6CCS3EEP Final Year
Cognitive and Full Duplex Radio for 5th generation wireless networks

Final Project Report

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Abstract

Future communication devices, and specifically 5G devices are expected to accommodate very high data rates and great quality of services to the users. The capacity of wireless channels is fundamentally limited by the amount of available frequency spectrum. In-band full duplex communication can potentially increase substantially the available frequency band that can be used by each user/device. This project combines full duplex and cognitive radio technologies for improving throughput of telecommunication networks with the generation of precoding matrix to cancel out interferences in the Beamforming design model.

Originality Avowal

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Contents

Abbreviations

5G Fifth-Generation.

ADC analog-to-digital conversion.

CR Cognitive Radio.

CRN Cognitive Radio Networks.

DOFS Degrees of Freedom.

DSA Dynamic Spectrum Access.

DSP digital-signal-processing.

DWN Down-link.

FCC Federal Communications Commission.

FD Full-Duplex.

FD-CRN Full-Duplex Cognitive Radio Networks.

FDD Frequency division duplex.

HD Half-Duplex.

IBFD In-Band Full Duplex.

IT Interference temperature.

MIMO Multiple-input and Multiple-output.

PRE Precoding Matrix.

PU Primary User.

QoS Quality of Service.

RF Radio Frequency.

S-BS Secondary Base Station.

SIC self-interference channel.

SLC Self-interference cancellation.

SNR Signal-to-Noise.

SU Secondary User.

TDD time division duplex.

UP Up-link.

Chapter 1

Introduction

1.1. Background and Motivation

With the world moving towards digitalization, there has been an exponential growth to the number of mobile and cellular networks. This led to a resulting increased number of global mobile traffic. It is predicted that in 2019, the number of global mobile traffic would be ten times the amount it was in 2014[1]. Frequency spectrum or specifically radio spectrum can be seen as a natural finite resource like oils or forests but in the case of radio spectrum they can be reused. Wireless radio spectrum occupies the frequency bands from 3Hz to 3THz. Electromagnetic waves in this frequency range are called radio waves. Radio spectrum are widely used for modern telecommunications and other modern technologies. There's a finite amount of them and they must be managed effectively and efficiently to avoid interferences between users. Fig.1.1 shows a fraction of the United States frequency allocation in 300Hz to 300GHz of the Radio Frequency (RF) range exhibiting the extent in which the frequency spectrum is already heavily congested by its allocation. As stated previously there exists a limited number of available spectra frequency bands in nature. Thus, making the spectrum an extremely valuable resource. In 2014, the Federal Communications Commission (FCC) held the US spectrum auction and generated $44.9 billion US dollars, with Verizon Communications Inc, AT&T Inc and T-Mobile US as the lead bidders. With 5G technology looming around the corner, certain upgrades and changes has to be made to existing systems to cope with the unprecedented growth of wireless devices.

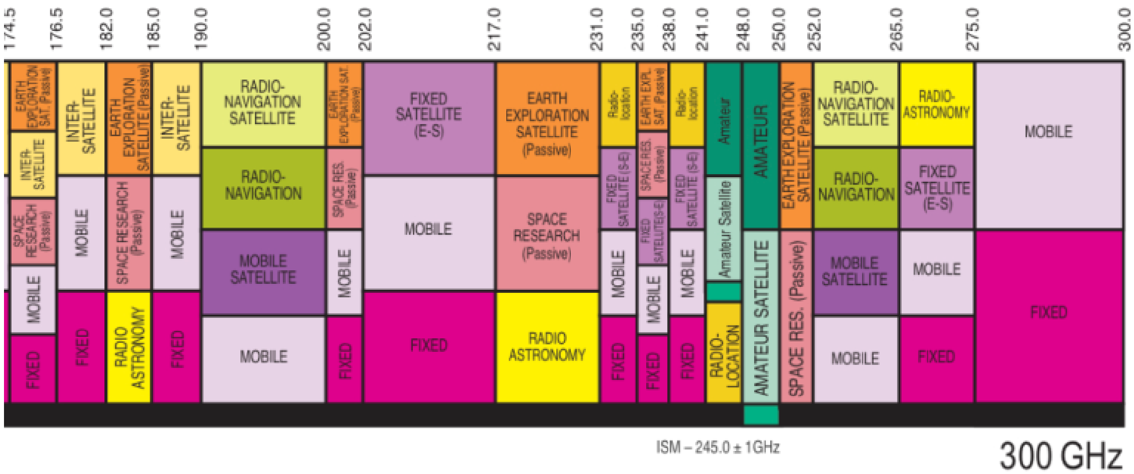

Figure 1.1: RF Spectrum Allocation from 3 kHz to 300 GHz, Source: U.S. DEPARTMENT OF COMMERCE National Telecommunications and Information Administration, Jan 2016

Today in a world that we cannot function with smart phones assisting us in our everyday lives; leading to the growth of the number of smart devices being massive over the recent years. To put the growth into perspective, Fig.1.2 shows the projected number of devices that is connected to the Internet to the year 2021. In addition, not only is the number of devices connected to the Internet expected to grow exponentially, but the amount of data usage is also expected to grow. In 2016 alone, the mobile data traffic increased by 63% according to Fig.1.3, which shows the projection of increasing mobile data traffic per month to the year 2021.

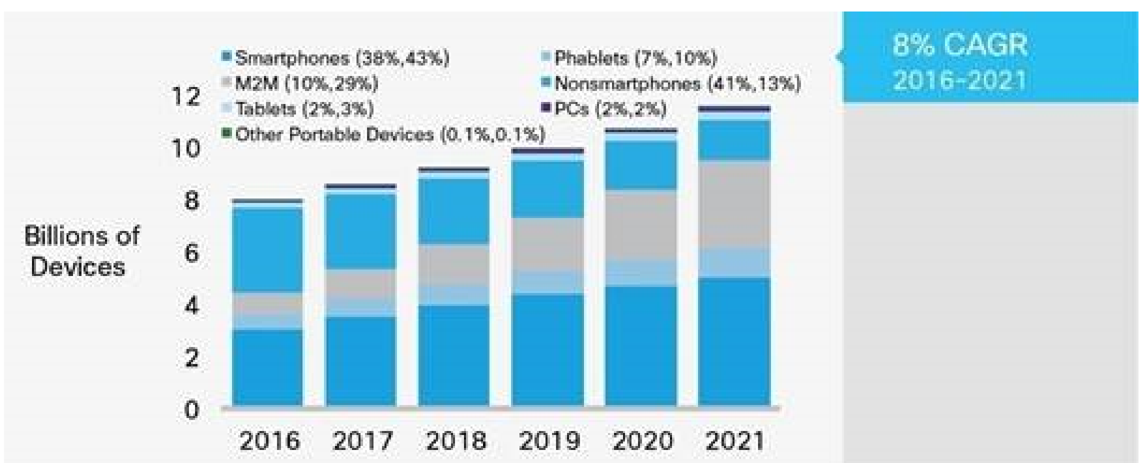

Figure 1.2: Global Mobile Devices and Connections Growth, Source: Cisco VNI Mobile, 2017

