Power Control for Underlay Cognitive Radio Networks with Full-duplex Transmissions

by

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Abstract

Radio communication, one of core contents in wireless communication, is facing a great crisis of running out of resource. Unlike other energy crisis which can be solved by using all kinds of alternative energy, the only resource of radio communication is channel, in another word, spectrum. Rather than sticking on trying to achieve the rest one percent of capacity, more and more scholars start to realize that methods reuse the existing available channel such as cognitive radio and full-duplex transmission lead a much brighter future.

Both cognitive radio (CR) and full duplex transmissions are effective means to enhance spectrum efficiency and network capacity. In this paper, we investigate the problem of power control in an underlay CR network where the CR nodes are capable of full-duplex (FD) transmissions. The objective is to guarantee the required quality of service (QoS) in the form of a minimum signal-to-interference-plus-noise (SINR) ratio at each CR user and keep the interference to primary users below a prescribed threshold. We design an effective distributed power control scheme that integrates a proportional-integral-derivative (PID) controller and a power constraint mechanism to achieve the above goals. We analyze the stability performance of the proposed scheme and develop a hybrid scheme that can switch between FD and half duplex modes. The proposed schemes are validated with extensive simulations.

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Chapter 1

Introduction

1.1 Cognitive Radio

In recent years, an unprecedented increase in wireless data has been observed, largely due to the proliferation of smartphones, tablets and other wireless devices. The exploding wireless data calls for effective technologies for enhancing spectrum utilization and wireless network capacity. To this end, cognitive radios (CR) have been recognized as one of the key technologies to meet this grand challenge on wireless network capacity. As an effective means of sharing spectrum among licensed (i.e., primary) users (PU) and unlicensed (i.e., secondary) users (SU), CR has been demonstrated to achieve high utilization of the scarce spectrum resource [23, 24].

Due to the rapidly running out of spectrum over available frequency in communication, CR has become a promising solution to reuse frequency resource. CR was motivated by recent spectrum measurements by the Federal Communication Commission (FCC), where temporal and geographical variations in the utilization of assigned spectrum are found to range from 15% to 85%, and a significant amount of the spectrum remains unutilized. A CR is an advanced radio device that enables dynamic spectrum access (DSA). It represents a paradigm change in spectrum regulation and access, from exclusive use by primary users to shared spectrum and dynamic access for secondary users, to enhance spectrum utilization and achieve high throughput capacity. CR has profound impact on how future wireless networks will be designed and operated and has become one of the suggested key concept of $5G$ criterion.

Figure 1.1: SDR product [2]

1.1.1 Software-defined Radio

Before saying something about CR, we need to acquire the concept about one of its key predecessor technology software-defined radio (SDR) first.

With the development of wireless communication and microelectronics technology, SDR has been officially introduced to the public in 1991. With its presence, it is defined as "A radio platform of which the functionality is at least partially controlled or implemented in software" [22]. According to the definition, if certain kind of waveform has been saved in the memory of SDR product, it should be able to be employed on any frequency.

Thanks to the industriousness of manufactures, the hardware needed for SDR has becoming quite affordable for commercial use. This also induced more attention about this technology and caused a virtuous cycle. Nowadays, SDR product like what is shown in Fig. 1.1 is quite common to see and benefits a lot of ensuing works.

1.1.2 The Birth and Definition of Cognitive Radio

Joseph Mitola III [1], who is now a professor at Stevens Institute of Technology, is well known as the father of CR technology. In 2000 he finished his doctoral defense with dissertation “Cognitive radio—An integrated agent architecture for software defined radio” and defined CR for the first time.

At first, CR is seen as a “intersection of personal wireless technology and computational intelligence” and should be defined as “A really smart radio that would be self-aware, RF-aware, user-aware, and that would include language technology and machine vision along with a lot of high-fidelity knowledge of the radio environment”. However, just like Hamlet in eys of different people, this definition is too large for a single technology and has caused various understandings. In “Cognitive radio: Brain-empowered wireless communication” [11], Simon Haykin redefined CR as “an intelligent wireless communication system that is aware of its surrounding environment, and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters in real-time, with two primary objectives in mind: highly reliable communications whenever and wherever needed; efficient utilization of the radio spectrum.” To simplify the conclusion, he used six words to represent the characteristcs of CR: “awareness, intelligence, learning, adaptivity, reliability, and efficiency”.

Due to the blossom of CR research, U.S. FCC has proposed their official and strict definition of CR which is “A Cognitive Radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The majority of cognitive radios will probably be SDR but neither having software nor being field programmable are requirements of a cognitive radio”. From then on, this definition becomes a recognized meaning for CR.

1.1.3 Interoperability and Dynamic Spectrum Access

For its all kinds of capabilities, CR has enabled a list of applications. However, the most well-known and widely used two implementations are Interoperability and DSA.

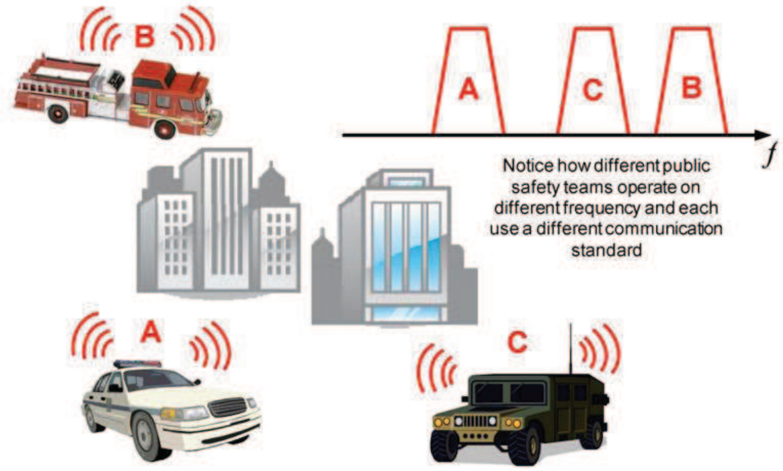

Figure 1.2: Safety teams with different standard or operating frequency [22]

Interoperability

How to understand interoperability? Let us start from a existing tragedy first: In August 2005, The Hurricane Katrina struck New Orlean, caused mass casualty and property loss. After the disaster, a lot of people has blamed government for reacting too slow. Not everyone knows that, but one important reason for the problem is the lacking of interoperability. The communication equipment used by local rescue teams (For instance, police and hospital) has different specifications so that they cannot cooperate with each other efficiently, like Fig. 1.2.

Imagine, if they can communicate with each team smoothly, how many lives can be saved? Although set their equipments all in a united frequency at the beginning is not possible due to feasibility and security problems, we could still solve the problem by benefiting from interoperability of CR. As we have discussed in the former parts, CR has the ability of adaptivity and is fully capable of dealing this. CR may reconfigure all the existing standards in a single form, thus to allow them communicating with everyone.

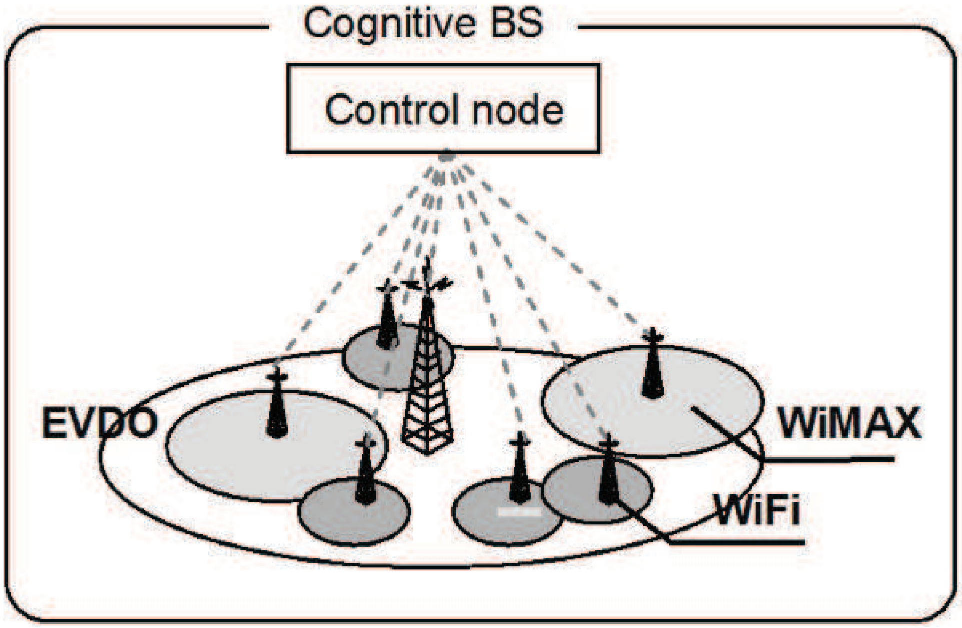

Figure 1.3: Platform for inter-radio system switching with CR [10]

Interoperability even have other practical use in commercial usage. Fig. 1.3 shows the design of inter-radio system with cognitive radio system. In the figure, a cognitive radio basestation has the ability to "translate" all kinds of wireless standards so users will be able to connect with each other even they used to be in a different network. Still fearing about phones cannot be used in a foreign country? That is an old story.

Dynamic Spectrum Access

Spectrum is now considered as a valuable resource in wireless communication, and resource is always accompanied with allocation problem. International Telecommunication Union (ITU) has provided a general plan for global spectral use and FCC is in charge of regulating spectrum use in the U.S.. As shown in Fig. 1.4, spectrum is allocated mostly for licensed users. Licensed user pays considerable money for occupying certain band in order to guarantee their QoS.

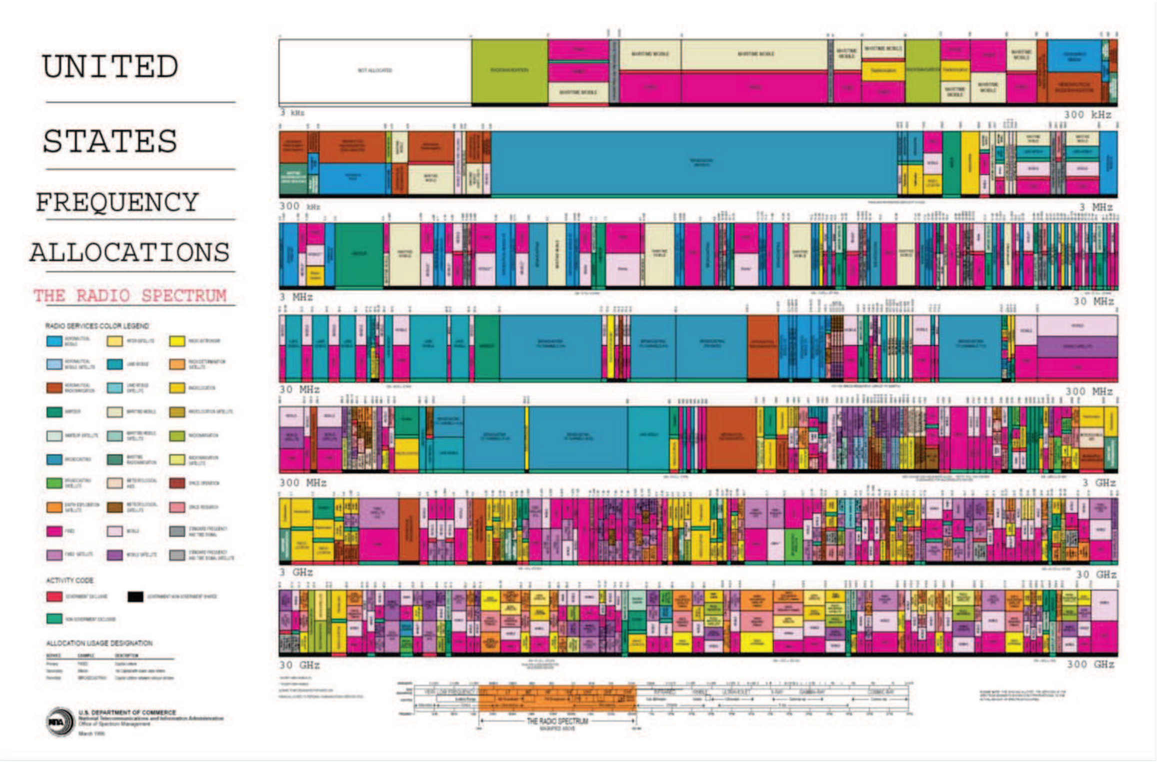

Figure 1.4: Frequency allocation charts for the United States [18]

