned}
$$

Considering all the possible events for the BS selecting the i^{th}, it follows that

$$
\begin{aligned}
F_{\gamma_s^*}^{SW-PA}(x) &= S_i^{PA} + P_F^{PA} S_i^{PA} + \left(P_F^{PA}\right)^2 S_i^{PA} + \cdots + \left(P_F^{PA}\right)^{m-1} S_i^{PA} + P_{no}^{PA} \\
&= P_{no}^{PA} + \sum_{j=0}^{m-1} S_i^{PA} \left(P_F^{PA}\right)^j \\
&= S_i^{PA} \, \frac{1-\left(P_F^{PA}\right)^m}{1-P_F^{PA}} + P_{no}^{PA},
\end{aligned} \tag{7.12}
$$

where $S_i^{PA} = \left[F_{\gamma_s^*}(x) - F_{\gamma_s^*}(\gamma_T)\right]$ denotes the probability of success of the i^{th} user. Thus, the CDF of the received SNR at the BS for the SW-PA scheme is expressed as

$$
F_{\gamma_{s_i}^{PA'}}^{SW-PA}(x) = \left[F_{\gamma_{s_i}^{PA'}}(x) - F_{\gamma_{s_i}^{PA'}}(\gamma_T)\right] \left[\frac{1-P_{no}^{PA}}{1-F_{\gamma_{s_i}^{PA'}}(\gamma_T)}\right] + P_{no}^{PA}. \tag{7.13}
$$

The CDF of the received SNR at the BS when $x < \gamma_T$ is given by $F_{\gamma_{s_i}^{PA'}}^{SW-PA}(x) = P_{no}^{PA}$. The ASE_{SW-PA} is obtained by replacing $F_{\gamma_s}(x)$ in the ASE definition (equation (4.19)) with (7.13).

Defining the feedback load as the number of users the BS must probe before finding a successful user, we can argue that the feedback load has a geometric distribution with parameter $\theta = 1 - P_F^{PA} = 1 - F_{\gamma_{s_i}^{PA'}}(\gamma_T)$. Thus, the average feedback load (AFL) nis expressed as

$$AFL_{SW-PA} = \frac{1}{\theta} = \frac{1}{1 - F_{\gamma_{s_i}^{PA'}}(\gamma_T)}. \tag{7.14}$$

The average delay of the SW-PA scheme is identical to (7.11).

CHAPTER VIII

NUMERICAL RESULTS

In this chapter, the performances of the proposed schemes are illustrated via selected numerical simulations. These examples demonstrate the trade-off between ASE and feedback, and each system performs under various conditions.

A. Random Distance Generation

The exact analytical values of the ASE, average BER, AFL, and average delay require the calculation of numerical K-fold integrals (in order to average over all the possible distances the K users can take). Rather than computing these burdensome integrals, we opted for Monte Carlo simulations to estimate them. The random distances are calculated according to the following steps [24].

1. The polar coordinates (d_{s_i}, θ_i) are randomly picked according to (4.1) and (4.2) as follows:

   (a) Generate K random, independent numbers x_i and y_i that are uniformly distributed in $[0, 1]$.

   (b) Generate the K polar coordinates (d_{s_i}, θ_i) as

$$d_{s_i} = R_o + (R_s - R_o)\sqrt{x_i} \tag{8.1}$$

$$\theta_i = 2\pi y_i \tag{8.2}$$

2. The distance between the i^{th} user and the PR is generated as follows:

$$d_{I_i} = \sqrt{D_{PS}^2 + x_i^2 + 2x_i D_{PS} sin(\theta_i)} \tag{8.3}$$

B. Numerical Examples

For all the numerical examples shown in this chapter, the minimum modulation threshold (SNR threshold) was set to $\gamma_T = \gamma_1$. The SNR threshold can be set to any value between γ_1 and γ_N; however, as the threshold increases, the average spectral efficiency increases but at the expense of a higher feedback load. Our focus is to minimize the feedback, so we set the threshold to γ_1, which sets the minimum modulation to BPSK (n=1 bit per symbol) and it minimizes the feedback of the proposed schemes compared to higher threshold values.

In Fig. 10, the ASEs of the proposed schemes are illustrated as a function of the number of users connected to the BS. The SC-PA scheme yields the highest ASE compared to all the schemes. Fig. 10 also shows that the full power adaptive setting significantly increases the ASE versus the On/Off power adaptive case for both the SCT and SWT schemes. Comparing the SCT scheme to the SWT scheme, the ASE of the SC schemes is higher than that of the SW schemes, and similarly for SC-PA and SW-PA. Furthermore, as the number of users connected to the BS increases, the ASE of SC schemes increases due to the fact that it becomes more probable that out of the larger selection of users, a user is found that has a larger γ_s. For the SW schemes, it is noticed that as the number of users increase, the ASE saturates. This phenomenon occurs due to the mode of operation of the scheme. Because the BS executes a *sequential* search of an acceptable user, the ASE is predominately dependent on the first successful user rather than the number of users connected to the BS.

The SCT scheme may be viewed as the optimal scheme when compared to the SWT scheme since it produces a higher ASE; however, SC comes with the disadvantage of a higher feedback load. The average feedback load of all the schemes are

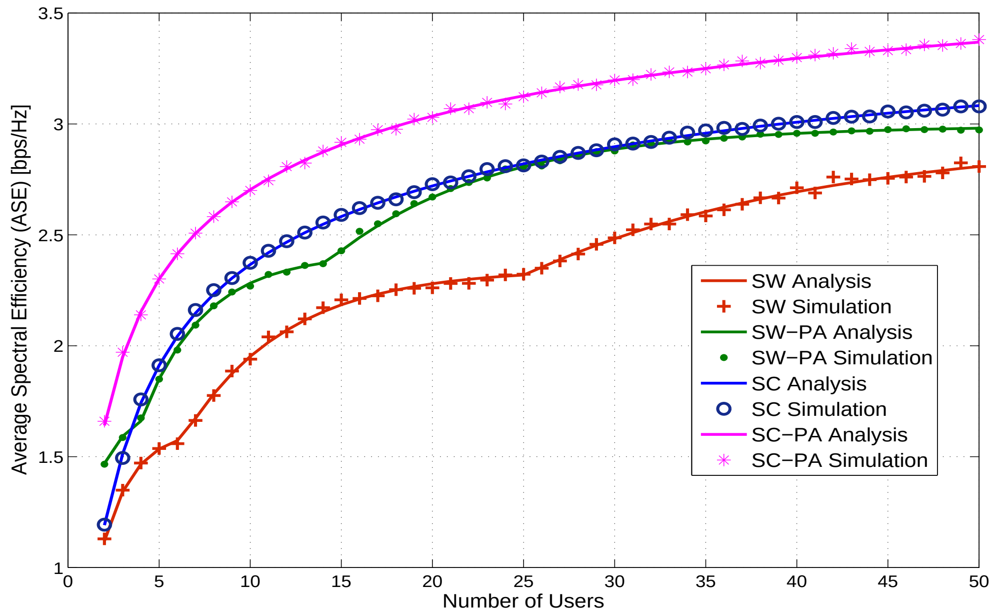

Fig. 10. Average spectral efficiency versus number of users connected to the BS for $Q_{dB} = 0$, $\overline{\gamma}_{req} = 5$ dB, $\mathrm{BER}_0 = 10^{-3}$, $P_{max} = 1$ dB, $\mathrm{R_o} = 10$m, $\mathrm{R_s} = 50$m, $\mathrm{D_{PS}} = 100$m, $\mathrm{d_o} = 10$m, α=2.1.

depicted in Fig. 11. As shown from Fig. 11, the SC-PA scheme yields the highest feedback load due to the fact that the users initially adapt their power to meet the PIC and therefore the number of feedback users is larger. The SCT scheme in the On/Off power adaptive scheme yields a slightly lower AFL compared to the SC-PA. For both power settings, the SWT schemes yield a significantly lower feedback load than the SC cases.