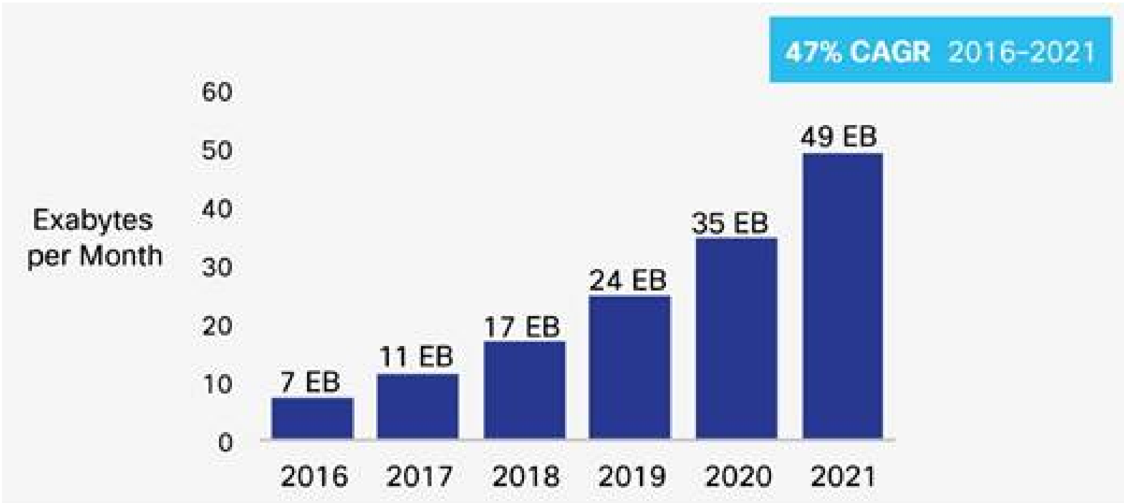

Figure 1.3: 49 Exabytes per Month of Mobile Data Traffic by 2021, Source: Cisco VNI Mobile, 2017

To keep up with the rising demand for better connectivity and increasing data transmission rate, increasing works have been done towards technologies such as the Cognitive Radio Networks (CRN) and the Full-Duplex (FD) technologies. CRN enhances spectrum utilization by using Dynamic Spectrum Access (DSA) in order to be able to obtain better spectrum efficiency allocation. Meanwhile, Full-Duplex allows transceivers to simultaneously sense and transmit. However, to perfect these technologies, a variety of problems that will be discussed in the literature review must be addressed. If successful, perfecting these technologies have revolutionary outcomes for the world. Utilizing Full-Duplex (FD) in CRN would eliminate problems existent in current available systems, making the technology more efficient. Full-Duplex (FD) allows Cognitive Radio Networks (CRN) to be able to sense and access the channel. Therefore, the Full-Duplex Cognitive Radio Networks (FD-CRN) users would utilize higher spectral efficiency and increase network capacity. Together, these technologies combined would improve the throughputs as we move towards Fifth-Generation (5G) technology and beyond.

There many potential solutions to achieve a more efficient spectrum utilization as well as better quality throughputs. The first approach is the sharing of licensed bands and unlicensed bands by primary and secondary users. The second approach is related to wireless transmission technologies, such as the Multiple-input and Multiple-output (MIMO) or interference suppression technologies. Out of these technologies Cognitive Radio Networks (CRN) and Full-Duplex (FD) stands out as feasible and potentially prospective ideas for future wireless communications. There already exists a vast amount of research into each of the approaches being used exclusively on its own. These technologies, however, do not oppose each other. Therefore, it is potentially seen as possible to combine these technologies essentially receiving benefits from both technologies. As a result, this project aims to explore the possibility of combining these technologies together, all with the aim of achieving better throughputs and a more efficient spectrum utilization.

Moreover, further literature reviews regarding both technologies can be accessed in Chapter 2. The system model Beamforming Design developed described in Chapter 3 combines Cognitive Radio Networks (CRN) and Full-Duplex (FD) which benefits from efficient spectrum utilization and lower latency due to simultaneous Up-link (UP) and Down-link (DWN). Both FD and CRN are seen as potential the future of wireless communications[2][3]. The information provided in this project will make contributions in helping accommodate the increasing number of users, as well as potentially aiding provision of faster wireless communications.

1.2. Structure of Project

Chapter 1 outlines the introduction, abstract, backgrounds, aims and motivation of the project.

In Chapter 2, in-depth literature reviews on Full-Duplex (FD) and Cognitive Radio Networks (CRN) is carried out; this includes the technologies' brief history, existing works, applications, benefits and overview.

Chapter 3 includes a Beamforming Design system model developed that combines both technologies and negates the interference levels making an acceptable throughput for both PU and SU. Literature reviews of other technologies used in conjunction with the two technologies such as the Precoding Matrix and Multiple-input and Multiple-output (MIMO) as well as the channel state will also be put into context and explored.

In Chapter 4, an analysis and evaluation of the simulations is carried out. Furthermore, comparison of the simulations to existing technology of HD-CRN is also undertaken.

In Chapter 5 conclusions and future work is discussed, along with potential research topics is proposed.

Chapter 2

Literature Review

2.1. Full-Duplex

"It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results." (Andrea Goldsmith, Wireless Communications[4])

The above quote is an assumption that has loomed over wireless communications in the past. Consequently, all radio wireless communications systems were therefore designed for Half-Duplex communications. This means that transceivers can only either receive or transmit, not simultaneously do both using the same frequency band. Most wireless communications today either employ HD or out of band FD modes, where they transmit and receive at different times using time division duplex (TDD) or different frequencies bands through the Frequency division duplex (FDD). However, both FDD and TDD have its own problems where TDD requires double time slots, which requires extremely precise timing and a synchronization system to make sure they do not overlap. Whilst FDD requires two different frequency spectrums which are valuable resources. On the other hand, in-band FD allows transmission and reception to happen simultaneously within the same frequency band.

The concept of FD first arose and was in use during the 1940's. Initially, the first implementation of the technology was for relaying, where constructing a wire line back-haul was difficult due to technological and geographical difficulties, as well as a need to increase coverage. Passive self-interference cancellation techniques such as antenna separation were used. FD is also widely used in Continuous wave (CW) radar systems in the 1950's. Here, one antenna was used for both transmitting and receiving in the same frequency channel. Furthermore, antenna separation techniques were also used along with reduction in transmitting power to reduce self-interference. However, by reducing the transmit power, the range in which the radar would be able to communicate also decreases. Therefore, they are only suitable for shorter range usage.