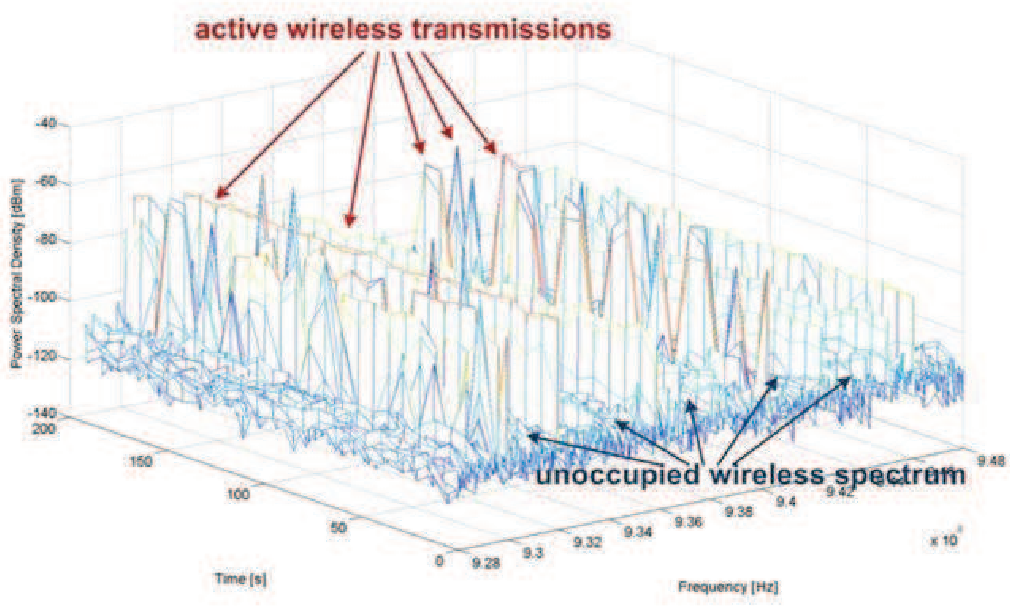

Figure 1.5: Spectrum measurement across the 928 to 948 MHz band on June 19, 2008 (Worcester, MA, USA) [22]

As we all know, spectrum is limited, with most of the spectrum occupied by licensed user, the usage of radio communication seems to be “dead” too. However, the efficiency of the current allocation mechanism has been challenged by more and more surveys. As a matter of fact, these surveys indicate considerable waste in the usage of licensed spectrum, like Fig. 1.5. Frequency around $800Hz$ is usually seen as one the best range since it is both good for wall-piercing and transmission. Knowing the value of such spectrum forces people rethink about current allocation.

Upholding the idea of saving and basing on the possible technology, FCC prompts the concept of DSA. DSA encourage unlicensed user to “borrow” spectrum from licensed users. Quite obvious, the CR platform is facing two problems here: The needing of being environmentally aware and the needing of rapidly reconfigurable. With the progress of CR technology, the idea of DSA which needs unlicensed user accessing to licensed spectrum while protecting primary user (PU) is completely realizable. For a secondary user (SU), usually there are two approaches to accomplish such task: Overlay and underlay.

In overlay approach, CR will try to find out some random, small idle bands rather than a single wode spectrum. This shows the "aggregate" ability of overlay CR. Figuratively, overlay CR is working like pouring sand into the crevice of stones. Stones are like SUs who has filled in the space, and sand like overlay SUs can fully utilize the rest resource. The main idea of overlay CR technology is to reuse all the unused spectrum, since there is no PU using it, it should never collide with PU. In another word, it is temporarily playing the role of a PU. One representative application for overlay is opportunistic spectrum access (OSA), which usually goes hand in hand with multicarrier modulations schemes and spectrum sensing technology. Overlay may sometimes offense the right of PUs due to false spectrum sensing. Although overlay is solving the problem, it sometimes has to face the pain of lacking stability.

To the opposite, underlay uses another way of thinking. While overlay is surely a great idea and is making good use of wasted spectrum, underlay is even astonishing and shows the ability of utilizing spectrum which is still in use. Rather than the sand in the crevice, underlay technology is more like the cream on a cup of Mocha. Coffee and cream stays in different layer, they never collide with each other and can stay together in peace. To achieve such characteristics, underlay technology has to apply power control technology and remain in a low interference. Underlay technology is capable of using any band due to its characteristic, however it also has problems like being unable to transmit in long distance due to low transmission power and its high frequency carrier wave.

In CR networks, the most important design factor is to balance the tension between PU protection and SU spectrum access gains [23]. On one hand, the capacity of SUs should be maximized to "squeeze" the most out of the spectrum. On the other hand, the adverse impact to PUs, resulting from sharing spectrum with SUs, should be kept below a tolerable level. Obviously, these are two conflicting goals that should be balanced in the design of CR networks. In the so-called overlay CR networks, PU protection is achieved by spectrum

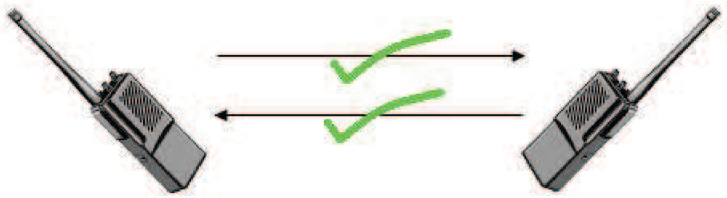

Figure 1.6: Full-duplex wireless transmission

sensing and spectrum access only when the PUs are sensed absent [23]. In the so-called underlay CR networks, both PU and SU transmissions coexist in the same spectrum band, and PU protection is achieved by carefully controlling the power of the SU transmitters [17].

1.2 Full-duplex Transmission

Recently, a breakthrough in wireless communications is FD transmission [5–7, 14]. Traditionally, wireless communications are all half duplex (HD) due to the large path loss typical in wireless transmissions. If FD transmission is allowed, the self-interference will be so strong (like the sun) and the weak received signal from a remote transmitter (like stars) will be completely overwhelmed and cannot be decoded. Recently, encouraging results have been reported on enabling FD wireless transmissions in both single link and a network setting [5–7, 14]. The enabler of HD is the recent advances in self-interference suppression (SIS). Various effective SIS techniques have been proposed and tested, such as antenna separation [7], antenna cancellation [6], signal inversion and adaptive cancellation [14], and combined optimal antenna placement and analog cancellation [20]. In [20], the author showed a practical implementation that can suppress self-interference (SI) for up to 80 dB, which should be sufficient for many application environments [3].

1.2.1 Definition of Full-duplex Wireless Transmission

FD wireless transmission is defined as a wireless transmission which is communicating in both directions simultaneously, as shown in Fig. 1.6.

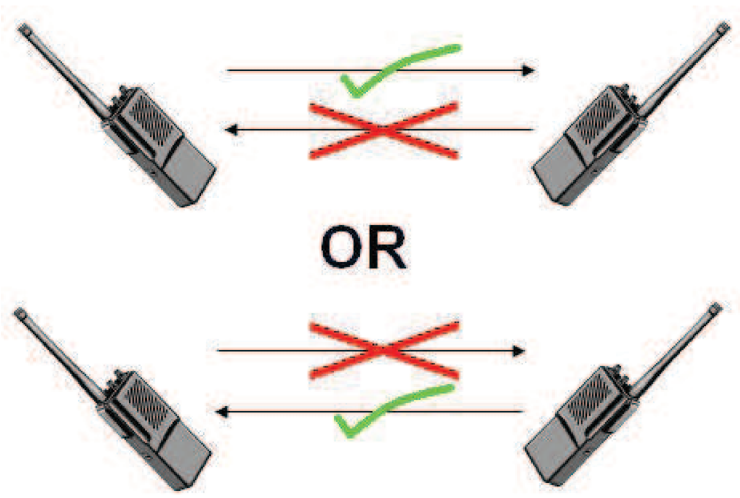

Figure 1.7: Half-duplex wireless transmission

FD is quite common in wired communication equipments, such as Ethernet. The technology is quite simple too: It simply enables connections work by making simultaneous use of two physical pairs of twisted cable, one pair for receiving packets the other is used for sending packets. However, when things come to single channel wireless network, everything has changed.

1.2.2 Problem and Ideas

Until today, most wireless equipments still remains in the half-duplex (HD) age like Fig. 1.7 Unlike the wired communication, wireless has some innate problem in implementing FD on a single channel: The direction of signal cannot be guided. For a wireless equipment, the self-issued signal is always omnidirectional and will also be received by the receiver of its own, with little path loss due to extremely near distance. Meanwhile, the desired signal coming from the other equipment is nearly negligible comparing to the signal transmitted by itself. As we may all know, a signal with too low SINR could not be decoded. And that is the problem of FD on a single channel: SI adds a destructive impact on its own receiving antenna.

After locking on the problem, some idea to solve the problem has already emerged, and they are all classified into SIS technology.

Radio Frequency Cancellation

Radio Frequency (RF) cancellation is a chip based SIS method [19]. Since we must know transmitted signal and received signals. So we could use them as inputs and take the difference of the received signal with the SI (the transmitted signal) as the output. By changing the amplitude and phase of the interference reference signal we can try to match the interference in the received signal. An RF splitter is also used to give the transmit signal to the cancellation circuit as the interference reference.

Digital Cancellation

Digital cancellation is another key technology for SIS. As for now, there are two well-known way for digital cancellation. First one is decode and cancellation. The transmitted packets are all marked with special symbol first. After receiving the original signal, the receiver decodes it, pick out all interference packets and then the packets are clean. The other digital cancellation is called coherent detection, which use a detector to correlates the incoming signal with the transmitted signal. Since the detector have full knowledge about the transmitted signal, it is capable to estimate the delay and phase shift of the received signal, so it can use the transmit signal to correlate with the interference. The second method need no modulation of the signal and is backwards compatible so this technique is somehow seen as a better one.

Antenna Cancellation

Antenna cancellation is maybe the most important technique of the three because it really has shown a significant ability in SIS. The idea of this method is using pairs of transmitters to destroy their effect on the receiver. As we all know, radio is a kind of electromagnetic

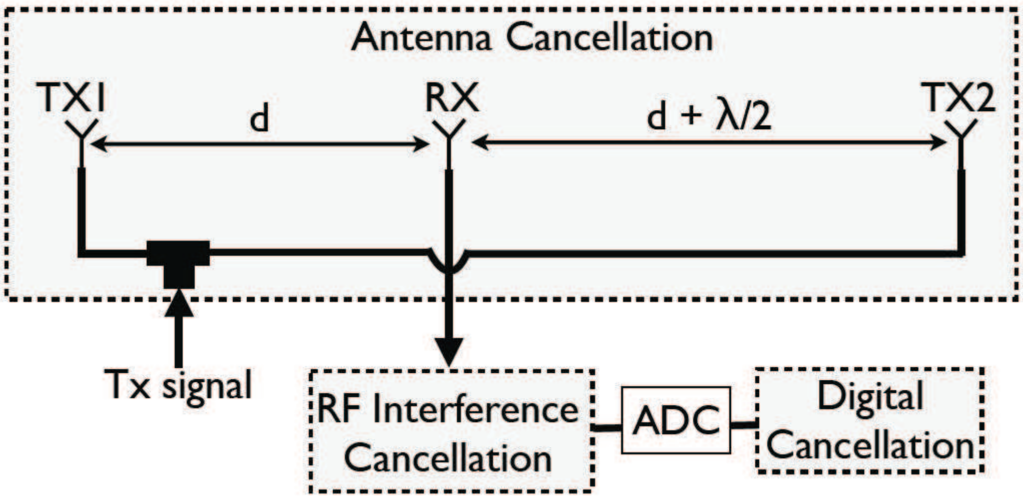

Figure 1.8: SIS design proposed in Mayank Jain et. al

wave and it has crest and trough, so by properly placed we can add crest with trough on the receiver's location so they will cancel each other. Although efficient, antenna cancellation is usually deployed together with other two method to ensure a better result, like the design in 1.8.

1.3 Motivation for Our Work

The high potential of FD has attracted substantial interest. However, the mainstream FD research nowadays has only focused on feasible physical layer techniques or the performance analysis for certain utilization. Although some advances have been made, the important problem of guaranteeing overall system performance is yet to be studied. Since the compelling objective of FD transmission for fully utilizing the limited resource of wireless networks meets the core purpose of CR technique, we propose to combine FD with CR. Thus, certain problems such as "If FD transmission could also improve the performance in CR networks under certain circumstances?" remains to be answered . Unlike HD transmission which mostly cares about distance as the fading parameter, FD transmission has to take more consideration of a set of much more complex data such as SI suppression factor and SINR ratio. Their relationship and impact are highly important for our research, and could lead a revolution to the new communication criterion.

1.4 Background and Related Work

FD transmission is a new technology to push the limit of single channel communications. In [6], the authors proposed basic concepts such as RF and digital cancellations and discusses potential MAC and network gains with full-duplexing. In [20], the authors presented the design and implementation of a real-time 64-subcarrier 10 MHz full-duplex OFDM physical layer, and demonstrated up to 80 dB SI suppression with experiments. In [14], the authors presented a full duplex radio design using signal inversion and adaptive cancellation, as well as a full duplex MAC design and evaluation results with a testbed of 5 prototype FD nodes. In [5], a MIMO FD design was presented, while FD cellular networks have been investigated in some recent papers [8, 21].