The delay that the On/Off power adaptive schemes experience is comparably higher than that of the full power adaptive schemes, as shown in Fig. 12. However, as the number of users connected to the BS increases, the delay in all schemes decreases due to a greater probability that a successful user is found by the BS.

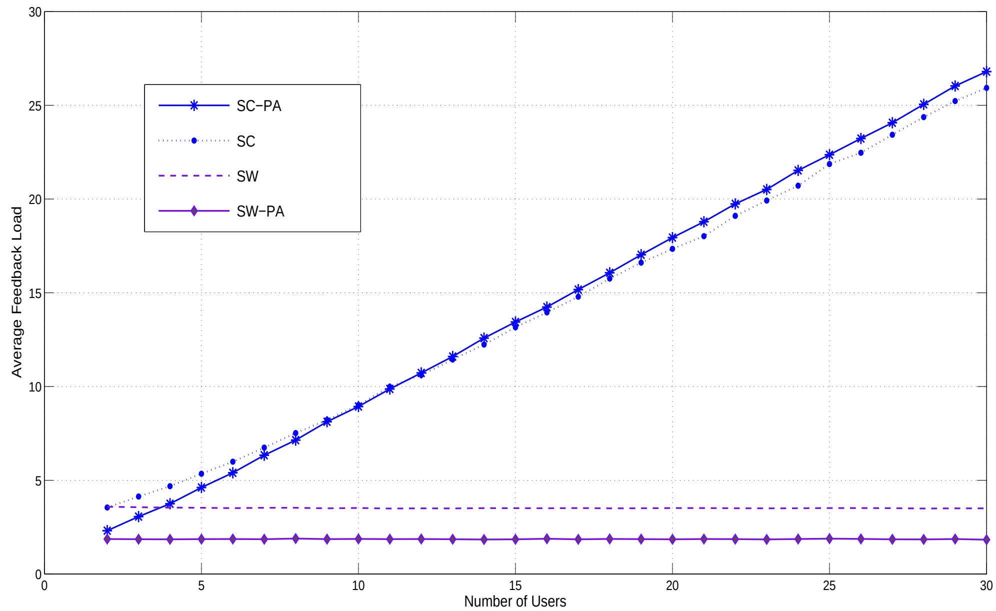

Fig. 11. Average feedback load versus number of users connected to the BS for $Q_{dB} = 0$, $\overline{\gamma}_{req} = 5$ dB, $\mathrm{BER}_0 = 10^{-3}$, $P_{max} = 1$ dB, $\mathrm{R_o} = 10$m, $\mathrm{R_s} = 50$m, $\mathrm{D_{PS}} = 100$m, $\mathrm{d_o} = 10$m, and α=2.1.

1. Simulation vs Analysis

Fig. 13 illustrates the ASE of the On/Off power adaptive schemes for a range of the peak interference constraint. The simulations are also confirmed analytically for the case when three users are connected to the BS. The figure shows that the SC scheme produces a higher ASE than the SW scheme. Furthermore, for low Q_{dB}, many users are not able to meet the stringent PIC, and therefore, the performance of the system suffers. However, as the PIC increases, the scheduling process becomes independent of the PIC and dependent only on the SNR threshold, significantly improving the ASE.

Fig. 14 depicts the AFL of the SC and SW schemes as a function of the PIC. For the SC scheme, when the PIC is small, more users are unable to satisfy the PIC and therefore the number of feedback users available to the BS is small. However, as

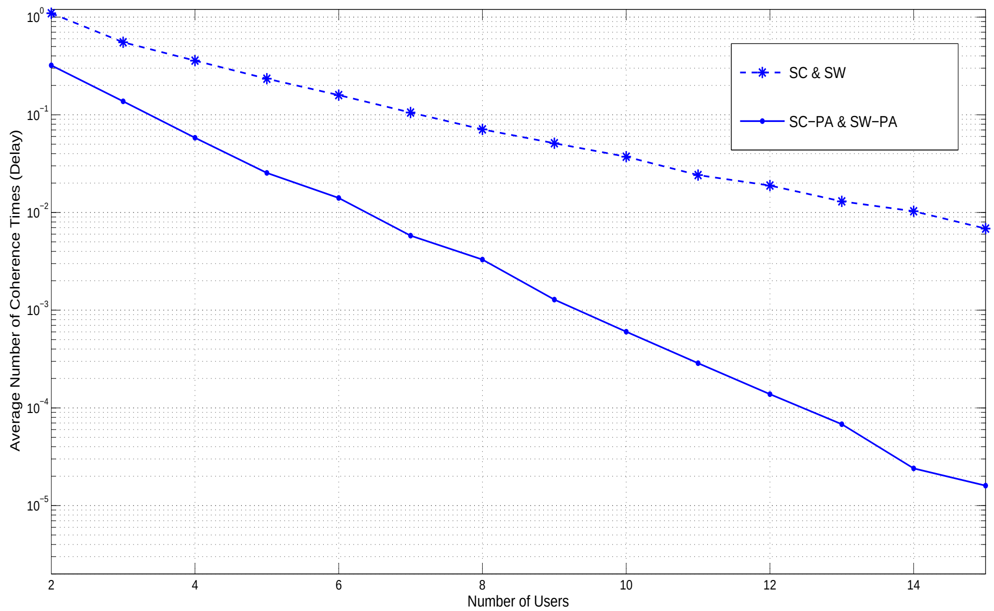

Fig. 12. Average number of coherence times (average delay) versus number of users connected to the BS for $Q_{dB} = 0$, $\overline{\gamma}_{req} = 5$ dB, $\mathrm{BER}_0 = 10^{-3}$, $P_{max} = 1$ dB, $\mathrm{R_o} = 10$m, $\mathrm{R_s} = 50$m, $\mathrm{D_{PS}} = 100$m, $\mathrm{d_o} = 10$m and α=2.1.

the PIC increases, more users are able to satisfy the PIC and therefore the number of users the BS must probe increases. This is the opposite for the SW case, namely, for small PIC, the feedback is large because the BS must probe more users before finding an acceptable user. However, as the PIC increases, the feedback of the SW schemes decreases because more users are able to satisfy the PIC and the BS is able to find an acceptable user earlier on in the probing process.