In-Band Full Duplex (IBFD) has only gathered attention recently when research and works had been done on the topic and has proven the above assumption that self-interference can be suppressed to be wrong. Many researchers have looked into the topic and have successfully developed in-band full duplex(transmit and receive simultaneously within the same frequency band) communication systems through various techniques. Although significantly more work has to be done before they can be used in real practical systems, the fact that in-band Full-Duplex systems is feasible and can be implemented sheds light on its significance and potential. In-band FD systems could double the spectral efficiency compared to its HD counterparts, whilst improving speed due to the fact that waiting for transmissions to be completed is no longer required. Moreover, other benefits achievable from in-band full duplexing is outlined below.

Benefits of Full Duplex

Several benefits of Full-Duplex are as follows:

- More efficient use of Time and Frequency Resources: The transceiver will be able to send and receive data simultaneously in the same frequency band. This is because IBFD doubles the link capacity as compared to HD systems.[5]

- Fading Characteristics: Sending and receiving will use the same frequency channel, meaning that they will have the same characteristics of propagation and fading. Therefore, wireless communication systems would be easier to manage as they can be predicted using more similar models.

- Filtering: In HD, more bands were required to be used. Therefore, the amount of filters required to filter the data also increases. This increases the amount of data loss and the likelihood of a drop in performance. In full duplex, less filters will be required. As a result, a it's a more likelihood in the data loss and there's more chance of a drop in performance.

- Hidden Terminal Problem: As FD communication enables sensing and transmission to be undertaken at the same time, the hidden terminal problem is solved. For example, at an access point with many users; when one user starts transmitting data to the access point, the AP can now transmit back simultaneously to the user. Therefore, other nodes would receive this information that data is being sent to the AP. Consequently, it stops trying to send data of its own to avoid any possible collision.

- Improved throughput: The throughput of FD communication could, in theory, double the rate of throughput of HD communication system.

- FD in Cognitive Radio: FD mode enables SU to look for available spectrum, while transmitting by sensing the PU's transmission. This would reduce the chance of collision and the interference on PU's transmission caused by SU's transmission improving the throughput.

- End-to-end delay: Transmission in communication system with relay would reduce the delay time. This is because the relay node can now simultaneously receive and transmit data to its destination at the same time as supposed to waiting for all data packets to be transferred.[6]

- Enhanced system security: As data will be simultaneously sent in both directions in the same channel, eavesdropping would be more complicated as the third party trying to decode the data would experience the superposition of two signals. [7]

The main reason why IBFD is not currently used in today's wireless radio network is due to when a transceiver experiences self-interference. Self-interference happens in full duplex as data is being transmitted and received in the same carrier frequency, which causes the received signal to interfere with the transmit signal. In other words, it is similar to trying to hear one person's whisper whilst another is shouting at the top of their lungs. Numerous studies and research have been carried out on self-interference cancellation, where sophisticated techniques have been introduced and tested. Out of all the techniques, the most successful one combines all the techniques in order to try and achieve total self-interference cancellation, ranging from antenna cancellation, analog cancellation to digital cancellation techniques and more. In order for a perfectly functioning full duplex radio system to be implemented, total self-interference cancellation must reach a certain point. For example, WiFi is transmitted at 20dBm and is given an average noise floor of about -90dBm, which means that a total of 110dB(20dBm-(-90dBm)) noise has to be suppressed[8]. If self-interference is not canceled or suppressed to a certain degree, the remaining self-interference would intervene with the received signal, acting as a noise. As a result, the Signal-to-Noise (SNR) ratio would decrease, reducing the quality of the throughput of the system. Fig.2.1 shows 2 transceivers in IBFD mode that are experiencing self-interference signals stronger than the desired received signal.

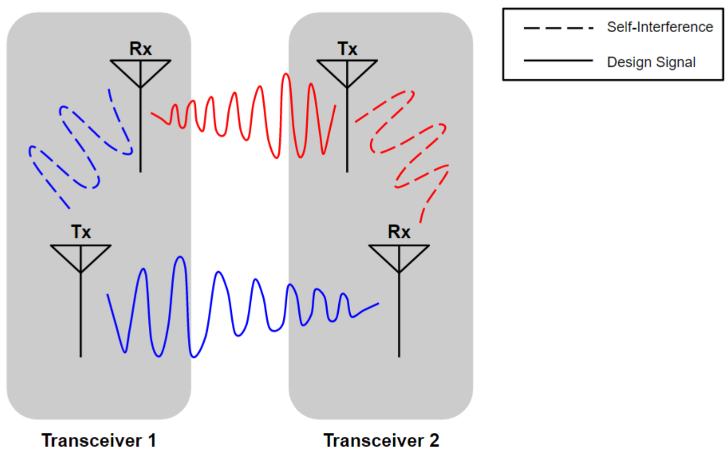

Figure 2.1: Self-interference Illustration

Self-interference cancellation (SLC) techniques that are researched as a part of FD can also be used for solving problems in half duplex systems. This suggests that these techniques can be implemented now onto current systems without needing to change the standard modifications. However, in order for full duplex to be employed in cognitive radio, certain steps in modifying the existing infrastructure must be taken to achieve full duplex mode. Fig.2.2 shows the application of full duplex into the current system, 5G and beyond 5G. The figure 2.2 shows SLC applications where some can be implemented without the need to modify current half duplex infrastructures.

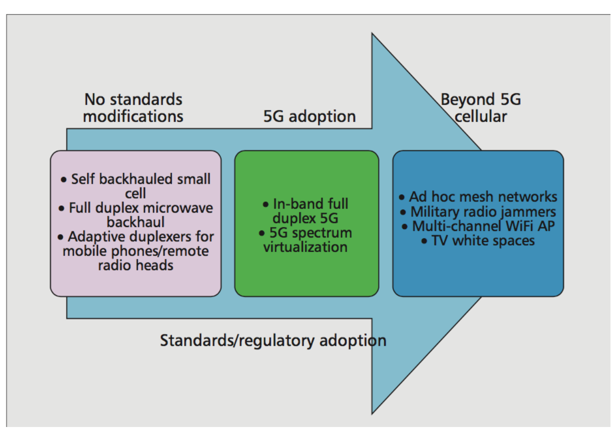

Figure 2.2: Self-interference-cancellation applications[9]

2.1.1 Self-Interference Cancellation Techniques

Using Full Duplex has not been popular until recently due to self-interference in transmitting and receiving in the same channel. Therefore, in order to employ FD, self-cancellation techniques have to be perfected to the point where self-interference is reduced to an acceptable level.

Self interference cancellation techniques can be classified into two major categories of:

- Passive techniques: these include techniques such as antenna separation and shielding the receiver from the transmission at the Full Duplex radio. The main purpose of the technique is to try isolate and shield the receiver from the transmitter antenna.

- Active techniques: these consist of analog and/or digital domain cancellation. These techniques aims to suppress self-interference in the analog receiver circuitry-chain before the Analog-to-Digital conversion. Contrastingly, in the digital domain, the aim is to suppress self-interference after the Analog-to-Digital conversion through the use of sophisticated signal processing schemes.