CR has been recognized as an important technology for enhancing spectrum access efficiency [23, 24]. In the class of overlay CR networks, SUs sense the spectrum and access the spectrum when PUs are absent. In the class of underlay CR networks, SUs coexist with PUs in the same spectrum conditioned on limited interference to the PUs. Both techniques can be transparent to PUs [23]. In a recent work [3], the authors proposed to combine FD with CRs. The FD capability can be utilized to allow current two-way transmissions for the SUs, as well as enabling SUs to transmit while sensing.

Feedback control has found wide application in communication and networking systems. A modern overview of functionalities and tuning methods for PID controllers was presented in [4]. In [12], a proportional (P) controller was developed for streaming videos to stabilize the received video quality as well as the bottleneck link queue, for both homogeneous and heterogeneous video systems. A modern overview of functionalities and tuning methods for PID controllers was presented in [4]. In [9], the author presented a PID based power adjustment algorithm that was later extended in [17], which developed a PID control for power control in underlay CR networks.

In this paper, we investigate several control model based on single channel full duplex cognitive radio, which is different from previous work. By taking interference cancellation factor into consideration we can surely acquire a better throughput and more accurate consequence. This work is inspired by the recent idea about single channel full duplex transmission and has utilized the model listed in [17]. Some math proofs may come after the previous work which has been finished in [16] and [3].

Chapter 2

System Model and Problem Formulation

2.1 System Model

Consider an underlay CR network as illustrated in Fig. 2.1. There is a primary network with active transmissions using a licensed spectrum band. A co-located secondary network consists of $(s + 1)$ secondary users (SU), termed TR_i, $i = 1, 2, \cdots, s + 1$, where s is an odd number. The SUs are paired to form $(s + 1)/2$ FD transmission links, i.e., TR_i is transmitting to, and simultaneously receiving from TR_{i+1}, while i is an odd index. Due to the underlay spectrum sharing policy, the SUs are allowed to use the same spectrum band as the primary network. For protection of the primary network, there are p detection points (DP) in the primary work that measure the interference from the secondary transmissions. Such interference should be kept below a threshold at the DP locations by effectively controlling the power of the secondary transmitters.

In Fig. 2.1, g_{ij} denotes the channel gain from TR_i to DP_j; h_{ij} represents the channel gain from TR_i to TR_j; and σ_i^2 is the sum of the total interference from primary transmissions and the noise power at TR_i. To simplify notation, we assume channel reciprocity, i.e., h_{ij} (or g_{ij}) is equal to h_{ji} (or g_{ji}) for all i, j.

For each FD link, the SI is $P_i(t)h_{ii}^2$, where $P_i(t)$ is the transmit power of TR_i and h_{ii} is the channel gain from TR_i's transmitting antenna to the receiving antenna. We assume that each TR_i utilizes SIS, and the residual SI is reduced to $\chi P_i(t)h_{ii}^2$, where χ is a constant in $[0, 1]$ depending on the specific SIS design. When $\chi = 0$, it is the perfect case where the SI can be completely canceled; when $\chi = 1$, it is the worst case without SIS and FD transmission is not possible. Usually χ is a small number, e.g., at least 45 dB across a 40 MHz band and up to 73 dB for a 10 MHz OFDM signal [14].

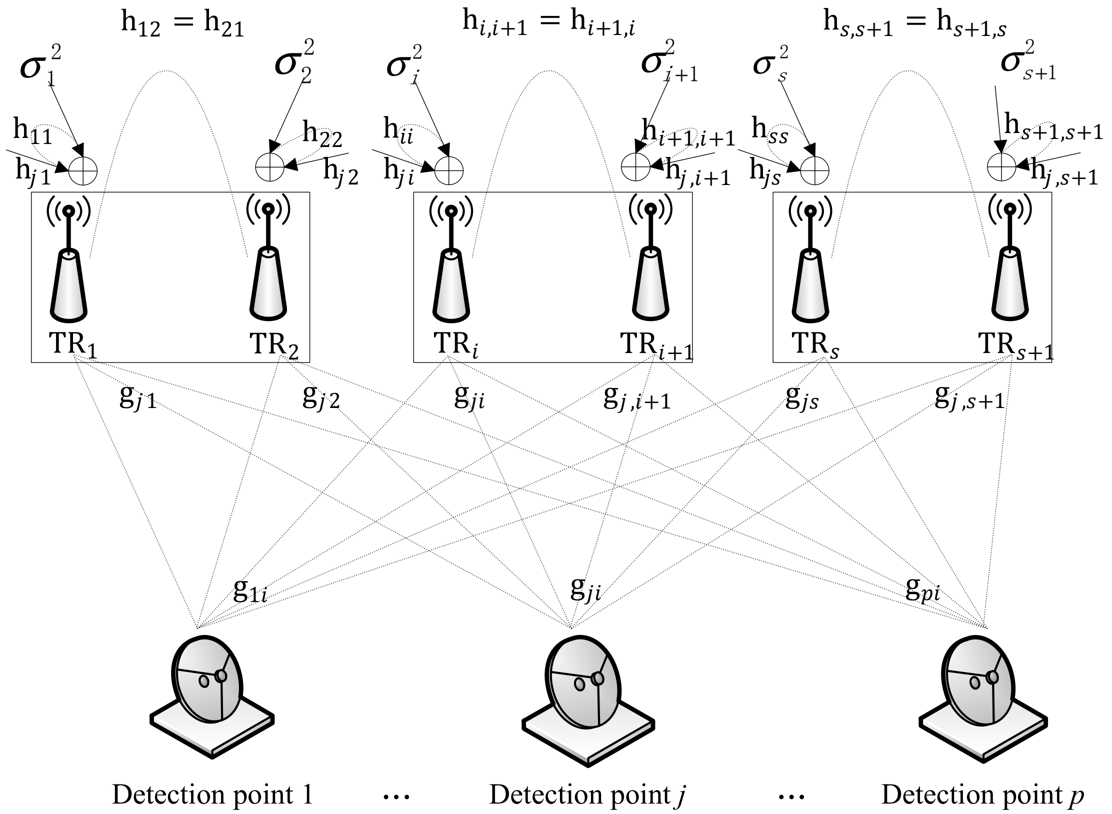

Figure 2.1: An FD underlay CR network considered in this paper.

2.2 Terms and Parameter Definition

Since this theis contains a lot of terms and parameters, this section aims to clarify the confusion for what each term or parameter stands for.

2.2.1 Signal-to-Interference-plus-Noise Ratio

Signal-to-interference-plus-noise ratio, or SINR is defined as the power of a certain signal of interest divided by the sum of the interference power and the power of noise. According to the value of interference power and noise power, SINR may also stand for Signal-to-interference ratio (SIR) or Signal-to-noise ratio (SNR).

In the thesis, we use γ to represent SINR.

2.2.2 Additive White Gaussian Noise Channel

Additive white Gaussian noise channel, as know as AWGN channel, express a certain kind of channel model. Here, the additive noise has a uniform power across the frequency band and is normal distributed in the time domain.

In the thesis, we assume the whole system is using AWGN channel.

2.2.3 Channel Capacity and Transmission Rate

Channel capacity is defined as the upper bound on the rate of information that can be reliably transmitted over a communications channel. According to Shannon, the channel capacity of AWGN channel is

$$C = Blog_2(1 + SNR) \tag{2.1}$$

Here, B is the bandwidth of channel.

In the thesis, we use R to represent the transmission rate, the transmission rate is ideal rate when there is no error possibility during transmission and has been normalized with $B = 1Hz$.

2.2.4 Fading Distance

Since wireless signal will lose power during transmission, we usually use maths model with distance to evaluate the path loss. The distance is what we call fading distance.

In the thesis, we use d_{ij} or $d_{i,j}$ to represent the fading distance.

2.2.5 Self-Interference Suppression Factor

In FD technology, the transceiver is capable to suppress its own transmission signal in the receiving antenna in order to enable FD transmission. However, the transmission signal cannot be cancelled completely so we use a SIS factor to denote the capability of suppression. It is defined as the power of processed SI divided by the power of orignial SI.

In the thesis, SIS factor is written as chi.

2.2.6 Mode Tuning Threshold

In our design, we propose a hybrid mode which would select HD or FD mode automatically in order to gain optimal throughput. The factor that decide the mode selection is the mode tuning threshold.

In the thesis, mode tuning threshold is represented with T.

2.3 Problem Statement and Equations

For the FD CR network to work properly, two conditions should be satisfied by controlling the transmit power of the TR_j's. The first condition is *primary user protection.* That is, the measured interference from secondary transmissions should be kept below a prescribed tolerance level D_j at each DP_j. The second condition is *guaranteeing the QoS of SUs.* That is, the SINR at the TR_i's should be kept above a prescribed threshold Γ, such that the SUs can be guaranteed with a minimum data rate.

We assume that time is slotted. To achieve these goals, in each time slot t, a centralized power control algorithm updates the transmit power of each TR_i, denoted as $P_i(t)$, according to the measured radio environment, as

$$P_i(t+1) = P_i(t) + u_i(t), \tag{2.2}$$

where $u_i(t)$ is the increment (positive or negative) of power at TR_i in time slot t.

We assume that the DPs can detect the interference from the SUs. For example, if the channel gains and the transmit powers from the primary transmitters are known, the DP can estimate the interference from primary transmissions. Alternatively, a quiet period as in IEEE 802.22 WRANs could be enforced for the SUs [13]. Since there is no secondary transmissions in the quiet period, the DPs can measure the interference from primary transmissions. Once the primary interference is known, a DP can estimate secondary interference by subtracting the primary interference from the total interference it receives.

As shown in Fig. 2.1, the total interference from the TR_i's to a detection point DP_j is

$$y_j(t) = \sum_{k=1}^{s+1} P_k(t) g_{kj}^2, \quad j = 1, 2, \cdots, p. \tag{2.3}$$

Then the primary user protection constraint becomes

$$y_j(t) \leq D_j, \quad j = 1, 2, \cdots, p. \tag{2.4}$$

For time slot $t+1$, the secondary interference $y_j(t+1)$ caused by the updated transmit powers should also satisfy (2.4), i.e.,

$$y_j(t+1) \leq D_j, \quad j = 1, 2, \cdots, p. \tag{2.5}$$

For the second constraint on guaranteeing the QoS of SUs, the SINR at the receiving antenna of TR_i can be written as

$$\gamma_i(t) = \begin{cases} \frac{P_{i+1}(t)h_{i+1,i}^2}{\sum_{j=1,j\neq i}^{s+1} P_j(t)h_{ji}^2 + \chi_i P_i(t)h_{ii}^2 + \sigma_i^2(t)}, & i \text{ is odd} \\ \frac{P_{i-1}(t)h_{i-1,i}^2}{\sum_{j=1,j\neq i}^{s+1} P_j(t)h_{ji}^2 + \chi_i P_i(t)h_{ii}^2 + \sigma_i^2(t)}, & i \text{ is even,} \end{cases} \tag{2.6}$$

where χ_j is the SIS factor [3].

Recall that $u_i(t) = P_i(t+1) - P_i(t)$. From the control point of view, (2.6) can be regarded as the state equation and $u_i(t)$ the input. The updated state is

$$\gamma_i(t+1) = \begin{cases} \gamma_i(t) + \frac{h_{i+1,i}^2}{I_i(t)} u_i(t) + \\ \qquad \frac{P_i(t+1)h_{i+1,i}^2[I_i(t) - I_i(t+1)]}{I_i(t)I_i(t+1)}, & i \text{ is odd} \\ \gamma_i(t) + \frac{h_{i-1,i}^2}{I_i(t)} u_i(t) + \\ \qquad \frac{P_i(t+1)h_{i-1,i}^2[I_i(t) - I_i(t+1)]}{I_i(t)I_i(t+1)}, & i \text{ is even,} \end{cases} \tag{2.7}$$

where

$$I_i(t) = \sum_{j=1,j\neq i}^{s+1} P_j(t)h_{ji}^2 + \chi_i P_i(t)h_{ii}^2 + \sigma_i^2(t). \tag{2.8}$$

It is shown that generally $I_i(t) - I_i(t+1)$ is much smaller than $I_i(t)I_i(t+1)$ [15]. It follows that (2.7) can be approximated as

$$\gamma_i(t+1) = \begin{cases} \gamma_i(t) + \frac{h_{i,i+1}^2}{I_i(t)} u_i(t), & i \text{ is odd} \\ \gamma_i(t) + \frac{h_{i,i-1}^2}{I_i(t)} u_i(t), & i \text{ is even.} \end{cases} \tag{2.9}$$