As for the AFL of the full power adaptive schemes depicted in Fig. 15, the AFL of the SW-PA scheme presents the same reasoning as in the On/Off setting. However, the SC-PA scheme starts with a high AFL for low Q_{dB} and decreases its AFL as the PIC increases. This phenomenon occurs due to the system operation mode. Because the users initially adapt their transmit power to satisfy the PIC, the number of users that contribute to the AFL is around three for this example. However, due to the power adaptive procedure, many users are unable to meet the SNR threshold for

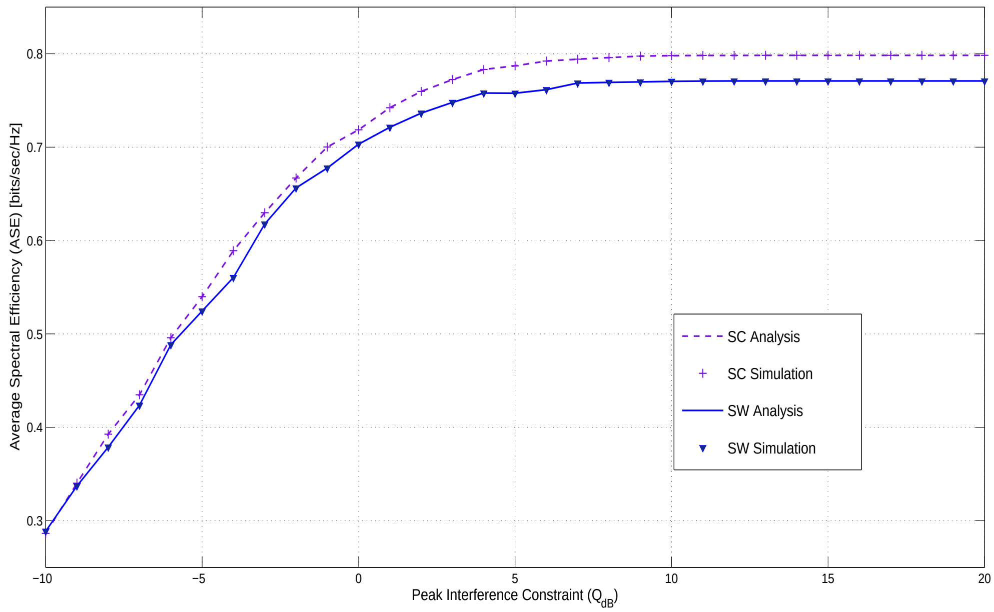

Fig. 13. Average spectral efficiency versus PIC for K=3 users, $\overline{\gamma}_{req} = 5$ dB, $\mathrm{BER}_0 = 20^{-3}$, $P_{max} = 1$ dB, $\mathrm{R_o} = 10$m, $\mathrm{R_s} = 50$m, $\mathrm{D_{PS}} = 100$m, $\mathrm{d_o} = 10$m and α=2.1.

low Q_{dB}. As a result, the feedback increases until a successful user is found. As Q_{dB} increases, users are able to satisfy both constraints and the AFL tends to be deterministic and equal to the number of users connected to the BS (three in our example).

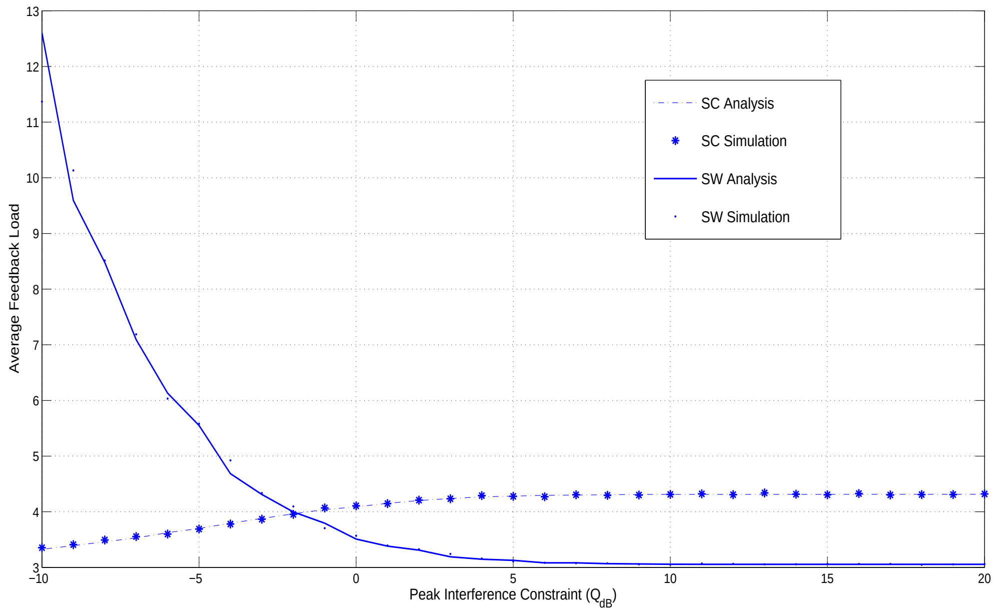

Fig. 14. Average feedback load versus PIC for K=3 users, $\overline{\gamma}_{req} = 5$ dB, $\mathrm{BER}_0 = 10^{-3}$, $P_{max} = 1$ dB, $\mathrm{R_o} = 10$m, $\mathrm{R_s} = 50$m, $\mathrm{D_{PS}} = 100$m, $\mathrm{d_o} = 10$m and α=2.1.

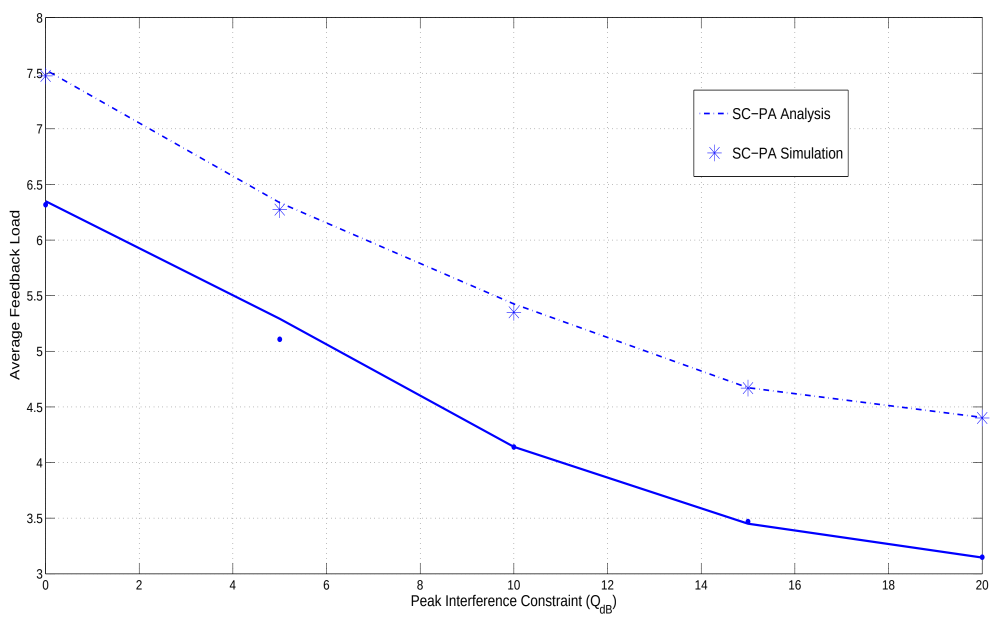

Fig. 15. Average feedback load versus PIC for K=3 users, $\overline{\gamma}_{req} = 5$ dB, $\mathrm{BER}_0 = 10^{-3}$, $P_{max} = 1$ dB, $\mathrm{R_o} = 10$m, $\mathrm{R_s} = 50$m, $\mathrm{D_{PS}} = 100$m, $\mathrm{d_o} = 10$m and α=2.1.