As for the actual techniques of self-interference cancellation, the three main types are propagation-domain, analog-circuit domain and digital-domain approaches. It is significant to acknowledge that most Full Duplex uses combinations of all techniques to try to suppress self-interference to the point where the Quality of Service (QoS) is acceptable.

Propagation-domain Self-interference Suppression Propagation-domain SI cancellation schemes attempts to separate the transmit and receive chain by using electromagnetic properties. In other words, trying to overcome self-interference before the signal returns back into the receiver. The primary advantage is that the receiver does not need to process signals with large dynamic ranges. This is done using a combination of path loss from antenna separation, cross-polarization and antenna directionally for separate antenna systems[10]. In contrast, shared antenna-systems depend on the use of a circulator. In the separate antenna system, path loss techniques are implemented by spacing the IBFD terminal's transmit and receive antennas apart with absorptive shielding in between them. However, the drawback of this technique is the device-form factor, meaning that if the device is too small, there is less room to implement the technique. For example, it is hard to implement this technique with modern hand-held devices, which are getting increasingly smaller in size. In the cross-polarization technique, the IBFD terminal will for example, only transmit horizontally polarized signals whilst only receiving vertically polarized signals. Therefore, resulting in different paths of the signals, leading to less interference and collision of the signals. Moreover, the IBFD terminal's antenna directionally aims to align the transmit and receiving antennas' null directions in order to achieve the same goal as cross-polarization. For example, placing the receiving antenna where the carrier waveforms are 180 degrees out of phase from the transmit antenna. Hence, canceling the self-interference signals. Nevertheless, a drawback for the propagation-domain self-interference suppression techniques is that they might also unintentionally reduce or cancel the desired received signals, as well as the self-interference. Additionally, although the techniques are effective when dealing with direct-path self-interference, their potential in dealing with reflected self-interference may be negated as their characteristics are unknown when the system is designed.

Analog-circuit-domain Self-interference Cancellation In the analog-circuit-domain cancellation techniques, self-interference is suppressed by the subtracting the self-interference signal with the transmit signal's knowledge acquired from the transmitter[11]. A copy of the transmit signal is taken from the transmitter and adjusted so that subtraction can occur with regards to the signals' delay, phase and gain. The drawback for tapping signals close to the antenna is that it requires analog-domain signal processing, which is difficult to implement in the presence of wide-band reflected-path self-interference. Regarding the adjustment of the transmit signal technique, the drawback that exists is that its cancellation precision is limited by the downstream analog-circuit.

Digital-domain Self-interference Cancellation The digital-domain self-interference techniques attempts to cancel self-interference after the analog-to-digital conversion (ADC) by utilizing digital-signal-processing techniques to the received signal[10]. It is usually implemented last after all other self-interference cancellation techniques. However, its drawback is that the ADC's dynamic range limits the amount of self-interference that can be reduced.

2.2. Cognitive Radio

Cognitive Radio (CR) is described as: "A radio that changes its transmitter parameters based on the interaction with its environment" according to [12]. It is a radio that can be configured to ensure that its usage can be optimized in the best wireless channels, to avoid or suppress users experiencing interference and traffic congestion. Its main objective is to find the best available channel for unlicensed users to use. This is done by sensing channels to see whether the licensed user is using the channel or if it is vacant. The vacant spots in the spectrum that CRN detects are called white space or spectrum holes. CR follows a White Spectrum Exploitation cycle, where it senses the available spectrum in the white space and makes a decision whether it can use the spectrum as well as identify the best available spectrum to use. If available, the system will coherently utilize that spectrum. It also makes sure that it doesn't collide with other users seeking to employ CRN through spectrum sharing.

In other words, CRN allows unlicensed users to have access to the licensed frequency bands when it is not currently in use by licensed users. It utilizes the process of Dynamic Spectrum Access (DSA) that is a spectrum sharing paradigm allowing secondary users to access spectrum holes or white spaces in licensed bands [13]. To further clarify this, specific terms used in this section are elaborated as follows:

Types of frequency bands

In the RF frequency range the frequency bands are often classified into 2 main categories of

- **Licensed bands**: These types of frequency bands requires paid fees in order to secure exclusive rights to specific frequency bands. As a result, others would not have access to using the band without permission. It also ensures that there is no interference from other wireless networks.
- **Unlicensed bands**: These types of frequency bands are not for sale and has been intentionally left out from auctions. They are usually used for low-cost communication such as Wi-Fi at approximately 2.4GHz. These bands may experience larger interferences due to a large user base competing for bandwidth within these bands.

Types of Users in CRNs

The two types of users in cognitive radio are as follows:

- Primary users(PUs): Users who possess a higher priority or legacy rights on the usage of a specific part of the spectrum.

- Secondary Users(SUs): Users who possess a lower priority and seeks to exploit the spectrum in a way that it does not cause interference to primary users.

When CRN detects a white space it allows SUs to access the spectrum. However, during its transmission, it would still sense the spectrum to check whether the PU will start to transmit during the SU transmission. In the case that the PU starts transmitting during the SUs transmission, the SUs would leave the spectrum to avoid interference for PUs and proceed to transition into a new white space. This is illustrated in Fig.2.3 below. The CR should also be able to detect the interference level the PU is experiencing due to the Underlay Paradigm (to be discussed further in the literature review), where SUs can still transmit simultaneously with PUs as long as it is not causing PU's throughputs to be unacceptable due to high interference levels.

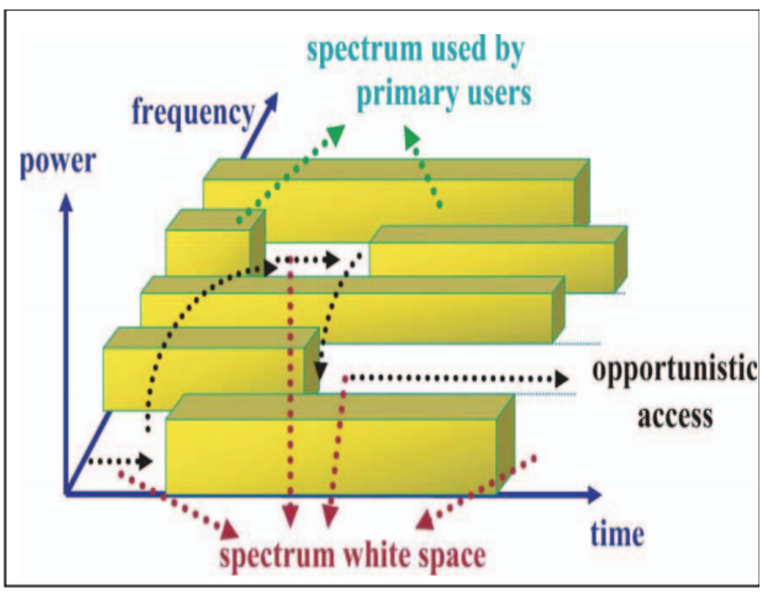

Figure 2.3: Cognitive Radio spectrum sensing, Source:[14]

CR concept was proposed in a seminar held at the Royal Institute of Technology(KTH) by Joseph Mitola III in 1998. With the potential of the technology presenting a better and more efficient way of managing the wireless spectrum's limited resource. It was later published in an article by Mitola and Gerald Q Maguire Jr in 1999, where they described it as “The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.”[15]. The first cognitive radio IEEE 802.22 was developed by the IEEE 802 LAN/MAN Standard Committee in 2011. It uses geolocation and spectrum sensing to find opportunistic spectrum. The main motivation behind the CR technology is the inefficient spectrum utilization usage problem. Fig.2.4 shows a spectrum utilization diagram where some frequency bands were heavily used, some with medium use where the remaining bands are unoccupied.