Let Γ denote the minimum required SINR for SU TR_i. The SU QoS constraint is

$$\gamma_i(t) \geq \Gamma. \tag{2.10}$$

The updated $\gamma_i(t+1)$ should also satisfy condition (2.10), i.e.,

$$\gamma_i(t+1) \geq \Gamma. \tag{2.11}$$

Define parameters a and b as

$$a = \begin{cases} [u_i(t) + P_i(t)]h_{i+1,i}^2, & i \text{ is odd} \\ [u_i(t) + P_i(t)]h_{i-1,i}^2, & i \text{ is even.} \end{cases} \tag{2.12}$$

$$\begin{aligned} b = \sum_{j=1, j\neq i}^{s+1} [u_j(t) + P_j(t)]h_{ji}^2 + \chi_i[u_i(t) + P_i(t)]h_{ii}^2 + \\ \sigma_i^2(t+1), i = 1, 2, \cdots, s+1. \end{aligned} \tag{2.13}$$

From (2.2), (2.5), and (2.11), we derive the following system of equations that can be solved for $u_i(t)$.

$$\begin{cases} a/b = \Gamma,\ i = 1, 2, \cdots, s+1 \\ [u_i(t) + P_i(t)]g_{ij}^2 + \sum_{k=1, k\neq i}^{s+1}[u_k(t) + \\ \qquad P_k(t)]g_{kj}^2 \leq D_j,\ j = 1, 2, \cdots, p. \end{cases} \tag{2.14}$$

If the channel gains vary over time (e.g., in a mobile SU network), we can defined parameters a^* and b^* as

$$a^* = \begin{cases} [u_i(t) + P_i(t)]h_{i+1,i}^2(t+1), i \text{ is odd,} \\ [u_i(t) + P_i(t)]h_{i-1,i}^2(t+1), i \text{ is even.} \end{cases} \tag{2.15}$$

$$\begin{aligned} b^* = \sum_{j=1, j\neq i}^{s+1} [u_j(t) + P_j(t)]h_{ji}(t+1)^2 + \chi_i[u_i(t) + \\ P_i(t)]h_{ii}(t+1)^2 + \sigma_i^2(t+1), i = 1, \cdots, s+1. \end{aligned} \tag{2.16}$$

A similar system of equations can be solved to determine $u_i(t)$ as

$$\begin{cases} a^*/b^* = \Gamma, i = 1, 2, \cdots, s+1 \\ [u_i(t) + P_i(t)]g_{ij}^2(t+1) + \sum_{k=1,k\neq i}^{s+1}[u_k(t)+ \\ \qquad P_k(t)]g_{kj}^2(t+1) \leq D_j, j = 1, 2, \cdots, p. \end{cases} \tag{2.17}$$

Chapter 3

Power Adjustment Schemes and System Analysis

In this chapter, we develop a power control scheme for adapting the transmit power of the secondary users [9]. The goal is to achieve the SU QoS requirement while satisfying PU protection constraint as given in (2.14). In the rest part of the chapter, we are going to discuss about the stability of our controller and find out our tuning point for FD and HD modes.

3.1 PID Controller Design

First, we consider the SU QoS constraint, while ignoring the PU protection constraint. The goal is to drive $\gamma_i(t)$ to converge to the the SU QoS requirement Γ, for all i. The difference between these two parameters should be considered and should be reduced as small as possible. Another consideration is that the error signal $e_i(t)$ should be related to the power $P_i(t)$, which is the parameter that we need to determine for each TR_i. Therefore $P_i(t)$ is used as the reference input. As we can see, the ratio of Γ and $\gamma_i(t)$ can be an indicator for the control error, and $\gamma_i(t) \propto P_i(t)$ if all other parameters remain the same. Thus, we could use $\frac{\Gamma}{\gamma_i(t)}P_i(t)$ as the feedback. The error $e_i(t)$ should be the difference of feedback and $P_i(t)$ and we have the diagram of the PID controller as in Fig. 3.1.

The PID controller collects the SINR of each TR at every time slot and uses it as feedback for the controller. For each time slot, let $z_i(t)$ denote the power increment from

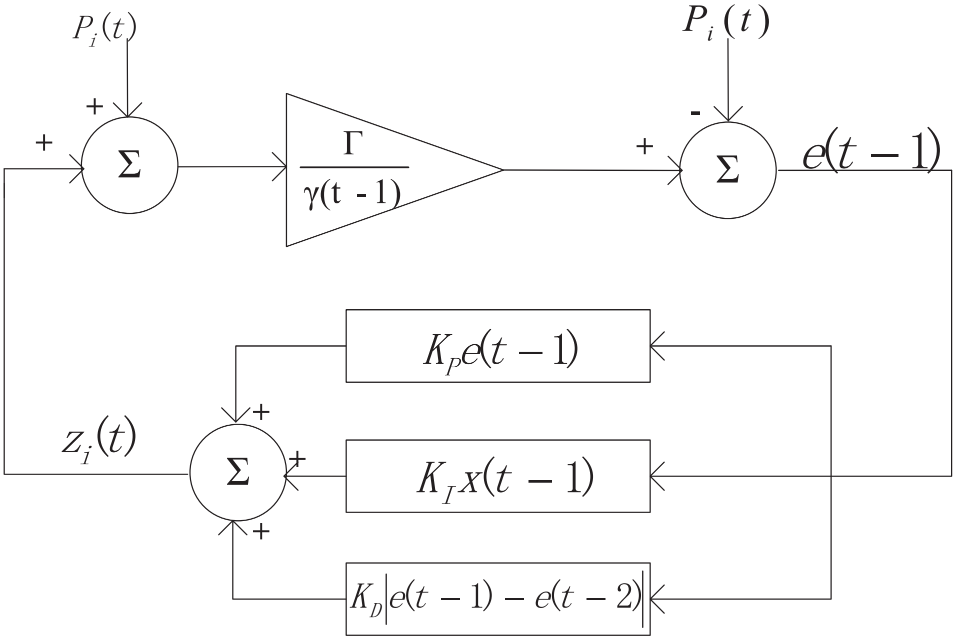

Figure 3.1: The PID controller design.

$P_i(t)$ to $P_i(t+1)$. With feedback $\frac{\Gamma}{\gamma_i(t)}P_i(t)$, the PID controller controls the system as

$$e_i(t-1) = \left\{ \frac{\Gamma}{\gamma_i(t-1)} - 1 \right\} P_i(t) \tag{3.1}$$

$$x_i(t-1) = x_i(t-2) + e_i(t-1) \tag{3.2}$$

$$z_i(t) = K_P e_i(t-1) + K_I x_i(t-1) + K_D \left| e_i(t-1) - e_i(t-2) \right|, \tag{3.3}$$

where $e_i(t-1)$, $x_i(t-1)$ and $|e_i(t-1) - e_i(t-2)|$ represent the proportional, integral and derivative parts, respectively; K_p, K_I, and K_D are the corresponding coefficients. Proper coefficients should be designed to achieve a stable and convergent control process for adjusting the $P_i(t)$'s to achieve the required minimum SINR Γ for each SU [4].

3.2 Power Adjustment Constraint

Next we take into account the PU protection constraint. The objective of this constraint is to prevent the SU transmission powers from violating the interference tolerance at the DPs. This constraint actually represents a relationship between $P_i(t)$ and D_j, for all i and j.

We first introduce the following two parameters.

$$D_{min} = \min_{j=1,2,\cdots,p} D_j \tag{3.4}$$

$$y_{max}(t-1) = \max_{j=1,2,\cdots,p} y_j(t-1). \tag{3.5}$$

D_{min} is the minimum tolerance value among all the DPs, and $y_{max}(t)$ is the maximum measured interference among all DPs. Since D_{min} is a constant and $y_{max}(t-1) \propto P_i(t-1)$, the additional power constraint should also be proportional $P_i(t-1)$. We follow a similar approach as in prior work [17] to introduce the following additional constraint on the power adjustment $z_i(t)$.

$$c_i(t) = \theta(t)P_i(t-1) - P_i(t), \tag{3.6}$$

where,

$$\theta(t) = \frac{D_{min}}{y_{max}(t-1)}. \tag{3.7}$$

According to (3.6) and (3.7), once the maximum interference $y_{max}(t-1)$ exceeds the minimum tolerance D_{min}, the constraint will reduce the transmit power with a proportion of $\theta(t)$, which will drive the maximum interference back to D_{min}.

Eqn. (3.6) enforces an additional constraint to the power increment $z_i(t)$ for the SUs, so as to satisfy the PU protection constraint as given in (2.4). Because the PU protection is a fundamental condition for spectrum sharing, the the constraint $c_i(t)$ cannot be exceeded.

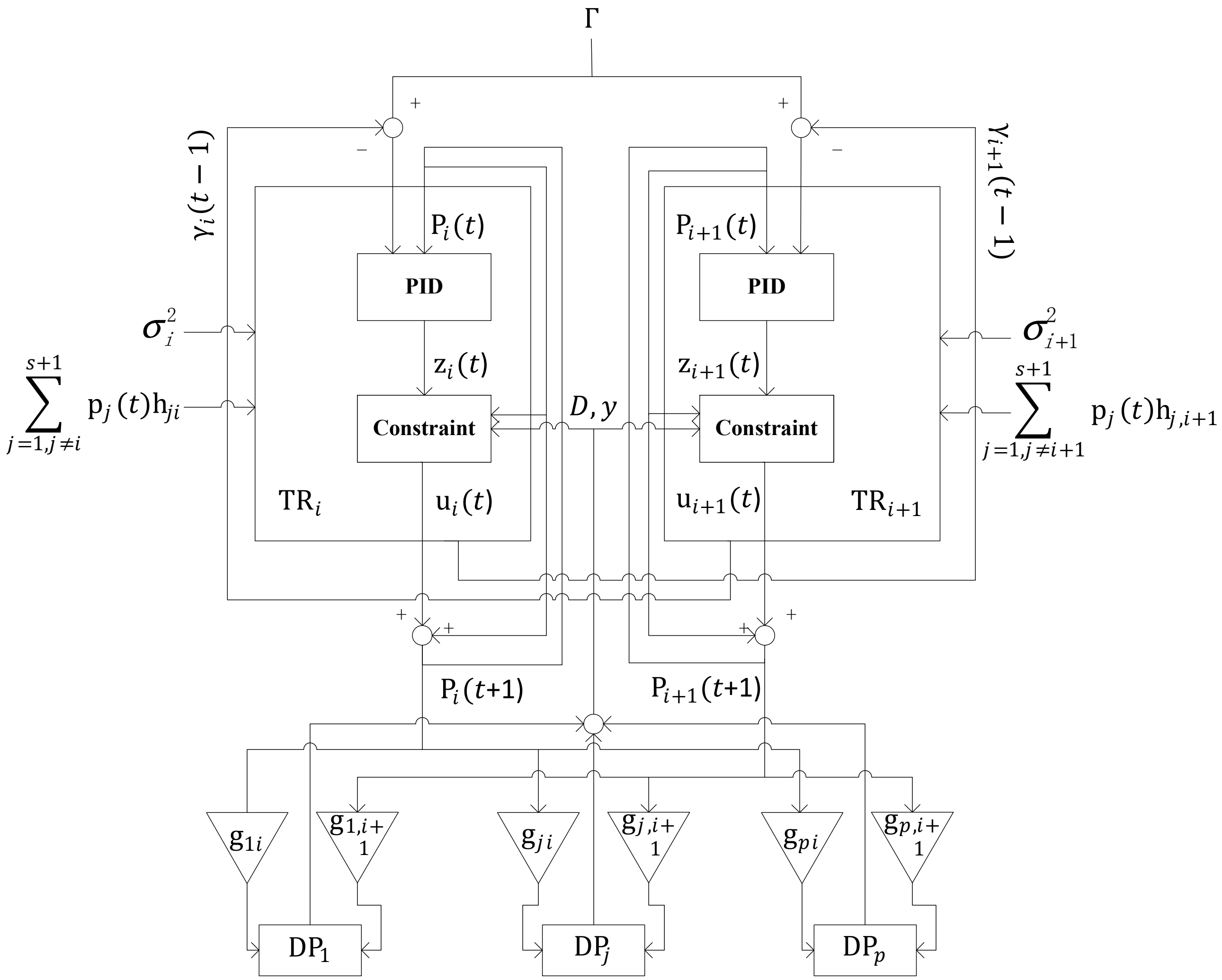

Figure 3.2: System control block diagram.

Therefore, we have the final allowed power increment $u_i(t)$ in time slot t for TR_i as

$$u_i(t) = \min\{z_i(t), c_i(t)\},\ i = 1, 2, \cdots, s+1. \tag{3.8}$$

With such adjustment, the transmit power can be limited in a safe range that does not lead to severe interference to the primary network, while trying to achieve the minimum required SINR for the SUs. The overall diagram of the proposed power controller is illustrated in Fig. 3.2.

3.3 Analysis of Stability

It is important to analyze the stability performance of the proposed power control scheme. The stability of the PID controller (i.e., without considering FD and the PU protection constraint (3.6)) has been studied in [9]. The stability of the overall scheme depends on the parameter settings. In the following, we examine two cases when each of the two constraints, i.e., $z_i(t)$ and $c_i(t)$, becomes the dominant factor at the beginning stage.