CHAPTER IX

SPECIAL CASE: I.I.D. RAYLEIGH FADING CHANNELS

In this chapter, the SC and SW schemes are analyzed under the assumption of i.i.d. Rayleigh fading channels. The i.i.d. case can be considered as a special case of the non-i.i.d. case, as will be shown in the subsequent analysis.

A. I.I.D. Rayleigh Fading Channels

Under the assumption of i.i.d. Rayleigh fading channels, users' secondary SNR have identical means and variances. The channel coefficients between the i^{th} user and the PR and the BS, h_{I_i} and h_{s_i}, are i.i.d Gaussian random variables with zero mean and variances σ_I^2 and σ_s^2, respectively. We note that in the i.i.d case, all channel coefficients have equal mean and variances. Thus, the channel coefficients $|h_{I_i}|^2$ and $|h_{s_i}|^2$ are exponentially distributed with means σ_I^2 and σ_s^2, respectively, and the interference and secondary SNRs of the i^{th} user are given by

$$\gamma_{I_i} = \frac{P_{t_i} |h_{I_i}|^2}{N_o} \tag{9.1}$$

and

$$\gamma_{s_i} = \frac{P_{t_i} |h_{s_i}|^2}{N_o}, \tag{9.2}$$

respectively. The average interference and secondary SNRs are calculated as follows:

$$\bar{\gamma}_{I_i} = E[\gamma_{I_i}] = \left[\frac{P_{t_i}\ |h_{I_i}|^2}{N_o}\right] = \frac{P_{t_i}\ E\left[|h_{I_i}|^2\right]}{N_o} = \frac{P_{t_i}\ \sigma_I^2}{N_o} \tag{9.3}$$

$$\bar{\gamma}_{s_i} = E[\gamma_{s_i}] = \left[\frac{P_{t_i}\ |h_{s_i}|^2}{N_o}\right] = \frac{P_{t_i}\ E\left[|h_{s_i}|^2\right]}{N_o} = \frac{P_{t_i}\ \sigma_s^2}{N_o}. \tag{9.4}$$

Another way of viewing the i.i.d case is by assuming that all users are located at the same position ($d_{I_1} = d_{I_2} = \cdots = d_{I_K} = d_I$ and $d_{s_1} = d_{s_2} = \cdots = d_{s_K} = d_s$), where the positions of the users are no longer random. Thus, the fading characteristics that each user experiences are identical, giving rise to the i.i.d. Rayleigh fading channels. Analyzing (4.6) and (4.7), it is found that

$$\bar{\gamma}_{I_i} = \frac{P_{t_i}\tau\left(\frac{d_o}{d_I}\right)^{\alpha}}{N_o} = \frac{P_{t_i}\sigma_I^2}{N_o} \tag{9.5}$$

and

$$\bar{\gamma}_{s_i} = \frac{P_{t_i}\tau\left(\frac{d_o}{d_s}\right)^{\alpha}}{N_o} = \frac{P_{t_i}\sigma_s^2}{N_o}, \tag{9.6}$$

where in the i.i.d setting, $\sigma_I^2 = \tau\left(\frac{d_o}{d_I}\right)^{\alpha}$ and $\sigma_s^2 = \tau\left(\frac{d_o}{d_s}\right)^{\alpha}$.

As mentioned previously, γ_{I_i} and γ_{s_i} are i.i.d. exponential random variables with means $\bar{\gamma}_{I_i}$ and $\bar{\gamma}_{s_i}$, respectively. The CDFs of the SNR are then given by:

$$F^{\star}_{\gamma_{I_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_I}\right), \quad x \geq 0 \tag{9.7}$$

and

$$F^{\star}_{\gamma_{s_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_s}\right), \quad x \geq 0, \tag{9.8}$$

where $\star$ is used to distinguish the i.i.d. case from the non-i.i.d. case.

B. ASE Analysis of the I.I.D. Scenario

Instead of defining a fixed minimum modulation threshold (SNR threshold), in this chapter we define γ_T (for fixed K and $\bar{\gamma}_s$) as the SNR threshold that maximizes the ASE. Specifically,

$$\gamma_T = \underset{\gamma_1 \leq \gamma \leq \gamma_N}{\arg\max}\,(\text{ASE}) \tag{9.9}$$

where ASE depends on the CDF scheduling scheme we are analyzing, namely SC, SW, SC-PA, or SW-PA. Because γ_T is no longer fixed and may lie in a modulation interval ($\gamma_n \leq \gamma_T \leq \gamma_{n+1}$), the ASE defined in (4.16) no longer holds. Therefore, looking back at the original definition of the ASE in (4.14), we derive the ASE when γ_T is placed in different fading regions as

$$\text{ASE} = \sum_{n=0}^{N} n P_n, \tag{9.10}$$

where

$$\begin{aligned} P_n &= \int_{\gamma_n}^{\gamma_{n+1}} f^{\star}_{\gamma_s}(x)dx = \int_{\gamma_n}^{\gamma_T} f^{\star}_{\gamma_s}(x)dx + \int_{\gamma_T}^{\gamma_{n+1}} f^{\star}_{\gamma_s}(x)dx \\ &= \left[F^{\star}_{\gamma_s}(\gamma_T) - F^{\star}_{\gamma_s}(\gamma_n)\right] + \left[F^{\star}_{\gamma_s}(\gamma_{n+1}) - F^{\star}_{\gamma_s}(\gamma_T)\right]. \end{aligned} \tag{9.11}$$

The integral above is divided into two parts because when $\gamma_n \leq \gamma_s < \gamma_T$, $R_n = 0$ bits/sec/Hz. Taking into account the different fading regions where γ_T can fall, the ASE is then expressed as

$$\text{ASE} = \begin{cases} R_q \left[F^{\star}_{\gamma_s}(\gamma_{q+1}) - F^{\star}_{\gamma_s}(\gamma_T)\right] + \sum_{n=q+1}^{N-1} R_n \left[F^{\star}_{\gamma_s}(\gamma_{n+1}) - F^{\star}_{\gamma_s}(\gamma_n)\right] & \\ \quad + R_N \left[1 - F^{\star}_{\gamma_s}(\gamma_N)\right] & \text{if } q \epsilon \{1, 2, \cdots, N-1\} \\ R_N \left[1 - F^{\star}_{\gamma_s}(\gamma_T)\right] & \text{if } q = N, \end{cases} \tag{9.12}$$

where the index q denotes the fading region in which γ_T is placed and $\star$ stands for the i.i.d. setting.

C. On/Off Power Adaptive Setting

In this section, we analyze the i.i.d. SC* and SW* schemes in the On/Off power adaptive setting. Because the users now present i.i.d. SNRs, their average secondary SNRs are all equal. Thus, the users are not required to adjust their initial transmit power. However, the users who do not satisfy the PIC or SNR threshold must set their power to zero, thus giving rise to the concept of the “On/Off” power adaptive scheme.