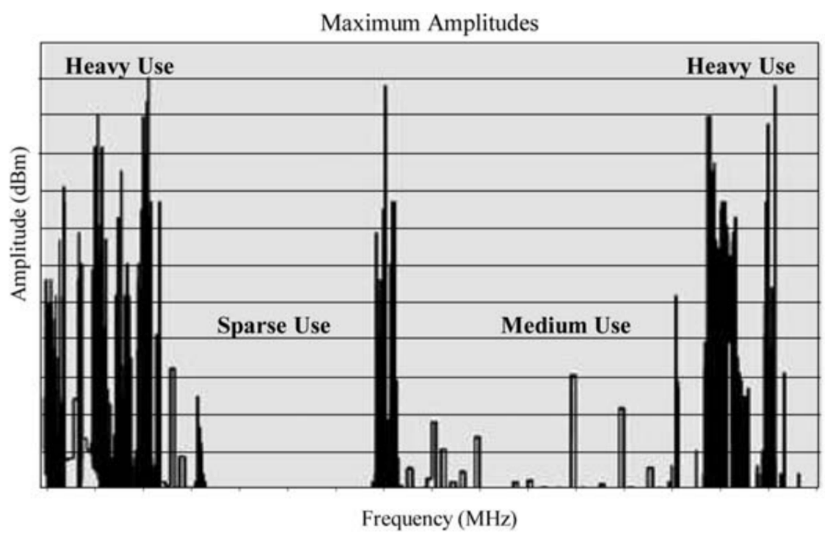

Figure 2.4: Frequency Spectrum Utilization, Source:[16]

2.2.1 Cognitive Radio Network Paradigms

There are three main types of CRN Paradigms:

- Underlay approach: SUs transmit simultaneously with PUs, as long as the interference sensed by the PU remains acceptable and does not exceed the interference temperature limit(IT) defined by the Federal Communications Commission (FCC), which is the limit the PU's receiver can still reliably sense regardless of the SU's simultaneous transmissions. In this approach the cognitive radio user must be able to detect the interference level at the PUs.

- Overlay approach: In this approach, SUs assist the PUs transmission rather than taking the spectrum for its own transmission. It helps improve the PU transmission by overhearing it and aiding cancellation of interference, or relaying the message to the PU receiver to improve the performance. The SU will transmit the same information with the PU, along with its own signal to relay the message. As a result, reducing interference from primary receiver and secondary transmitter.

- Interleave approach: This approach was developed to attempt to utilize the unoccupied spectrum holes by non-cognitive radio users from both the unlicensed and licensed bands. The white space should be monitored and predicted to see which spectrum is available at that time. This paradigm originates from the original idea for cognitive radio that spectrum are not efficiently used according to the FCC.

Moreover, hybrid techniques of combining the paradigms above have also been proposed, maximising the transmission rate when available spectrum is detected[17].

Spectrum Sensing

In CRN, SUs should be able to sense PUs to see whether they are transmitting or idle, as well as identify their interference level. So that the SUs can act accordingly based on the information received from the PUs. This is considered the core of the CR technology, as it enables secondary users to take advantage of available white space. The different types of spectrum sensing are outlined as follows:

- Energy Detection: SU analyses the received signal's energy from the PU. If the energy received is more than the threshold, it can be assumed that the PU is transmitting. In contrast, if the energy sensed is less than the threshold it can be assumed that the PU is idle and that frequency spectrum is available for the SUs to use. With that being said, the threshold value is different for each individual system, as it is calculated from the conditions of the channel which will vary with different systems. It is known to be the most common type of spectrum sensing due to its simplicity in implementation and low computational requirements.[18] An ON/OFF energy based sensing approach was developed in [19], where multiple antenna types were used in conjunction with hybrid self-interference cancellation techniques.

- Matched Filter Detection: Matched filter requires prior knowledge of the PUs signal, as it will be used as a comparison to the received or sensed signals to analyse whether the PU is transmitting or idle. This method of spectrum sensing is the best type of PU sensing if the signal transmit is known beforehand[20]. The advantage of matched filter is that it requires less time to obtain high processing gains compared to other techniques. However, it requires flawless knowledge of the PU signal modulation, bandwidth etc. which can be hard to simulate given the nature of the channel fading and noise.

- Cyclostationary: In cyclostationary spectrum sensing, the cyclostationary characteristics of the received signal will be analysed. These characteristics include the mean, periodicity and the autocorrelation of the signal. These characteristics of the signal will provide an insight to aid SUs in differentiating the signal from the noise in order to decide whether the PU is transmitting or idle[21].

The table2.5 illustrates the advantages and disadvantages for each spectrum sensing technique.

Spectrum sensing techniques	Advantages	Disadvantages
Energy detection	Does not require any prior knowledge about the PU signal so it is easy to implement.	Difficult to differentiate the signal types.
Matched filter detection	Short time is required to achieve probability of false alarm and high gain.	Require prior knowledge about the user and it consumes more power.
Cyclostationary feature detection	It can easily differentiate the signal types and the hidden PU problem can be minimized by high probability of detection	Require partial information about the primary user and high implementation cost.

Figure 2.5: Spectrum Sensing Techniques comparison. Source [21]

Network Architecture

In terms of the spectrum sharing network architecture of CR, the two main types are 'Centralised Sharing' and 'Distributed Sharing'. Their characteristics, advantages and disadvantages are as follows:

- Centralised Sharing: This is when there is a central control where all CR nodes send their information to. The central control creates an allocation map that makes it able to allocate the spectrum to the nodes without collision. An advantage of this is that it makes optimal decisions through the overall knowledge of the network. Moreover, it is fair as it allows all SUs to be prioritised equally. Nonetheless, it is also able to prioritise individual most important SUs. However, a drawback is that there exists high signaling between the SUs and the spectrum server. Furthermore, it is also vulnerable when the spectrum server is down[22].

- Distributed sharing: This is when each SU decides and chooses spectrum allocation and access by itself or in cooperation with other SUs. There is no central control for allocating spectrum in this scheme. The benefits are that spectrum allocation will generally be faster so they can adapt quickly to network failures. However, the drawbacks are that the decisions SUs make will not be optimal. Furthermore, it is difficult to obtain fairness between the SUs[23].