Case I: $z_i(t) > c_i(t)$ **Initially**

From (3.1), (3.2) and (3.3), we have $P_i(0) = P_i(1) = P_i(2)$, and $x_i(0) = e_i(0) = 0$ for the initial time slots. There is no power adjustment in the first time slot, and the first power adjustment occurs at $t = 2$, as

$$z_i(2) = (K_P + K_I + K_D)e_i(1). \tag{3.9}$$

If $z_i(2) > c_i(2)$, from (3.8) we have $u_i(2) = c_i(2)$ and

$$\begin{cases} P_i(3) = \theta(2)P_i(1) \\ P_i(4) = \theta(3)P_i(2). \end{cases} \tag{3.10}$$

After the power adjustment in time slot 2, the detected total SU interference at DP j in time slot 3 is

$$\begin{aligned} y_j(3) &= \sum_{i=1}^{s+1} P_i(3)g_{ij}^2 = \sum_{i=1}^{s+1} \theta(2)P_i(1)g_{ij}^2 \\ &= \frac{D_{min}}{y_{max}(1)} \sum_{i=1}^{s+1} P_i(1)g_{ij}^2. \end{aligned}$$

The maximum measured interference among all the DPs is

$$
\begin{aligned}
y_{max}(3) &= \max_{j=1,\cdots,p} y_j(3) = \frac{D_{min}}{y_{max}(1)} \max_{j=1,\cdots,p} \sum_{i=1}^{s+1} P_i(1) g_{ij}^2 \\
&= \frac{D_{min}}{y_{max}(1)} y_{max}(1) = D_{min}. \qquad (3.11)
\end{aligned}
$$

Therefore the maximum measured interference will remain at D_{min} and the constraint $c_i(t)$ will remain at 0 starting from time slot 3. According to (3.8), $u_i(t)$ will also remain at 0 after time slot 3. All the transmit powers converge to the steady value and the primary goal of PU protection is satisfied. However, there is no guarantee that the target SU QoS requirement can be achieved by the converged TR powers. If $\gamma_i(3) < \Gamma$, the SU QoS requirement cannot be satisfied since the transmit powers cannot be adjusted anymore.

If $z_i(t)$ remains non-negative, $u_i(t)$ will always be 0 since $c_i(t) = 0$ for all $t \geq 3$. All the TR powers will remain the same and the maximum measured interference remains at D_{min}. Otherwise, if $z_i(t) < 0$ due to some disturbance, the TR_i power will be reduced with $z_i(t)$, until the target SINR Γ is reached. However, if the above two situations both happens during the control process, we can predict that there will be oscillation and the system will enter a bounded oscillation state. Therefore, the system can be called bounded-in-bounded-out (BIBO) stable. In summary, for all the three cases discussed above, the system will be stabilized by the proposed power control scheme.

Case II: $z_i(t) < c_i(t)$ Initially

On the other hand, if the control function is initially dominated by the PID controller adjustment $z_i(t)$, the pattern changes. If the transmit powers to achieve the desired SINR cause a smaller measured interference than the D_j's, that is, if the primary network has high interference tolerance D_j's, the additional constrain enforced by $c_i(t)$ can be ignored, and the power control will become a stable PID control process. The stability of such a system has been demonstrated in [9].

However, if the desired SINR Γ cannot be achieved due to a small D_{min}, the PU protection constraint will take over the control during the process and will drive the TR powers to the maximum allowed value. The other situation is that due to the impact of some disturbance, the control process may enter the same BIBO state as discussed in Section 3.3.

3.4 HD-FD Tuning Point

Recall that the SIS factor χ depends on the particular SIS design and is a small value in $[0, 1]$. Clearly, χ, along with other network dynamics such as the channel gains, the number and locations of SUs and DPs, and the prescribed control goals (i.e., Γ and D_j's), all have big impact on the system performance. So in a practical underlay CR network, it is not true that FD transmissions will always achieve a better performance; when χ is large, the residual SI will be so large that HD transmissions will be a better choice. Therefore, a hybrid scheme that can switch between FD and HD modes depending on the system parameters and states would be highly desirable. In the following, we investigate the condition under which a switching between HD and FD modes should be made.

We use Shannon's capacity to approximate the throughput of an SU, i.e., $C = B\log_2(1+ \mathit{SINR})$. Since bandwidth B is a constant for all SUs, we use the spectrum efficiency $\log_2(1+\mathit{SINR})$ for comparing the efficiency of the two operation modes in the following. Let γ_i^{FD} and γ_i^{HD} denote the SINRs of TR_i in the FD mode and HD mode, respectively. We can derive the average throughput for the SU pair in the HD mode, denoted as R_i^{HD}, as follows.

$$R_i^{HD} = \begin{cases} \frac{1}{2}\left[\log_2(1+\gamma_i^{HD}) + \log_2(1+\gamma_{i+1}^{HD})\right], & i \text{ is odd} \\ \frac{1}{2}\left[\log_2(1+\gamma_i^{HD}) + \log_2(1+\gamma_{i-1}^{HD})\right], & i \text{ is even,} \end{cases} \tag{3.12}$$

where,

$$\gamma_i^{HD} = \begin{cases} \frac{P_{i+1}(t)h_{i+1,i}^2}{\sum_{j=1,j\neq i}^{s+1} P_j(t)h_{ji}^2+\sigma_i^2(t)}, & i \text{ is odd} \\ \frac{P_{i-1}(t)h_{i-1,i}^2}{\sum_{j=1,j\neq i}^{s+1} P_j(t)h_{ji}^2+\sigma_i^2(t)}, & i \text{ is even.} \end{cases} \tag{3.13}$$

In the FD mode, the throughput for the SU pair is

$$R_i^{FD} = \begin{cases} \log_2(1+\gamma_i^{FD}) + \log_2(1+\gamma_{i+1}^{FD}), \ i \text{ is odd} \\ \log_2(1+\gamma_i^{FD}) + \log_2(1+\gamma_{i-1}^{FD}), \ i \text{ is even,} \end{cases} \tag{3.14}$$

where γ_i^{FD} is given in (2.6).

In each time slot t, we estimate the expected throughput for each SU pair in both the FD and HD modes and decide which mode to adopt for the time slot. The cross-over point for the two modes is derived by solving the following equation.

$$R_i^{HD} = R_i^{FD}. \tag{3.15}$$

It can be seen that (3.15) can be rewritten as

$$\begin{cases} \sqrt{(1+\gamma_i^{HD})(1+\gamma_{i+1}^{HD})} = (1+\gamma_i^{FD})(1+\gamma_{i+1}^{FD}), \\ \qquad\qquad\qquad\qquad\qquad\qquad i \text{ is odd} \\ \sqrt{(1+\gamma_i^{HD})(1+\gamma_{i-1}^{HD})} = (1+\gamma_i^{FD})(1+\gamma_{i-1}^{FD}), \\ \qquad\qquad\qquad\qquad\qquad\qquad i \text{ is even.} \end{cases} \tag{3.16}$$

Define a ratio T as follows.

$$T_i = \begin{cases} \frac{\sqrt{(1+\gamma_i^{HD})(1+\gamma_{i+1}^{HD})}}{(1+\gamma_i^{FD})(1+\gamma_{i+1}^{FD})}, \ i \text{ is odd} \\ \frac{\sqrt{(1+\gamma_i^{HD})(1+\gamma_{i-1}^{HD})}}{(1+\gamma_i^{FD})(1+\gamma_{i-1}^{FD})}, \ i \text{ is even.} \end{cases} \tag{3.17}$$

Thus, we have the following proposition for determining the operation mode for TR_i in the hybrid scheme.

Proposition 1. *A TR_i should operate in the HD mode if $T_i \geq 1$, and it should operate in the FD model if $T_i < 1$.*

Chapter 4

Simulation and Analysis

4.1 Simulation Configuration

To evaluate the performance of the proposed power control scheme for FD underlay CR networks, we conduct extensive simulations using a MATLAB implementation. We use one network in a 100×100 area and another network in a 1000×1000 area. The outdoor channel model $h = 40\log_{10}(d) + 10$ dB is used in all the simulations, where d is the distance between the transmitter and receiver. In each simulation, the noises powers σ^2 are i.i.d. random variables evenly distributed in a fixed range, while the range may change in different simulations. As discussed, the performance of FD systems are greatly affected by χ. We choose $\chi = 0.00005$ in most of the simulations, unless otherwise specified.

There are eight TRs and four DPs in the network. The location of the TRs and DPs are shown in Fig. 4.1 and Fig. 4.13. We assume each TR can communicate with all the DPs through a control channel to obtain information about detected interference level at the DPs (i.e., $y_{max}(t-1)$). The control goals Γ and D_j's are prescribed and is known to all the TRs. Such information is used as input to the control scheme executed at each TR to adjust its transmit power.

4.2 Control Performance Analysis

In this section, we evaluate the performance of the proposed controller in the FD and HD modes. First, we simulate the 100×100 network under fixed Γ and fixed χ. We set $\Gamma = 0.1$ and $\chi = 0.00005$ in the simulation. Noise σ^2 is uniform distributed in $[1.2 \times 10^{-6}, 2.4 \times 10^{-8}]$ W. DP's tolerance limit is set as $D_j = 5 \times 10^{-10}$W for all j.

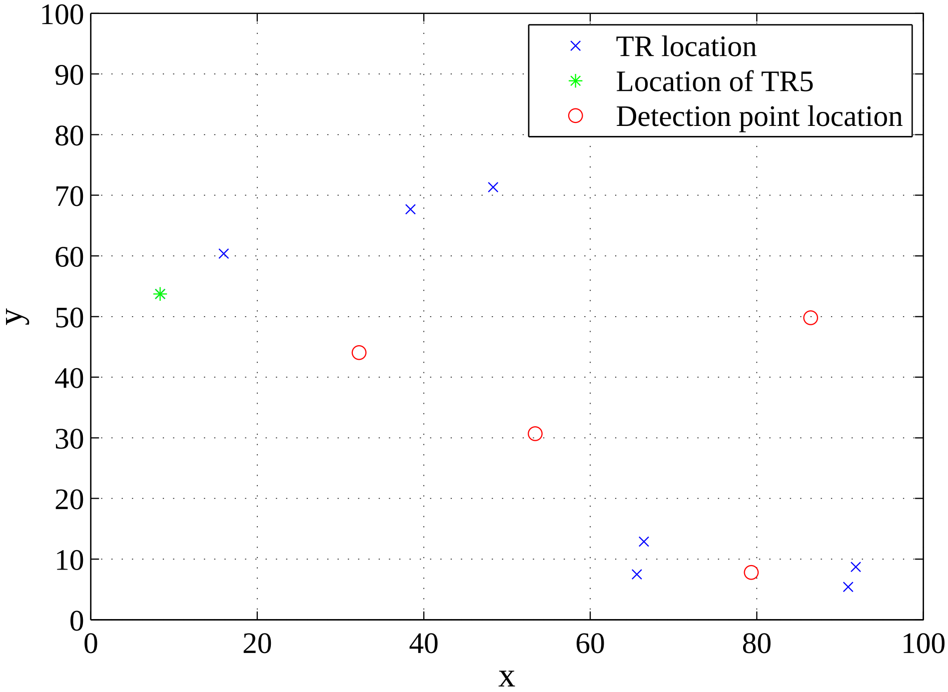

Figure 4.1: Distribution of the TRs and DPs in the 100×100 network.

Take TR_5 as an example. The evolutions of its SINR $\gamma_5(t)$ and transmit power $P_5(t)$ are plotted in Fig. 4.2 and Fig. 4.3, respectively. It can be seen that both the SINR and power curves quickly converge to the neighborhood of the stable values, and then fluctuate around the stable values. In Fig. 4.2, the HD SINR is slightly higher than that of HD. However this does not mean that the throughput of an FD link is lower than that of an HD link, since the FD link throughput is the sum of that of the two end TRs. In Fig. 4.3, it can be seen that a higher transmit power is used in the FD mode to overcome the residual SI in order to achieve the target SINR value Γ.