The probability that a single user fails to meet the PIC (i.e., $\gamma_{I_i} > Q$) is given by:

$$P^{\star}_{F_Q} = P(\gamma_{I_i} > Q) = 1 - P(\gamma_I \leq Q) = 1 - F^{\star}_{\gamma_I}(Q), \tag{9.13}$$

where $F_{\gamma_I}(\cdot)$ is given by (9.7). Similarly, the probability that a user fails to meet the SNR threshold (i.e., $\gamma_{s_i} < \gamma_T$) is

$$P^{\star}_{F_T} = P(\gamma_{s_i} < \gamma_T) = F^{\star}_{\gamma_s}(\gamma_T), \tag{9.14}$$

where $F_{\gamma_s}(\cdot)$ is given by (9.8). Analyzing the probability that a single user meets both the PIC and SNR threshold and the probability that a user is unable to meet either or both conditions, the probability of success and failure of the i^{th} user are given by

$$P^{\star}_{S_i} = F^{\star}_{\gamma\, I}(Q)[1 - F^{\star}_{\gamma\, s}(\gamma_T)] \tag{9.15}$$

and

$$P^{\star}_{F_i} = 1 - P^{\star}_{S_i}. \tag{9.16}$$

Assuming all K users are unable to satisfy either the PIC or SNR threshold, the probability of no transmission is expressed as

$$P^{\star}_{no} = \sum_{j=0}^{K} \binom{K}{j} (F^{\star}_{\gamma_p}(Q)^j \left[1 - F^{\star}_{\gamma_p}(Q))\right]^{K-j} (F^{\star}_{\gamma_s}(\gamma_T))^j = \prod_{i=1}^{K} P^{\star}_{F_i} = (P^{\star}_F)^K \quad . \tag{9.17}$$

1. Performance of the SC* Scheme

In the selection combining scheme, the BS starts the scheduling process by first selecting those users (out of the K total users that are connected to the BS) that meet the PIC. The BS then selects yet another subset of users from the feedback users that meet the SNR threshold. Of these users, the BS selects the user with the best channel quality (the user with the highest secondary SNR, γ_s). If no user is able to meet either condition, the BS selects the last user for simplicity but does not allow it to transmit ($P_t = 0$).

Consider now the problem of finding the CDF of the received secondary SNR at the BS (γ_s^*), which is similar to (6.10), but because the interference SNRs (γ_I) are i.i.d, the CDF's expression is greatly simplified. Thus the CDF for when $x \geq \gamma_T$ is given by

$$\begin{aligned} F_{\gamma_s^*}^{SC\star}(x) &= \sum_{j=0}^{K} \binom{K}{j} \left[F_{\gamma_I}^{\star}(Q)\right]^j \left[1 - F_{\gamma_I}^{\star}(Q)\right]^{K-j} \\ &\times \sum_{i=0}^{j} \binom{j}{i} \left[F_{\gamma_s}^{\star}(\gamma_T)\right]^{j-i} \left[F_{\gamma_s}^{\star}(x) - F_{\gamma_s}^{\star}(\gamma_T)\right]^{i}. \end{aligned} \tag{9.18}$$

The CDF of γ_s^* when $x < \gamma_T$ is equal to $P_{no}^{\star}$.

The average feedback load of the SC* is evaluated by first defining the possible feedback per-time-slot:

$$\begin{aligned} U_F^{\star} =& (K)P(\text{ K users meet PIC}) + (K-1)P(\text{K-1 users meet PIC \& 1 user fails PIC}) \\ &+ \cdots + (1)P(\text{one user meets PIC \& K-1 users fail PIC}) \\ &= \sum_{j=1}^{K} j \left[F_{\gamma_I}^{\star}(Q)\right]^j \left[1 - F_{\gamma_I}^{\star}(Q)\right]^{K-j}. \end{aligned} \tag{9.19}$$

Thus, the $AFL_{SC^\star}$ is given by:

$$AFL_{SC\star} = \sum_{j=0}^{+\infty} \binom{K}{j} U_F^{\star} \left(P_{no}^{\star}\right)^j. \tag{9.20}$$

The average delay is found in a similar manner to the non-i.i.d. case, namely,

$$\bar{D}^{SC\star} = \sum_{m=0}^{+\infty} m\ P(D = m) = \sum_{m=0}^{+\infty} m\ (P_{no}^{\star})^m (1 - P_{no}^{\star}) = \frac{P_{no}^{\star}}{1 - P_{no}^{\star}}, \tag{9.21}$$

where D denotes the number of coherence times the system must wait before a successful transmission occurs.

2. Performance of the SW* Scheme

In the scan-and-wait scheme, the BS initiates a sequential search of the users in an attempt to find an acceptable user that meets the PIC and SNR threshold. If the user that the BS is probing satisfies both constraints, it is given channel access in the subsequent transmission time interval. However, if that user fails either constraint, the BS switches to the next user. If all K users are unable to meet the PIC and the SNR threshold, the BS selects the last user, but does not allow it to transmit. Thus, the BS essentially delays the transmission for that time-slot and begins the probing process during the guard period of the subsequent time-slot.

The CDF of the received SNR at the BS of the SW* scheme when $x \geq \gamma_T$ is given by

$$\begin{aligned} F_{\gamma_s^*}^{SW\star}(x) &= P(\gamma_s^* \leq x) = \sum_{i=1}^{K} P\left(\gamma_{s_i} \leq x \mid \gamma_s^* = \gamma_{s_i}\right) P\left(\gamma_s^* = \gamma_{s_i}\right) \\ &= P\left(\gamma_{s_i} \leq x \mid \gamma_s^* = \gamma_{s_i}\right) \\ &= P_{no}^\star + S^\star \sum_{i-1}^{K-1} (P_F^\star)^j \\ &= P_{no}^\star + S^\star \frac{1-P_{no}^\star}{1-P_F^\star}, \end{aligned} \tag{9.22}$$

where $S^\star = F_{\gamma_I}^\star(Q)\left[F_{\gamma_s}^\star(x) - F_{\gamma_s}^\star(\gamma_T)\right]$ and denotes the probability that a user is selected. The CDF for $x < \gamma_T$ is equivalent to $P_{no}^\star$.

Defining $F^\star$ as the number of users that must be probed until the first success, we notice that $F^\star$ has a geometric distribution with success probability given by $\theta^\star = P_S^\star$. Thus, the AFL of the SW* scheme is given by

$$AFL_{\mathrm{SW}\star} = \frac{1}{\theta^\star} = \frac{1}{P_S^\star} = \frac{1}{F_{\gamma_I}^\star(Q)[1 - F_{\gamma_s}^\star(\gamma_T)]}. \tag{9.23}$$

The average delay of this scheme is given by

$$\bar{D}^{SW\star} = \frac{P_{no}^{\star}}{1 - P_{no}^{\star}}. \tag{9.24}$$

D. Full Power Adaptive Setting

In this section, users adapt their transmit power according to $|h_{p_i}|^2$ to satisfy the PIC at the primary receiver. That is, a secondary user allocates it peak power (P_{max}) for transmission if the interference constraint is satisfied with the peak power. Otherwise, it adaptively adjusts its transmit power to the allowable level so that the interference observed at the PR is below the maximum interference level Q. Correspondingly, the transmit power of the i-th secondary user is given by

$$P_{t_i} = min\left(P_{max}, \frac{QN_o}{|h_{I_i}|^2}\right). \tag{9.25}$$

Because all the users operate with i.i.d. SNRs, once the users adapt their transmit power according to (9.25), they automatically satisfy the PIC. Thus, the scheduling process simplifies to only checking that a user's received SNR at the BS exceeds the SNR threshold. With power adaption, a user's secondary SNR takes the expression

$$\gamma_{s_i}^{PA\star} = \frac{P_{t_i}|h_{s_i}|^2}{N_o} = \frac{min\left(P_{max}, \frac{QN_o}{|h_{I_i}|^2}\right)\ |h_{s_i}|^2}{N_o}. \tag{9.26}$$