2.2.2 Cognitive Radio Applications

Wireless Sensors Network

CR capabilities will be extremely useful in dense network environments such as a sensor networks to reduce interference. Hospitals or homes for elders requires simultaneous sensors to monitor the well-being of individuals. Otherwise, delays or interference can cause an unacceptable consequences. In addition, with the Internet of Things(IoT) increasingly receiving attention, devices and household appliances will have access to the Internet which increases the network congestion even more[24].

Public Safety Networks

With the spectrum allocated to public safety use being increasingly congested in urban areas[25] as compared to rural areas, there is a higher probability of accidents happening. Due to the nature of the wireless communication for emergency providers (such as police and fire stations) being arguably the most important for quick response and problem solving, CR allows the increased spectrum efficiency in SUs ability to access licensed bands in cases where the regulated spectrum for public safety may be full. Moreover, video surveillance cameras and sensors play an important role in ensuring public safety. However, their ability to wirelessly communicate data back to safety service agencies may not always be reliable in terms of delay and outage depending on the service the tools were using and their allocated spectrum.

Cellular Networks As mentioned earlier with the increase in amount of traffic congestion especially in cellular networks, not only does the amount of users increase, but the amount of data each in which user uses has also increased. This is primarily due to the growing popularity of social media platforms such as Facebook and Youtube, which allows users to upload and download larger data such as viewing higher quality videos. CR presents a more efficient frequency spectrum usage. Other emerging uses of CRN is explored in [26] such as its potential uses in the smart grid networks and wireless medical networks.

2.3. Full Duplex Cognitive Radio

As stated in previous sections, FD and CR technologies are both promising technologies that have potential to replace existing wireless communication systems, evidently in [27][28]. They both have the ability to enhance spectrum allocation and utilization more efficiently. Other benefits of employing FD in CRN will be explored later in the section, providing reasons and motivations to combine the two technologies. Currently, there exists research on employing HD in CRNs [29][30] which can potentially be upgraded to FD. Most existing works attempts to detect and avoid collisions between PUs and SUs using FD to continuously sense the throughput throughout transmission in the interleave paradigm. For example, [31] proposes a way in which SUs can scan for PUs whilst transmitting using cancellation techniques such as antenna cancellation and RF Interference cancellation. [32] proposes the SU's modes of 'transmit sense mode' and 'transmit and sense simultaneously' to determine the state of the primary user in the interleave scenario. Similarly [33] tries to achieve this using directionality of multi-reconfigurable antennas.

Most CRN nowadays use HD which results in two main problems. Firstly, users cannot simultaneously sense and use the spectrum as it is in HD mode. Therefore, a very precise and accurate spectrum sensing has to be employed, as an error in this department could allow SUs to transmit and interfere with the PU's data transmission. As a result, HD-CRNs users would have to use the valuable spectrum of time for robust spectrum sensing to make sure this does not happen. Consequently, leaving a smaller time slot for the actual data transmission. Secondly, as mentioned previously that spectral space is very valuable, HD-CRN systems require two separate spectral channels, one for transmission and one for receiving. Moreover, there will also be more latency time for HD-CRN, as two channels in the white space has to be detected for white space exploitation. Furthermore, HD-CRN devices utilize two separate/orthogonal channels for data transmission and reception. This two-channel operation not only requires more valuable spectral resources than a single-channel operation, but also increases latencies as two channels need to be sensed for white space exploitation. Therefore, to address existing problems of HD-CRNs, the Beamforming Design developed in Chapter 3 proposes an upgrade to the current HD-CRNs by employing FD mode into CRNs. Comparisons of the new design to existing HD-CRN will also be made in terms of PU and SU transmission (of information) rate in Chapter 4 of the project. Other benefits of FD-CRNs are listed in the following subsection.

2.3.1 Benefits of Full-Duplex in Cognitive Radio Networks

The benefits of employing FD in CRN are as follows:

- As compared to HD-CRN, in the FD-CRNs, SUs will be able to sense PU's transmission simultaneously whilst it is transmitting with FD. Therefore, it can detect whether the PU's transmission is experiencing interference over the Interference temperature (IT) - where interference temperature is a metric for measuring interference proposed by the FCC.
- FD enables the CRNs to find available white spaces simultaneously while it is transmitting, which makes the system easier to shift to another white space.
- Transmissions of the SUs will not be interrupted by the need to stop transmission to sense the PU's state.
- Reduction of the chance in which SU's transmission interferes with one another.
- Improvement in security of data transfer, as signal jamming during data transmission with FD technology can be employed to prevent eavesdropping.

2.3.2 Challenges of Employing Full-Duplex in Cognitive Radio Networks

Although FD has been around for a very long time, it is yet to be widely used in real practical system given its benefits. The main challenges and problems to achieving practical FD-CRN system is outlined below.

1) Self-interference: Self-interference is defined as "the interference that a transmitting IBFD terminal causes to itself, which interferes with the desired signal being received by that terminal"[10]. The problem arises when a node transmits and receives data simultaneously in the same frequency band, causing the two signals to interfere resulting in an unwanted signals. For example, in the contemporary femto-cell cellular systems, femto base stations and mobile handsets transmit at 21dBm with the receiver having a noise floor (the measure of noise and unwanted signals within the system) of -100dBm. This means that any signal less than the noise floor cannot be taken with certainty. In this example, the base station's self-interference is illustrated in figure2.6)

$$21 - 15 - (-100) = 106\text{dB above the noise floor} \tag{2.1}$$

Therefore, in order to achieve a SNR(signal to noise ratio) equal to the HD, the system must

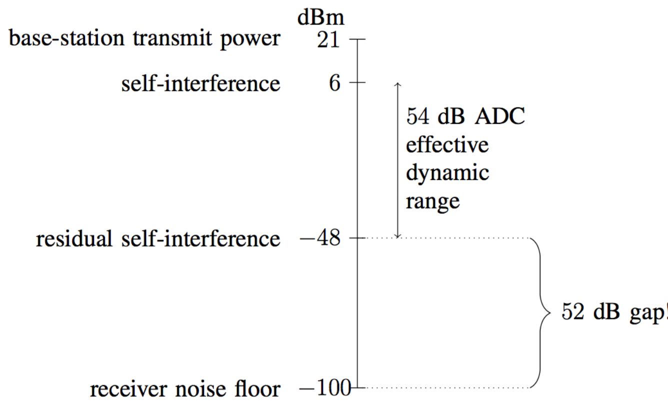

Figure 2.6: Limited ADC dynamic range produces a noise of 52 db above the receiver noise floor. Source:[10]

contain self-interference of over 106dB which is a very tough task to accomplish. Every system that utilizes FD will have to face challenges in self-interference and requires advances SLC (self-interference cancellation) techniques to overcome the self-interference.