Due to the parameters used, in the HD mode the power adjustment of TR_5 is initially dominated by the PU protection constraint (3.6), and then controlled by the SU QoS constraint (3.3). In the FD case the control of the power adjustment is jointly done by both constraints. This can be witnessed by comparing $u_5(t) = \min\{z_5(t), c_5(t)\}$, $z_5(t)$, and $c_5(t)$ as plotted in Fig. 4.4, Fig. 4.5, and Fig. 4.6, respectively. In a few time slots the control

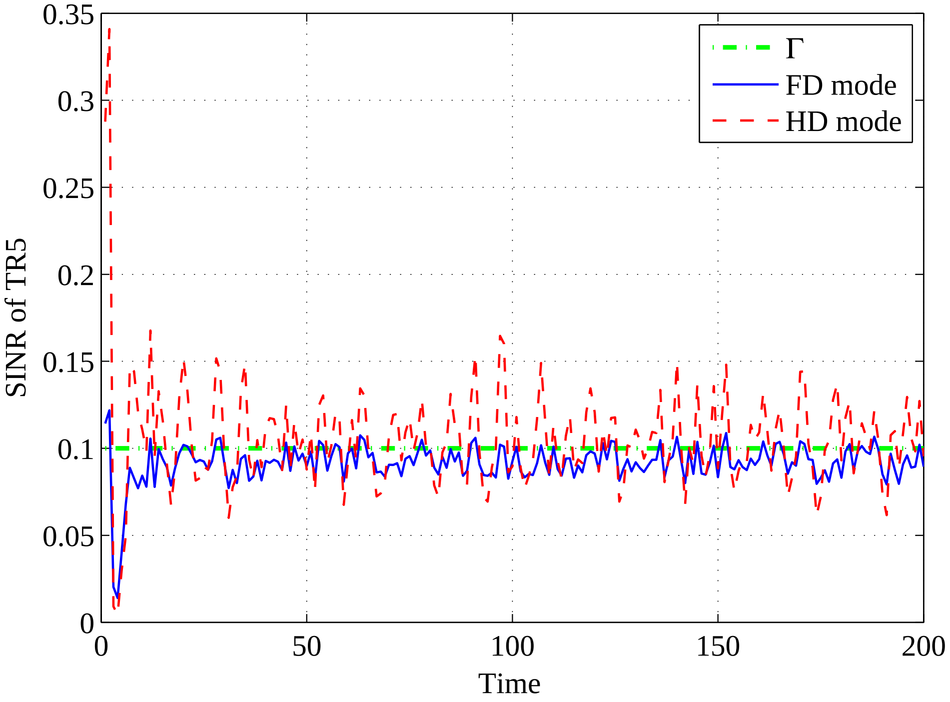

Figure 4.2: Evolution of the SINR at TR_5 when $\Gamma = 0.1$ and $\chi = 0.00005$.

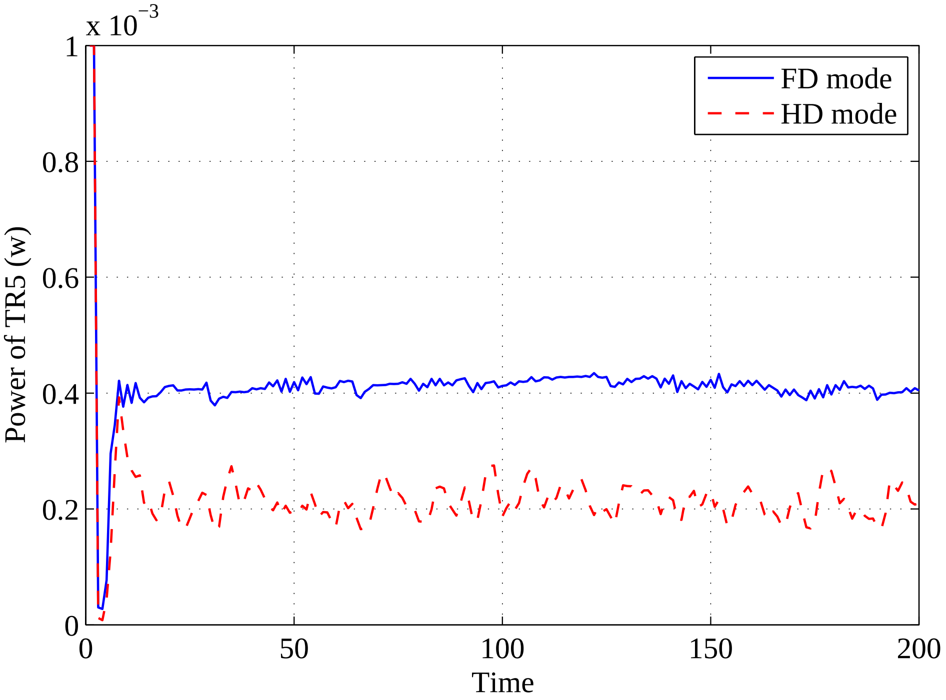

Figure 4.3: Evolution of the transmit power at TR_5 when $\Gamma = 0.1$ and $\chi = 0.00005$.

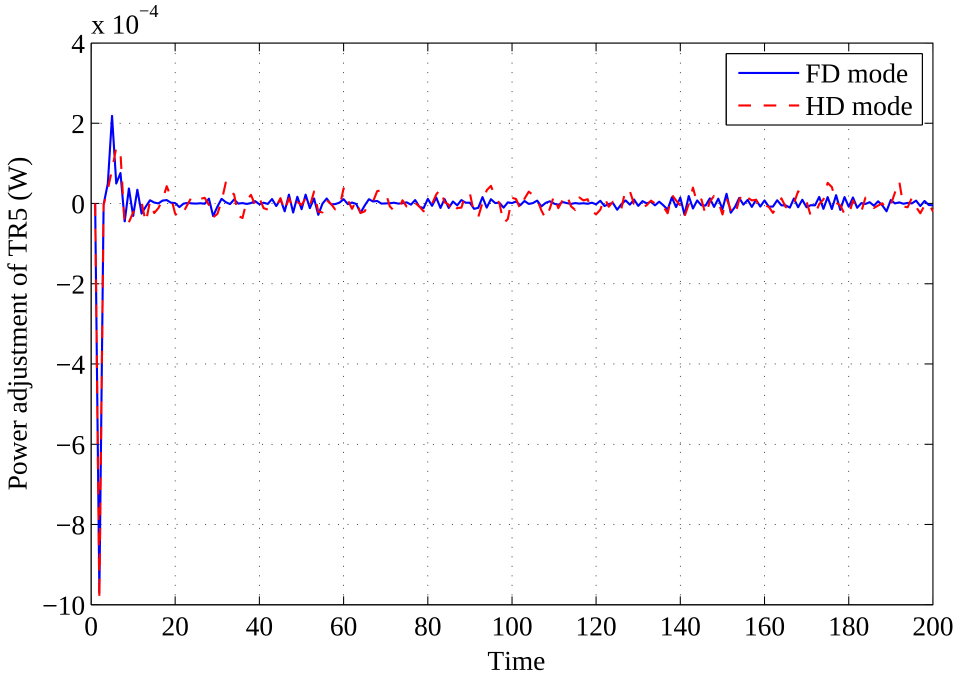

Figure 4.4: Power adjustment $u_5(t) = \min\{z_5(t), c_5(t)\}$ of TR_5 when $\Gamma = 0.1$ and $\chi = 0.00005$.

process $u_5(t)$ reaches the stable value 0 and achieves the optimal SINR with the given D for TR_5.

In Fig. 4.7, we demonstrate the PU protection performance by plotting the PU interference tolerant D and the maximum measure interference at the DPs for the FD and HD modes. It can be seen that with the proposed power control scheme, the maximum DP detected interference y_{max} defined in (3.7) quickly drops below D after a few time slots. Therefore the PU protection goal is well achieved by the proposed power control scheme. In the meantime, the controlled power remains around 0.4 W for the FD mode and 0.2 W for the HD mode (see Fig. 4.3), which are sufficient to satisfy the required SINR $\Gamma = 0.1$ for TR_5, as shown in Fig. 4.2. Since the controlled power of TR_5 has achieved both PU protection and SU QoS goals, the power adjustment $u_5(t)$ will stay within a narrow range around 0.

Next we try a large value of $\Gamma = 0.3$ in the simulation to evaluate the case of an overly high QoS requirement of the SUs that cannot be supported in the underlay CR network. That is, there is no feasible solution to satisfy both PU protection and SU QoS constraints

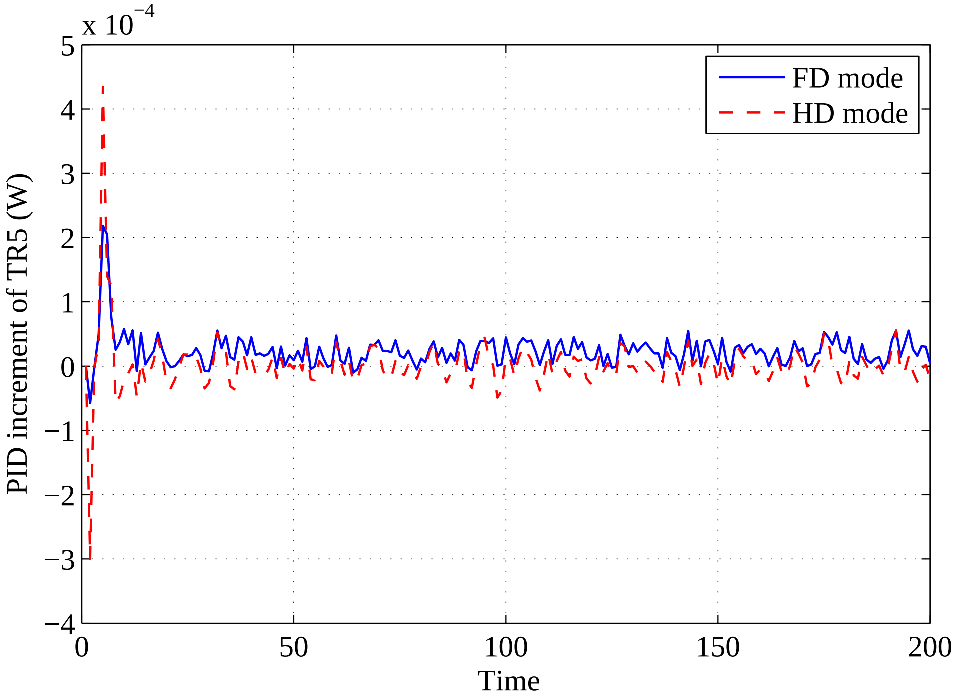

Figure 4.5: PID controller adjustments $z_5(t)$ when $\Gamma = 0.1$ and $\chi = 0.00005$.

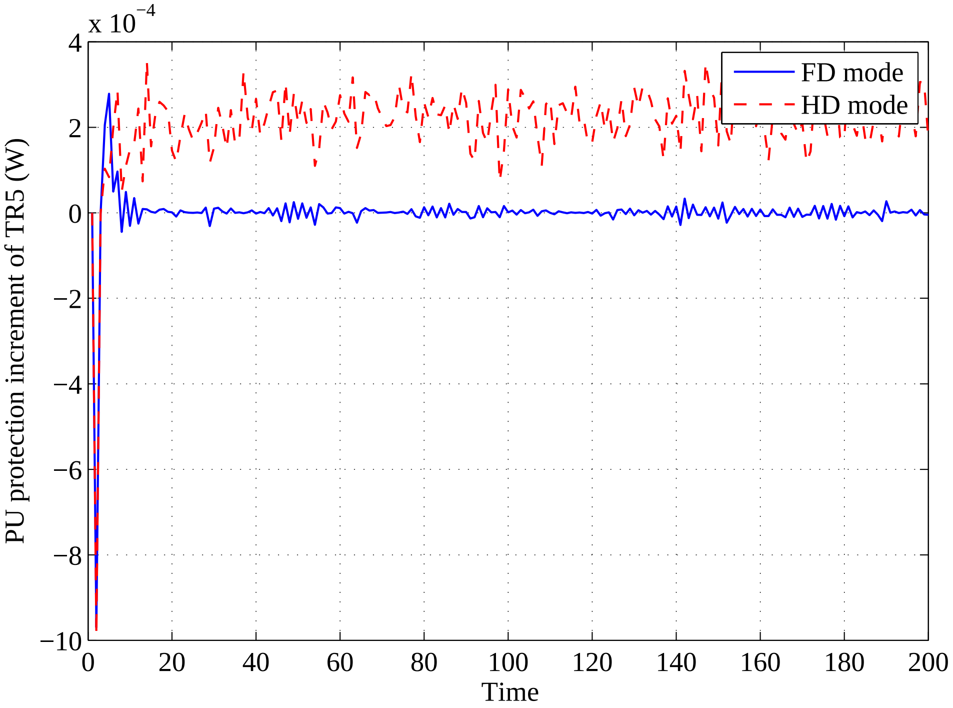

Figure 4.6: PU protection constraint adjustments $c_5(t)$ when $\Gamma = 0.1$ and $\chi = 0.00005$.