The CDF of $\gamma_{s_i}^{PA\star}$ is then shown to be equivalent to

$$F_{\gamma_{s_i}^{PA\star}}(x) = P\left(\gamma_{s_i}^{PA\star} \leq x\right) = 1 - \left(1 - \frac{1}{1 + \frac{\sigma_s^2}{\sigma_I^2}\frac{Q}{x}} e^{-\frac{QN_o}{\sigma_I^2 P_{max}}}\right) e^{-\frac{xN_o}{\sigma_s^2 P_{max}}}. \tag{9.27}$$

Analyzing the probability that no user is able to meet the SNR threshold, the probability of no transmission of both SC* and SW* schemes is expressed as

$$P_{no}^{PA\star} = \prod_{i=1}^{K} P(\gamma_{s_i}^{PA\star} < \gamma_T) = \left[F_{\gamma_s^{PA\star}}(\gamma_T)\right]^K. \tag{9.28}$$

1. Performance of the SC*-PA Scheme

Analyzing the mode of operation of the selection combing scheme after the full power adaption, the BS probes all K users and selects the user with the highest secondary SNR among the subset of users that meet the SNR threshold. We note that the interference SNR is not considered because the transmit power that the users have chosen guarantees that they meet the PIC. Thus, the CDF in (9.18) is simplified such that the interference channel is no longer a factor. Accordingly, the CDF of the received SNR at the BS of the SC*-PA for when $x \leq \gamma_T$ is expressed as

$$F_{\gamma_s^*}^{SC\star-PA}(x) = \sum_{i=0}^{K} \binom{K}{i} \left[F_{\gamma_s}^{PA\star}(\gamma_T)\right]^{K-i} \left[F_{\gamma_s}^{PA\star}(x) - F_{\gamma_s}^{PA\star}(\gamma_T)\right]^i. \tag{9.29}$$

For the case when $x < \gamma_T$ the CDF is equivalent to $P_{no}^{PA\star}$.

Since in this setting, all the users meet the PIC, the feedback load *per-time-slot* is deterministic and equal to K. The average feedback load, defined as the number of users probed until a successful user is found, is given by

$$AFL_{\text{SC}^\star\text{-PA}} = K(1-P_{no}^{\star}) \sum_{j=0}^{+\infty} j\,(P_{no}^{\star})^{j-1} = \frac{K}{1-P_{no}^{PA\star}}. \tag{9.30}$$

Defining $D^\star$ as the number of times the system must delay transmission before success user is found, the average delay of the SC*-PA is then found to be

$$\overline{D^\star} = \sum_{n=0}^{+\infty} nP(D^\star = n) = \sum_{n=0}^{+\infty} n\left(1-P_{no}^{PA\star}\right)\left(P_{no}^{PA\star}\right)^n = \frac{P_{no}^{PA\star}}{1-P_{no}^{PA\star}}. \tag{9.31}$$

2. Performance of the SW*-PA Scheme

In the full power adaptive SW* scheme, the BS starts a sequential search of the user in an attempt to find a user who meets the SNR threshold. The BS gives channel access to the first user it finds that satisfies the SNR threshold. Once again, the interference channel is not considered since all users meet the PIC in the full power adaptive setting.

The CDF of the received SNR at the BS is similar to (9.22); however, the probability that a user is selected by the BS is $S^{PA\star} = \left[F_{\gamma_s}^{PA\star}(x) - F_{\gamma_s}^{PA\star}(\gamma_T)\right]$. Thus the CDF when $x \geq \gamma_T$ is expressed as

$$F_{\gamma_s^*}^{SW\star-PA}(x) = P_{no}^{PA\star} + S^{PA\star}\frac{1-P_{no}^{PA\star}}{1-F_{\gamma_s^{PA\star}}(\gamma_T)}. \tag{9.32}$$

The CDF for $x < \gamma_T$ is equal to $P_{no}^{PA\star}$.

The average feedback load of this scheme is similar to(9.33) with the exception that the success probability now becomes $\theta^{PA\star} = 1 - F_{\gamma_s^{PA\star}}(\gamma_T)$. Thus the AFL is given by

$$AFL_{\mathrm{SW}\star-\mathrm{PA}} = \frac{1}{\theta^{PA\star}} = \frac{1}{1-F_{\gamma_s^{PA\star}}(\gamma_T)}. \tag{9.33}$$

The average delay is given by

$$\bar{D}^{SW\star-PA} = \frac{P_{no}^{PA\star}}{1-P_{no}^{PA\star}} \tag{9.34}$$

E. Numerical Analysis of I.I.D. Case

In this section, the performances of the proposed schemes operating under i.i.d. Rayleigh fading channels are illustrated by several numerical results. These numerical examples are obtained by Monte-Carlo simulations and are confirmed by analytical results. The values $\overline{\gamma}_s = 10$dB, $\overline{\gamma}_I = 0$dB, $P_{max} = 1$dB, and $\mathrm{BER}_0 = 10^{-3}$ are fixed for all examples.

The optimal SNR threshold that maximizes the ASE for different number of users connected to the BS is shown in Fig. 16 for the SW* and SW*-PA schemes. As shown, the SNR threshold for all the schemes changes as the number of users connected to the BS (K) changes. Generally, as the number of users increase, the SNR threshold tends to increase. This is understandable since the SNR threshold is a function of ASE, which is a function of many variables, including K and Q. Fig. 16 also illustrates how the SNR threshold is affected by the PIC. It is shown that the SNR thresholds for $Q = 0$dB are less than the SNR thresholds when $Q = 10$dB.

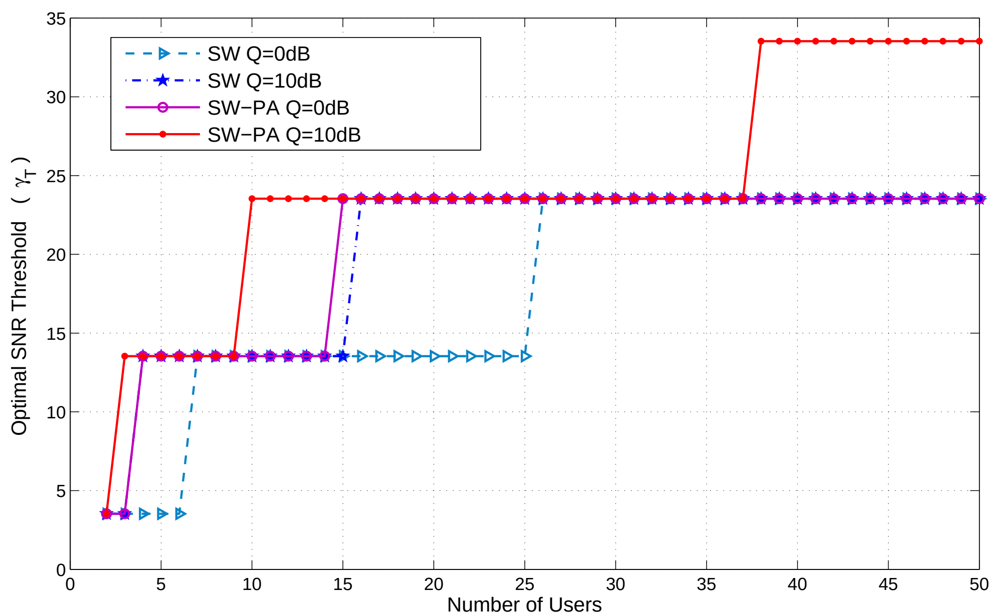

Fig. 16. Optimal SNR threshold for the SW* and SW*-PA Schemes for BER$_0 = 10^{-3}$, $\overline{\gamma}_s = 10$dB, $\overline{\gamma}_I = 0$dB, and $P_{max} = 1$dB.