2) Hardware Imperfections: In FD-CRN systems, imperfections in hardware could negatively affect the system greatly. It can also reduce the Self-interference cancellation(SLC) schemes in the system, causing the system to be unusable. For example, a non-linearity of a power amplifier in the FD-CRN system's transceiver could cause spectral regrowth of the output signal, causing Adjacent Channel Interference.[34] Adjacent-channel interference (ACI) is the interference caused by signals in other channels' excessive power.

3) Resource Allocation: FD-CRN systems require more power than HD-CRN therefore, resource allocation is complicated (especially with an increased number of antennas in transceivers).[35]

4) Communication Protocols: Most current communications still employ HD. Therefore, many hardware/software resources are required to be re-designed, such as the physical layer to support FD.[36]

5) Spectrum Sensing: FD-CRN requires continuous spectrum sensing. Therefore, spectrum sensing algorithms should be redesigned to support FD.

2.3.3 Case Study of Existing FD-CRNs

In this section, existing FD-CRNs studies are showcased to outline FD-CRN's capabilities to be used in many contexts, ranging from D2D (Device-to-Device) to Cellular networks systems. Although FD-CRNs have shown its capabilities in doubling the spectral efficiency and the throughput, in practical systems the capabilities decrease due to imperfect self-interference cancellation and other real-life factors not shown in the simulations.

Device-to-Device FD-CRNs

In [37], D2D and FD-CRN were used jointly. In the study, D2D link underlays the FD-CRN link in secondary networks, while the D2D transmitter is used as a FD-CRN node to help increase throughput quality in the transmission between secondary users. The results simulated in the study were that the D2D communication with the help of underlaying FD-CRN improved the overall throughput of the system and reduced outage probability, as compared to traditional cognitive wireless networks.

Cellular Networks FD-CRNs

Secondary base station is proposed in [38], as it has FD capabilities to sense the spectrum allocation available from the primary spectrum whilst it transmits to secondary users. The study shows that power allocation is very important for the secondary base station, as it can affect sensing capabilities and transmission capacity. Therefore, the author combined the power allocation and spectrum management problem and came up with a proposed solution. The proposed solution in the study - shown through simulations - managed to increase the throughput of the secondary transmission of the secondary base station.

LTE and WLAN FD-CRNs

In [39], FD-CRN was introduced into LTE and WLAN unlicensed application. So, simultaneous transmission and sensing is possible, which increases the spectral efficiency of both communication systems. The study focuses on using cyclostationary spectrum sensing on the FD-CRN transceiver, as it will be affected by self-interference. The self-interference cancellation techniques used in the study combines both the analog and digital self-interference cancellation techniques. The results show that even without all the self-interference suppressed, the impact of the self-interference in the system is minimal when the secondary signal is 5dB more than the noise floor. Moreover, through simulations, it showed that the effect of self-interference can be reduced by reducing the bandwidth of the secondary signal and maintaining the power of the transmit signal.

Relay Network FD-CRNs

The [40] case study presented adaptive transmission scheme for relay networks that was used in three modes of HD, FD and direct transmission. Simulations have shown that the scheme managed to increase the throughputs as compared to traditional transmission.

2.3.4 Future Cognitive Radio Full Duplex Applications

1. Distributed Spectrum Access Scheme: PUs in the distributed spectrum access scheme in FD-CRN are no longer ”blind” to SUs when the SUs are transmitting data. This is because the SUs can detect in real time the changes of PUs and other SUs at all times, and when there is potential collision the SU can withdraw immediately before transmitting the whole packet of data.

2. FD MIMO systems: With this having separate antennas for sensing transmission and reception, FD MIMO systems can support bidirectional communication. Consequently, reducing collisions which cause self interference. It is worth acknowledging that the Beamforming Design proposed in Chapter 3 also incorporates MIMO in its design.

Chapter 3

Beamforming Design for Cognitive Radio Full Duplex System

3.1. Motivation and Objectives

As previously stated in Chapter 1, to accommodate the increasing the number of users as well as improve quality of throughputs, existing technologies should utilize the frequency spectrum more efficiently. FD is seen to be the future for wireless communications. If CR were to be employed in the future, they would be most likely be in FD mode. Moreover, as there already exists many works on FD-CRNs in the interleave paradigm (as mentioned in Chapter 2), this project focuses on the 'underlay' paradigm that also shows to have great potential. As supposed to an 'interleave' case of cognitive radio where majority of research was on avoiding collisions between PUs and SUs through the use of proposed spectrum sensing, the 'underlay' case allows both PU and SU to use the spectrum simultaneously. In theory, this doubles the spectral efficiency and is seen to have great potential if accomplished successfully. As stated in Chapter 2's literature review, CRNs with HD mode had certain limitations. Therefore, by employing FD in CRNs, not only will these problems be negated, but there are many benefits that come with it. Chapter 3 aims to introduce a FD-CRN model that successfully combines FD and CRN, given that both PU and SU's throughputs experience acceptable interference levels and can successfully communicate.

3.2. Project Contributions

In the model developed, many state of the art technologies are used alongside FD and CR. Beamforming (or spatial filtering) is a signal processing technique used in wireless communication systems for directional signal transmission or reception. In other words, the Beamforming concept is where the transmission antenna(s) concentrate its transmission directly to the receiver, rather than radiating out into the atmosphere in all directions with hopes that some transmission reaches the receiver antenna(s). It is achieved by combining elements in an antenna array that result in constructive interference for desired signals and destructive interference for undesired signals(interference). In the Beamforming Design system model proposed, zero-forcing precoding is used to achieve Beamforming in order to cancel interference as well as boost performance of desired communication link(s). Zero-forcing is a method of spatial signal processing in which by the use of multiple transmit antennas 'null' out interferences at the receiver in wireless communications.

In [41] the author proposes a Generalized Design of Multi-User MIMO Precoding Matrices that optimises the whole system using available spatial resources and minimises the interference experience by users. This project adopts their concepts and applies it to the proposed model. Beamforming is achieved by having transmitters and receivers that utilize MIMO (multiple-input, multiple-output) technology. Multiple antennas are becoming a key component in today's wireless standards, such as the IEEE 802.11ac (Wi-fi), 3G and 4G[42]. This leads to benefits of having degrees of freedom that is used in this project. Precoding supports multi-stream transmission in a multiple antenna wireless communication. Therefore, MIMO allows a degree of freedom in which a precoding matrix can boost a desired throughput while canceling undesired interference. In addition, for the precoding to be feasible, channel state information(CSI) must be known. Hence, a commonly used technique of training sequence in acquiring the channel state will be discussed. Furthermore, a secondary base station was used for the SU to generate the precoding matrix. The secondary base station(S-BS) contains multiple transmission antenna and receiver antenna for simultaneous Up-link and Down-link of the SU in FD mode.