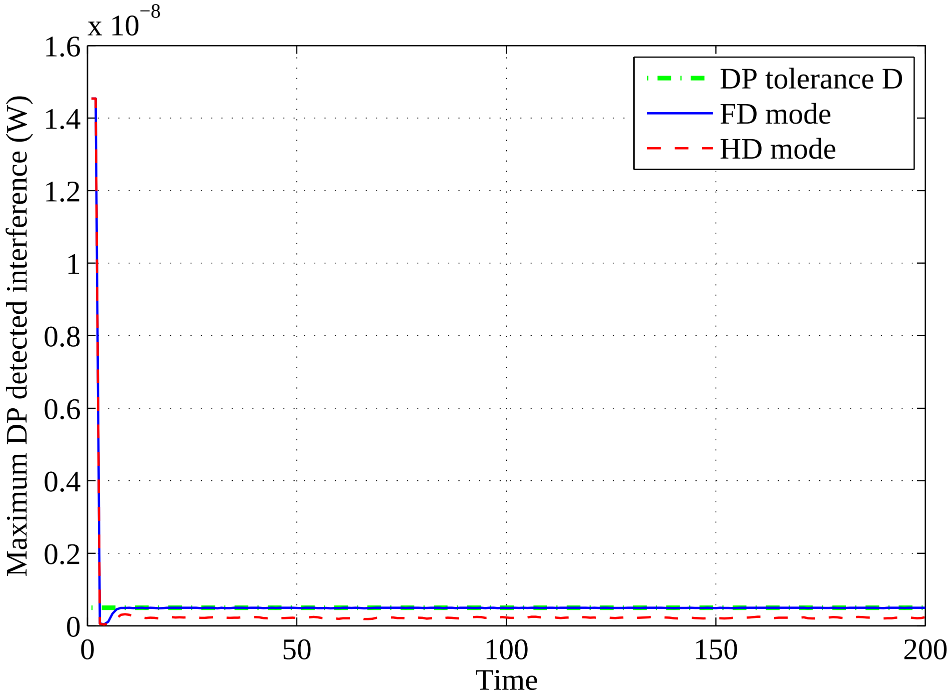

Figure 4.7: Maximum measured interference among all the DPs when $\Gamma = 0.1$ and $\chi = 0.00005$.

in this case. In this case, the power control scheme will try to achieve PU protection as a primary goal, as the prerequisite condition for spectrum sharing, and then try to maximize the SINR of the SUs as a secondary goal. The maximum DP detected interferences to PUs are plotted in Fig. 4.8 for the FD and HD modes. It can be seen that the proposed power control scheme can effectively guarantee that the interference to PUs is below the tolerance D. The achieved SINR for TR5 is also plotted for the FD and HD modes in Fig. 4.9. It can be seen that the SINR of TR_5 is stabilized around 0.17 for the HD mode and 0.1 for the FD mode, although the desired SINR for TR_5 is 0.3. Since the maximum allowed interference has been reached (i.e., $D = 5 \times 10^{-10}$ W as in Fig. 4.8), the power of TR_5 cannot be further increased to reach the target SINR level $\Gamma = 0.3$. Note that although the HD mode achieves a higher SINR than the FD mode as in Fig. 4.9, this does not necessarily mean the HD throughput is higher than that of the FD model. We will examine the throughput performance in Section 4.3.

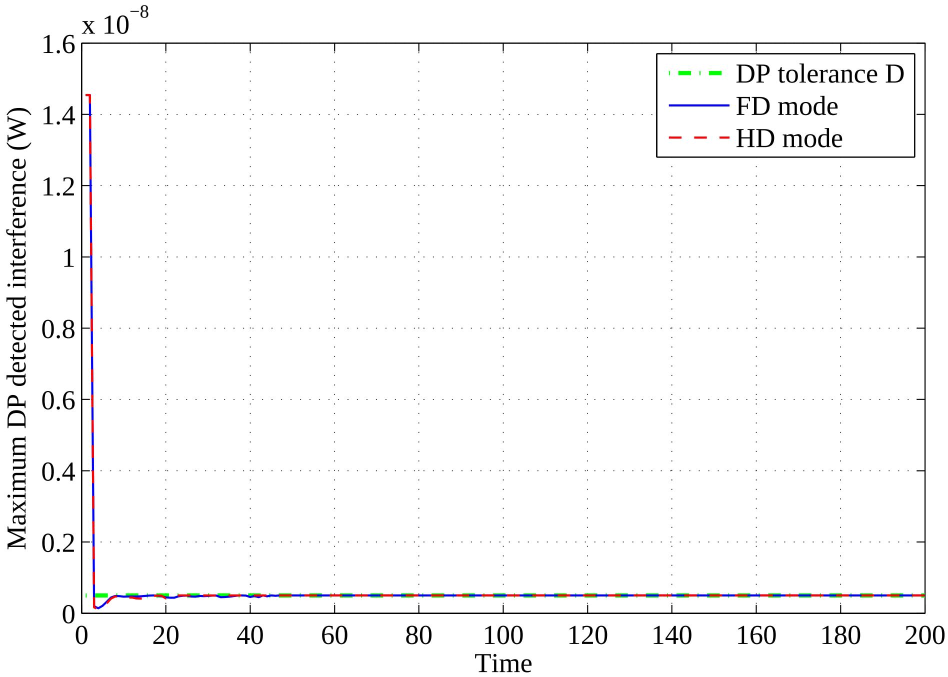

Figure 4.8: Maximum measured interference among all the DPs when $\Gamma = 0.3$ and $\chi = 0.00005$.

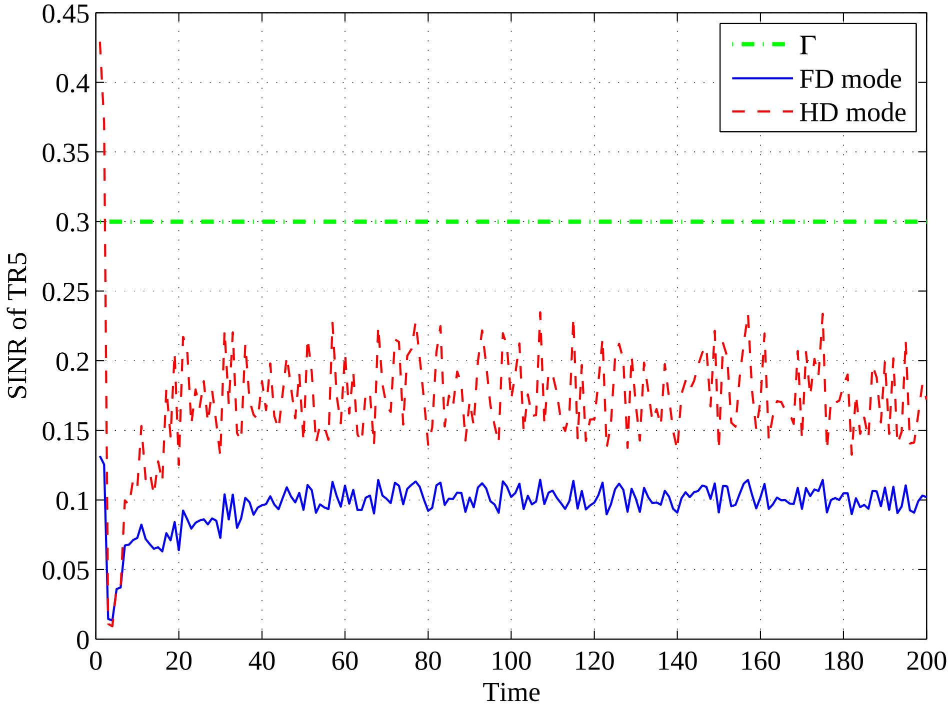

Figure 4.9: Evolution of the SINR at TR_5 when $\Gamma = 0.3$ and $\chi = 0.00005$.

Table 4.1: Setting of Γ.

	Time slot (t)	1-50	51-100	101-150	151-200
Fig. 4.10	Γ	0.1	0.05	0.05	0.1
Fig. 4.11	Γ	0.05	0.1	0.15	0.2

Finally, we demonstrate the performance of the proposed power controller under varying SU QoS requirements. In particular, we vary the SU SINR requirement Γ as given in Table 4.2. In Fig. 4.10, the required SINR is with the range such that the proposed controller can achieve both PU protection and SU QoS goals. It can be seen that the SINR can be stabilized around the target SINR for the full range. In Fig. 4.11, the SINR is continuously increased, from the feasible range to the infeasible range both goals cannot be met simultaneously. In Fig. 4.11, the HD SINR curve is controlled well and the SINR of TR_5 can quickly follow Γ from 0.05 to 0.2. On the other hand, the FD SINR curve cannot follow the increased Γ byond 0.1, because of a larger power is required to combat the residual SI in order to achieve the same SINR, which, however, is not allowed since the primary constraint of PU protection will be violated. In Fig. 4.12, the maximum measured interference among the DPs is also plotted. It can be seen that the primary goal of PU protection is always achieved by the proposed scheme.

4.3 Throughput Performance

In this section, we evaluate the achievable throughput by the proposed power control scheme. We focus on the proposed hybrid scheme in the simulations, with which the operating mode for each TR is determined as given in Section 3.4. The large 1000×1000 network with eight TRs and four DPs is used in the following simulations, as shown in Fig. 4.13.

In the simulation, we increase χ from 0.000005 to 0.005 with step size of 0.000005. With each χ value, we simulate the system for 200 time slots each with a random noise level, which has been shown to be sufficient long for convergence in our previous simulations. We plot

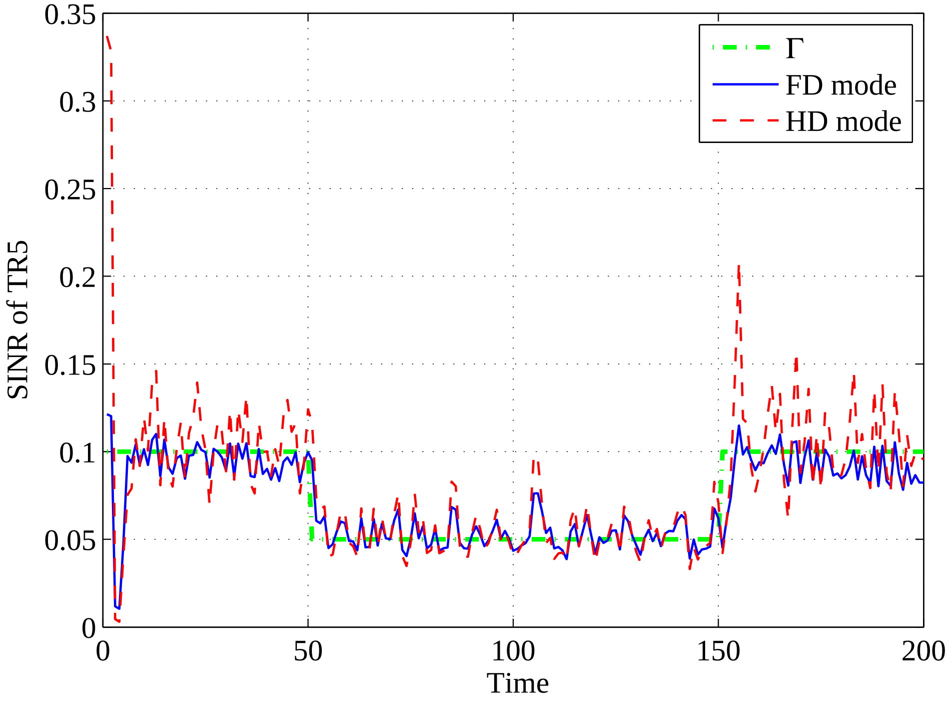

Figure 4.10: Evolution of the SINR at TR_5 under varying Γ.

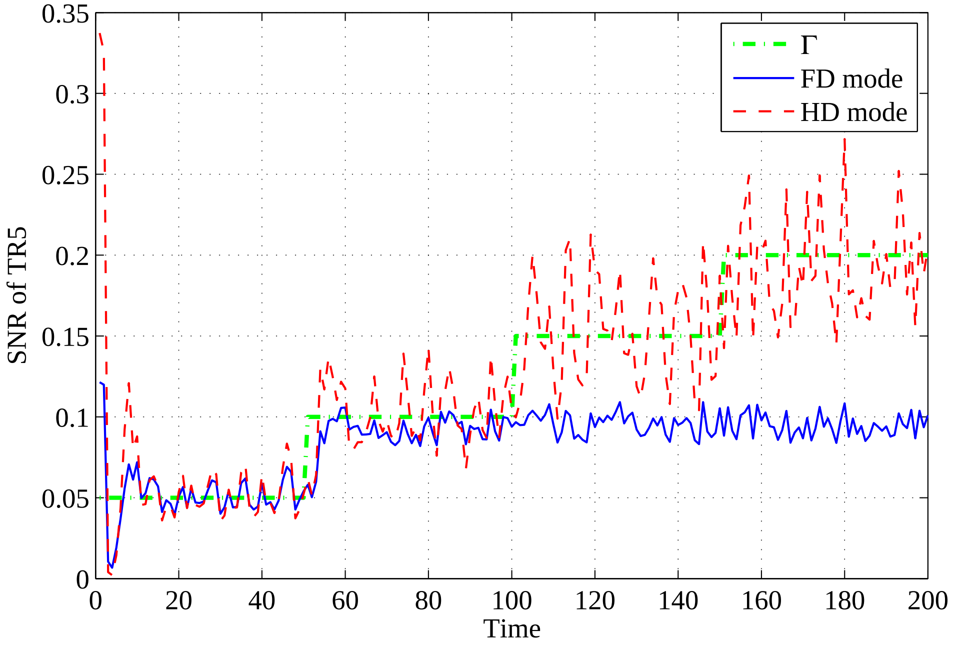

Figure 4.11: Evolution of the SINR at TR_5 under varying Γ.

the average throughput of the 200 time slots for each χ value in the figure for the FD, HD and hybrid schemes.