The ASE versus the number of users connected to the BS for all of the schemes are illustrated in Fig. 17. It is noticeable that the SC-PA scheme yields the highest ASE and that the full power adaptive cases significantly increase the ASE versus the On/Off power adaptive cases for both the SC and SW schemes. Comparing the SC scheme to the SW scheme, the ASE for the SC is higher than that of the SW scheme, and similarly for SC-PA and SW-PA.

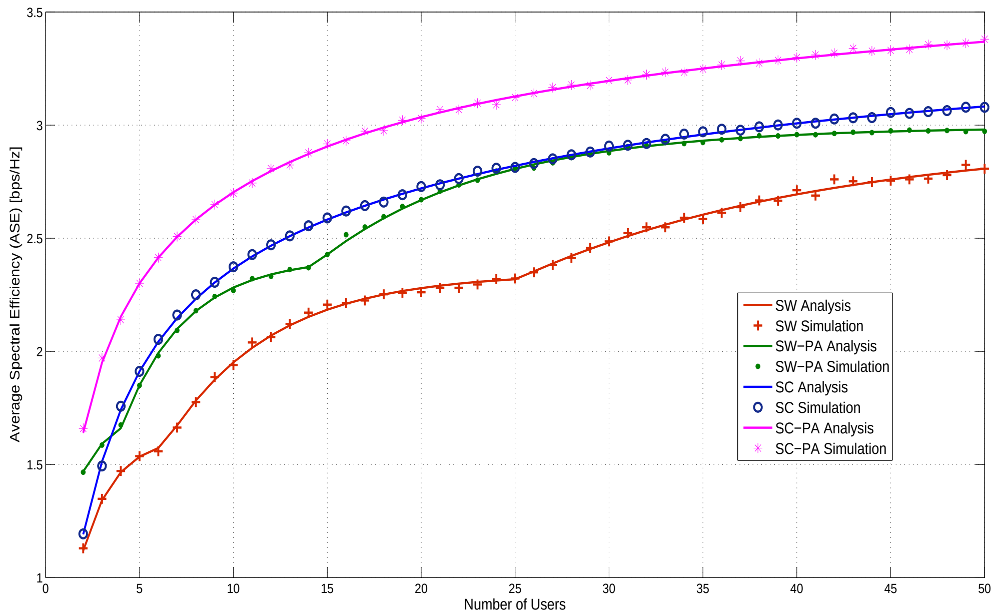

Fig. 17. Average spectral efficiency of all schemes for $\text{BER}_0 = 10^{-3}$, $Q = 0$dB, $\overline{\gamma}_s = 10$dB, $\overline{\gamma}_I = 0$dB, and $P_{max} = 1$dB

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Although the SC schemes yield higher ASE, they come with the disadvantage of a higher feedback load, as depicted in Fig. 18. The SC*-PA schemes yields the highest feedback due to the fact that all users adapt their power to meet the PIC. Thus, the BS must probe all K user each time slot in an attempt to find the best user. The SC* yields the second highest feedback compared to the all the schemes. As for the SW* and SW*-PA schemes, the average feedback loads looks a bit different. The jumps that are seen are due to the changing SNR threshold. Comparing the jumps that occur in the AFL of the SW schemes, they coincide to the jumps shown in Fig. 16 for $Q = 0$dB.That is, when the SNR threshold increases, the BS must probe more users in order to find an acceptable user that meets the higher SNR threshold, thus it increases the feedback load associated with the SW* and SW*-PA schemes.

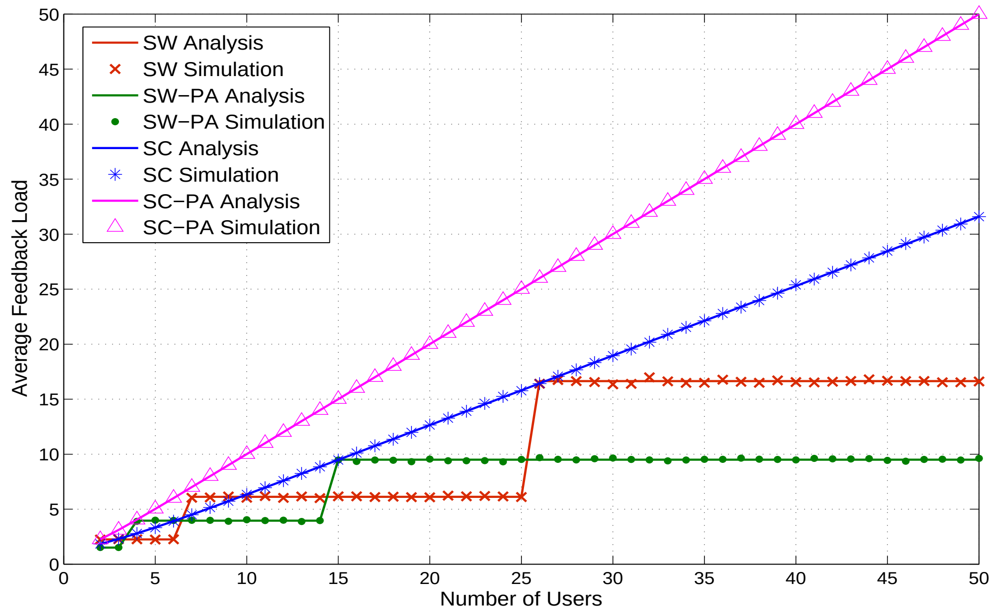

Fig. 18. Average feedback load of all schemes for $\text{BER}_0 = 10^{-3}$, $Q = 0\text{dB}$, $\overline{\gamma}_s = 10\text{dB}$, $\overline{\gamma}_I = 0\text{dB}$, and $P_{max} = 1\text{dB}$.

In Fig. 19, the average number of no transmissions observed by the BS (average number of delay) is depicted for all the proposed schemes. Since each scheme operates with a different optimal switching threshold, the delay for each scheme is different. For the SW scheme, there are many spikes in the graph. The non-smooth characteristic of the delay is due to the changing value of the optimal switching threshold and the increasing number of users connected to the BS. As the switching threshold increases, it becomes intuitive that the delay will increase since it becomes more probable that users will not be able to satisfy the switching constraint. On the other hand, as the number of users increases, it becomes more likely that an acceptable user is found that meets the constraint. These two opposing forces lead the delay graphs to exhibit such behavior. However, in general, the full power adaptive schemes produce less average delay when compared to the On/Off power adaptive schemes.