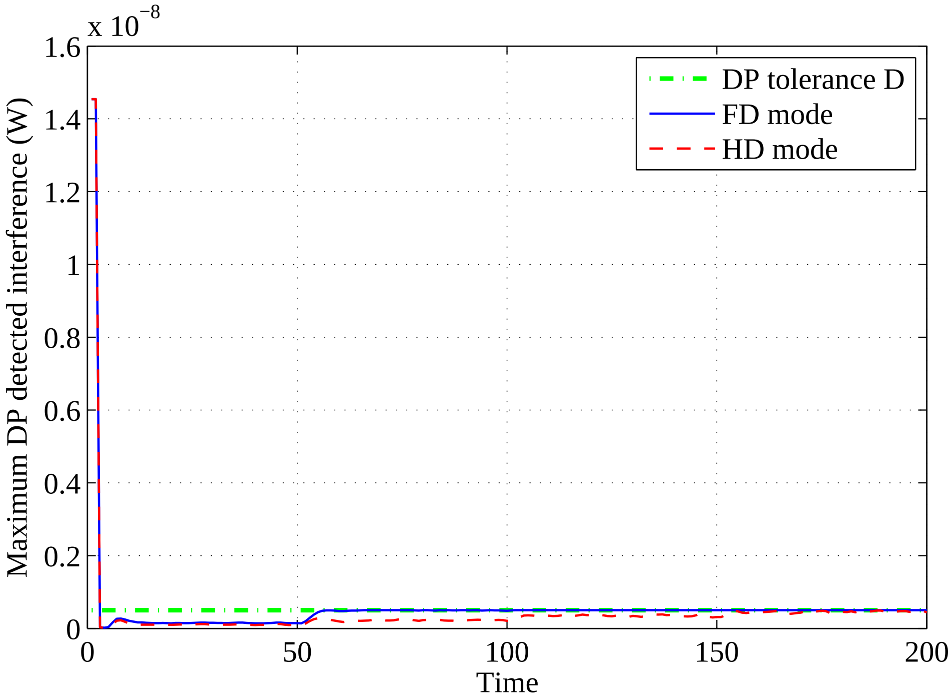

Figure 4.12: Maximum measured interference among all the DPs under varying Γ.

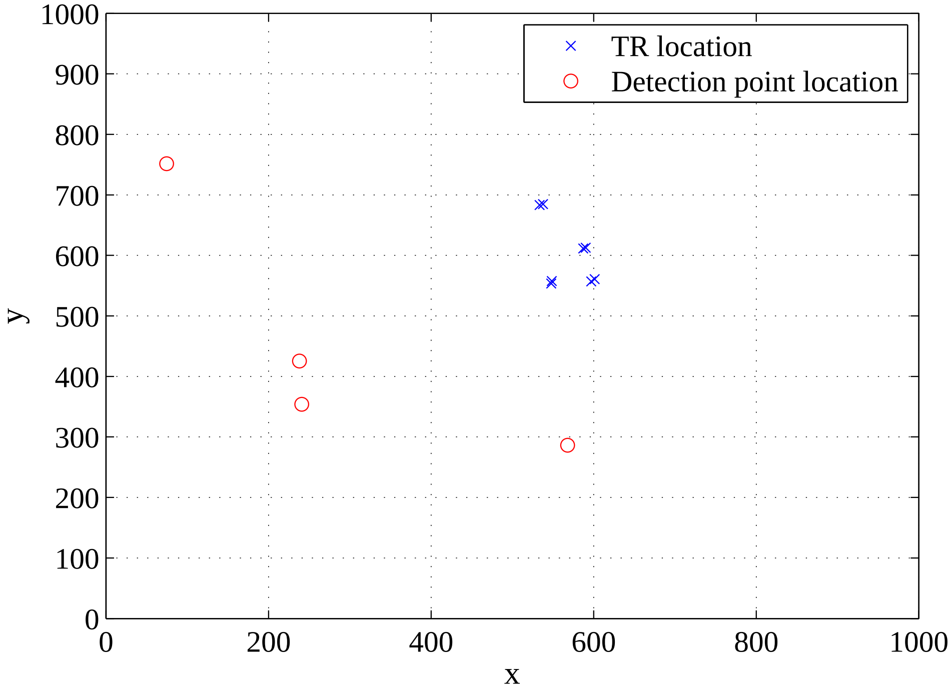

Figure 4.13: Distribution of the TRs and DPs in the 1000×1000 network.

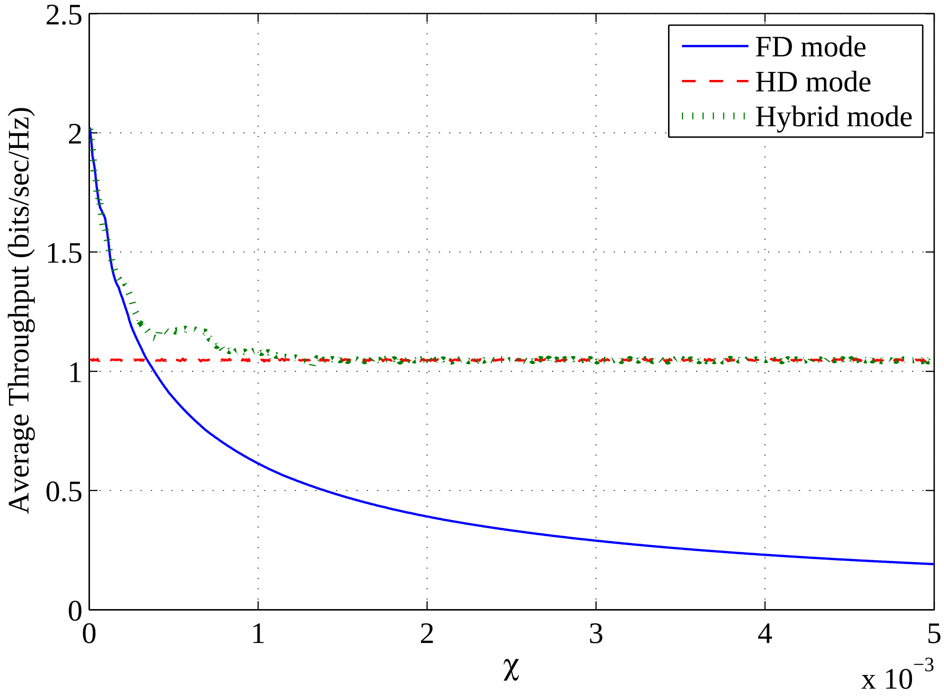

Figure 4.14: Average throughput of the FD, HD, and hybrid modes for different values of χ.

It can be seen in Fig. 4.14 that the hybrid scheme achieves the highest throughput for the entire range of χ. In particular, when $\chi \leq 3.43 \times 10^{-4}$, SIS is very effective and most of the TRs operate in the FD mode. The hybrid scheme achieves the same throughput as FD, which is higher than that of HD. As χ is increased, the advantage of FD transmissions diminishes and HD begins to achieve higher throughput than FD. When $3.43 \times 10^{-4} \leq \chi \leq 1.3 \times 10^{-3}$, some TRs operate in the FD mode and some others in the HD mode. When $\chi \geq 1.3 \times 10^{-3}$, all the TRs operate in the HD mode since the residual SI is so strong, there is no benefit for using FD transmissions. The proposed hybrid scheme compares the gains of FD and HD, and always chooses the better operating mode to achieve the highest throughput for the entire range of χ.

Finally, we investigate the impact of noise level. In the simulation, we set χ to 0.0005 and increase the noise power σ^2 from $10^{-6}W$ to $10^{-3}W$. The throughput results for the three schemes are presented in Fig. 4.15. As expected, the hybrid scheme achieves the highest throughput among the three, and the throughput decreases when noise is increased

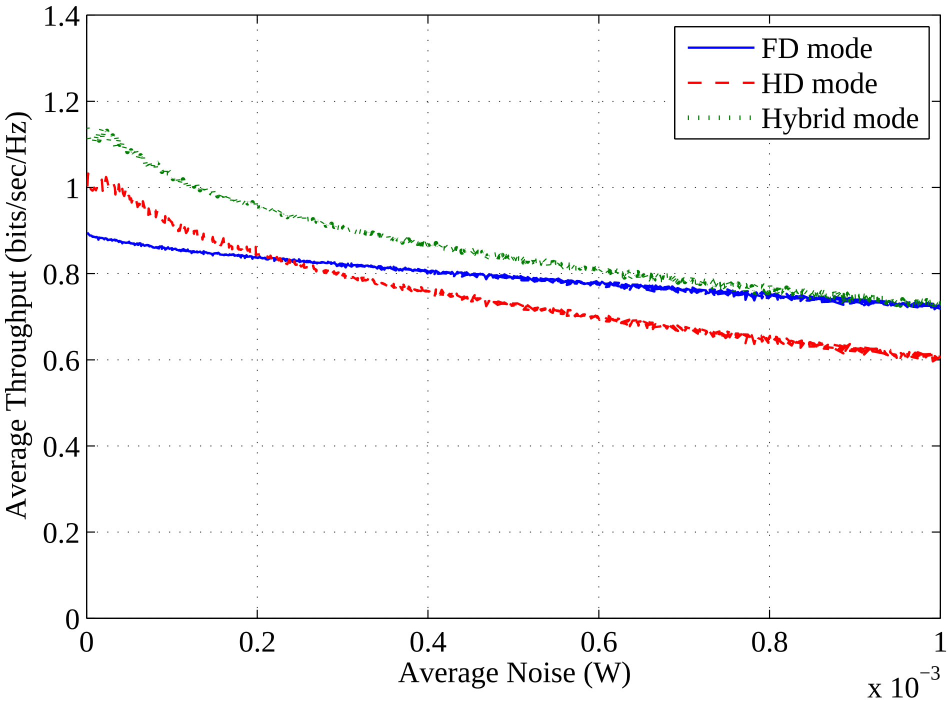

Figure 4.15: Average throughput of the FD, HD, and hybrid modes for different values of σ^2.

for all the three schemes. However, the influence of noise on throughput is different for the three schemes.

As shown in (2.6), the FD mode has one extra interference source, i.e., the residual SI, making it less sensitive to the varying noise power. This is why the throughput of HD decreases faster than FD. The hybrid scheme can use FD instead of HD even though the χ value is larger in this simulation. The hybrid scheme always achieves the highest throughput in all the scenarios simulated.

Chapter 5

Conclusions and Future Work

5.1 Conclusion

In this paper, we investigate the design of effective power controllers for single channel underlay CR networks, where FD transmissions are exploited to improve the network capacity. Taking the SIS factor into consideration, we investigate the design of a PID controller and a hybrid FD-HD scheme to achieve the dual goals of PU protection and SU QoS provisioning. The stability performance of the proposed scheme is analyzed and evaluated with simulations.

In the previous chapters, we developed a hybrid mode power controlled transmission system over underlay CR network, which enables SUs achieving optimum throughput while remaining undetected from CR PUs. Our research includes PID controller design, network optimization, performance analysis and simulation validation.

In the begining of Chapter 2 we explicitly stated our system, which is very practical in reality. In the following, we also discussed the problem, which is a underlay CR network based power control and throughput optimization quest.

Then, we designed our general PID controller in Chapter 3 to control transmission power in order to gain optimal throughput. However the PID controller could not guarantee the control systems stealth ability, so we set a constraint to every power adjustment to enable such function.

Then, during researching on our system, we analyzed the stability of the system. Meanwhile we found simply using FD or HD mode would not provide us with optimal performance, or in another word, throughput. So we also tackled with this more challenging problem and found the tuning point of the two modes. Finally we combined our former proposed system with the hybrid mode to gain a better throughput than any of the former two modes.

In the end, we had lots of detailed and accurate simulations under different environments in Chapter 4. The results which has been shown by the results suggested both stability and undoubtable superior performance of our system.

5.2 Future Work

Although our proposed system has already shown considerable advantages comparing to original CR network, there are still many topics to be explored which can make our system even better. For example, maybe we could design an optimization algorithm to allocate the transmission power for each SU to gain a even better, organized overall throughput; We could also do more work on the constraint, which may degrade the performance of PID controller. The optimization and the reestablishment of constraint could even be studied together to create a dynamic condition which assures better efficiency of the system.

Also, certain validation may still be needed. Since we have only simulated the system using software, the real performance may not be guaranteed. Thus, further verification like testbed based hardware simulation should be performed in order to check the availability in reality. Throughout the booming development of FD hardware, testbed validation which is much more convincing should definitely be our next target.

Last but not the least, our proposed system shows some potential ability of combining with other technology. For instance, relay network, which need fairness as well as optimal throughput. The problem of general optimization we've mentioned before could be studied together with relay network and may generate some interesting tradeoff during researching.

If such kind of tasks we have listed before can be accomplished, we are sure that the system will present an even better availability and efficiency.

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