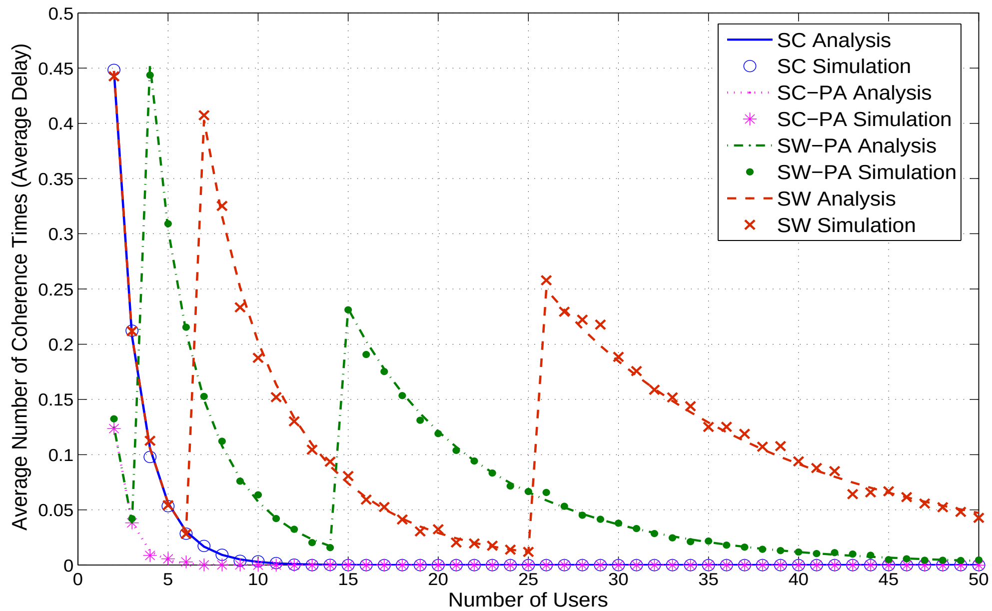

Fig. 19. Average delay of all schemes for $\text{BER}_0 = 10^{-3}$, $Q = 0\text{dB}$, $\overline{\gamma}_s = 10\text{dB}$, $\overline{\gamma}_I = 0\text{dB}$, and $P_{max} = 1\text{dB}$.

Fig. 20 shows how the average feedback load of each scheme changes as the PIC increases for a total of 10 users connected to the BS. As the PIC constraint increases, more users are able to satisfy the interference constraint and thus for the scan-and-wait schemes, the feedback decreases since it becomes more probable that an acceptable user is found. However, this is the opposite for the selection combining schemes since the number of users that the BS must probe increases as more users meet the PIC.

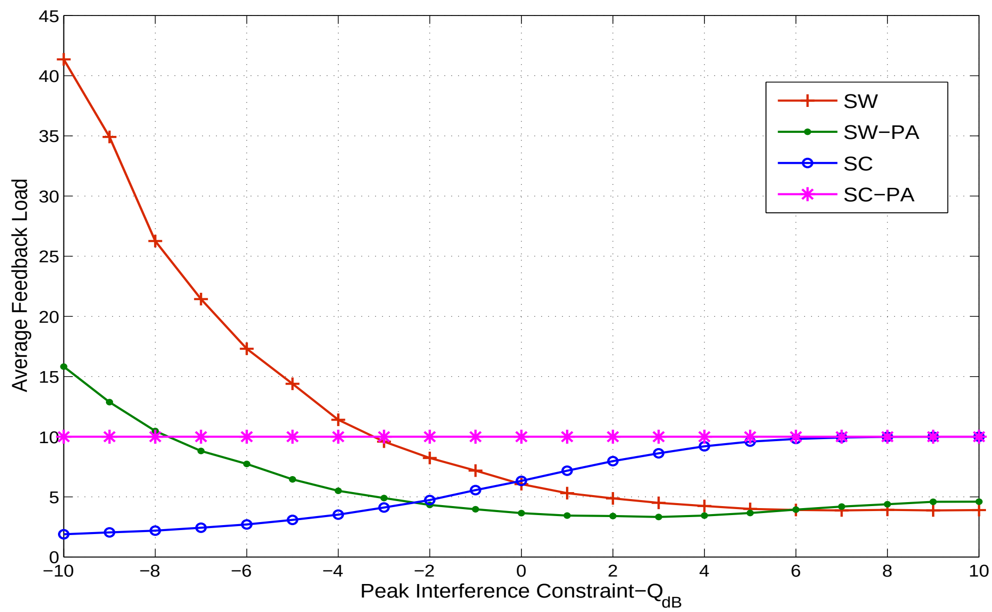

Fig. 20. Average feedback load vs PIC for $\text{BER}_0 = 10^{-3}$, $K = 10$, $\overline{\gamma}_s = 10$dB, $\overline{\gamma}_I = 0$dB, and $P_{max} = 1$dB.

CHAPTER X

CONCLUSION AND FUTURE WORK

A. Concluding Remarks

Cognitive radio devices exhibit the ability to potentially facilitate the increased demand of the already crowded radio spectrum. In spectrum sharing systems, secondary users are able to simultaneously share the primary user's spectrum as long as they do not exceed an interference threshold with the primary. Multiuser secondary systems operating in spectrum sharing networks face the challenge of fairly scheduling the secondary users while avoiding interference with primary users. Two scheduling schemes have been proposed whereby users must meet the interference threshold with the primary as well as the minimum modulation threshold in order to be considered for scheduling. In the selection combining scheme, the best user observing the best channel quality that meets both constraints is given channel access. This scheme is associated with a high feedback load. In an attempt to decrease the feedback load and simplify the scheduling procedure, the scan-and-wait scheme is analyzed whereby a sequential search of the users is executed in an effort to find the first user that satisfies both constraints. This scheme was found to significantly decrease the feedback load; however, it performed slightly lower in terms of spectral efficiency when compared to the selection combing scheme.

Initially, all users are assumed to be randomly distributed within the coverage regions. Thus they experience non-identical fading characteristics. To increase fairness, users adjust their transmit power such that they meet a required average SNR. This power setting was referred to as the On/Off power adaption. In the full power adaption setting, users must adjust their power such that they stay below the interference threshold while transmitting with the required average SNR. A special case was investigated in which all users operate under i.i.d. Rayleigh fading channels. In both cases, it was shown that the schemes operating the full power adaptive setting performed better in terms of spectral efficiency and average system delay compared to the On/Off power setting. However, the selection combining setting was characterized with a higher feedback load for both power settings when compared to the scan-and-wait scheduling scheme.

B. Future Work

There are numerous directions for future research work and extensions to the work carried out in this thesis. First, the interference from the primary to the secondary communication channel is of interest and will be studied in the future. Furthermore, in this study, each user was equipped with a single antenna. However, the concept of transmit diversity (antenna diversity) has proven to be promising in terms of creating diversity and improving system attributes such as decreasing delay and improving spectral efficiency. Thus, it is also of great interest to study how the systems discussed in this thesis perform under the assumption that the secondary users are equipped with several transmit antennas.

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