3.3. System Model

Fig.3.1 shows the system model proposed, it consists of 1 PU, 1 SU and a S-BS. In real practical systems, the PU and SU here can be in 2 states, either ON or OFF. This means that if the PU is transmitting, the channel is occupied resulting in being not idle state and vice versa. In this project, a scenario where both PU and SU will be in the ON state will be considered to simulate the 'underlay' paradigm. Thus, effective interference suppression is required for both users to experience quality throughputs. In the 'underlay' scenario, the SU is seeking to transmit simultaneously with the PU. Moreover, the Up-link and Down-link is also occurring simultaneously through the S-BS incorporating FD mode into the system along with PU's transmission. The generation of a precoding matrix at the S-BS is used for 2 purposes, one for cancellation of interference and the other for boosting performance for SUs. For this particular model, an assumption has been made that the secondary transmitter signals do not create interference with the primary receiver. It is also assumed that the channel remains constant throughout transmission. To simulate this, Rayleigh block fading has been used. Therefore, the channel state is assumed to have remained the same throughout the transmission. The S-BS is constructed with 4 antennas, 3 for transmitting and 1 for receiving. The reason behind these numbers of antenna selection is to ensure simplicity and effectiveness of generating the precoding matrix to cancel interference levels. Whilst other transceiver(PU and SU transmitter and receivers) will have 1 antenna each either for transmission or reception. Furthermore, the number of antennas at the S-BS was carefully selected so that it ensure that there exists sufficient degrees of freedom(DoFs) to cancel out all interferences due to having 2 interferences (see dotted lines in Fig.3.1) that needs to be taken care off in ensuring the quality of all communication links.

In addition, further information regarding the selection of the number of antennas will be discussed later in the chapter in the 'Precoding Matrix Generation and Degree of Freedom' section. The model will focus on using a precoding matrix to carry out partial zero-forcing Beamforming. The precoding matrix was generated at the S-BS using channel knowledge of interferers and was used in interference cancellation. Moreover, analysis for the 'underlay' case (where both the PU and SU is transmitting simultaneously) was performed for the model. The SINR and SNR matrix was used in calculating the transmission rate as a form of comparison and analysis for the communication links. The equations for the communication links is outlined later in this Chapter.

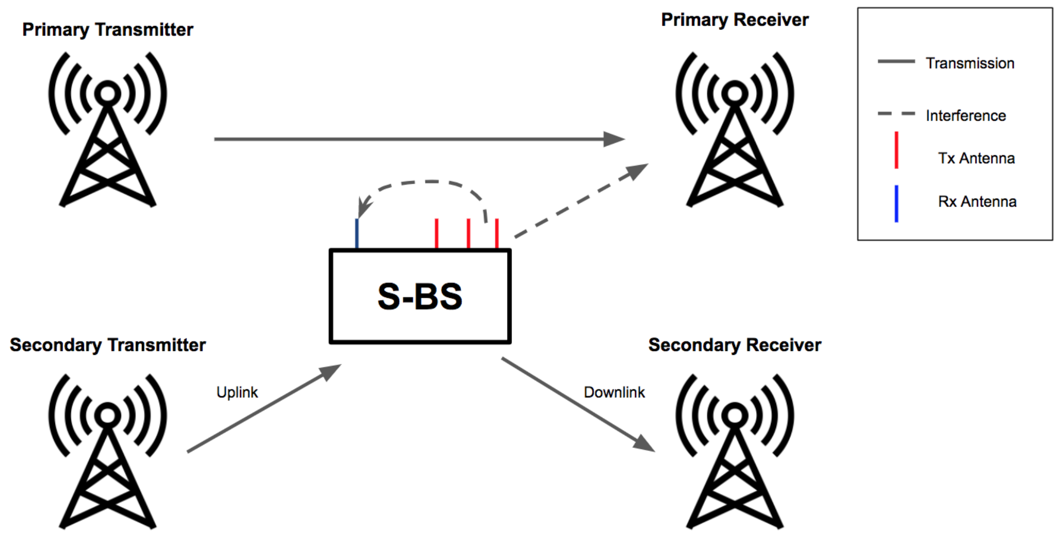

Figure 3.1: System Model

Overall, there are 3 communication links(see solid lines in Fig.3.1) that requires to be guaranteed in terms of quality. Therefore these links used to analyze and compare the quality of throughputs of the model, consisting of the PU's receiver as well as the Up-link and the Down-link for the SU. The PU's receiver and the receive antenna on the S-BS (which receives Up-link from the secondary transmitter) faces interference caused by the transmission antenna on the S-BS. The PU and the Up-link uses SINR(Signal-to-interference-plus-noise ratio) to generate the transmission rate due to the fact that they face interference. Whereas the Down-link from the S-BS to the secondary receiver can use SNR(Signal-to-noise) due to the lack of interference and is solely affected by noise. A ratio of SNR and SINR that is greater than 1:1 indicates a higher ratio of desired signal than the unwanted signals of noise and interference. The SNR and SINR are scientific measurements of the quality of transmission that has been used in many works as a comparison of throughputs' performances. After having calculated SNR and SINR by Eq.3.1 and Eq.3.2, the transmission rate of each link was then calculated to analyze the performances of the links using the Eq.3.3.

$$\text{SNR} = \frac{P_S}{P_N} \tag{3.1}$$

P_S=**Power of Signal**

P_N=**Power of Noise**

$$\text{SINR} = \frac{P_S}{P_I + P_N} \tag{3.2}$$

P_S**=Power of Signal**

P_N**=Power of Noise**

P_I**=Power of Interference**

$$R = log_2(1 + SINR) \tag{3.3}$$

R=Transmission Rate

Primary User

The primary user Eq.(y_p) is as follows:

$$y_p = \sqrt{P_p} H_p S_p + \sqrt{P_d} \mathbf{H}_{dp} \mathbf{p} S_d + n \tag{3.4}$$

y_p **= primary receiver's received signal**

P_p **= transmit power of the primary transmitter**

H_p **= primary user's channel**

S_p **= primary user's transmit symbol**

P_d **= Down-link transmit power**

$\mathbf{H}_{dp}$ **= transmit antenna to primary receiver channel**

S_d **= Down-link symbols**

p = precoding matrix

n **= noise**

The first part of the equation $\sqrt{P_p} H_p S_p$ represents the primary receiver's desired received signal transmitting from its primary transmitter counterpart. However, the primary receiver would face interferences denoted by $\sqrt{P_d} \mathbf{H}_{dp} \mathbf{p} S_d$ from the S-BS transmit antenna that is simultaneously transmitting Down-link signals to the secondary receiver represented by the dotted line in Fig.3.1. Here, a precoding matrix $\mathbf{p}$ generated at the S-BS with given channel knowledge $\mathbf{H}_{dp}$ will attempt to cancel out the interference signals mentioned above. The channel matrix had to be transpose in order for the dimensions to match with the precoding matrix as shown in the Eq.3.4. Since the PU has higher priority and legacy rights for the spectrum, its quality of throughput must be ensured while the SU attempts to share the spectrum. The SINR of the primary user then is equal to:

$$\mathrm{SINR}_p = \frac{P_p|H_p|^2}{P_d|\mathbf{H}_{dp}^T\mathbf{p}|^2 + P_n} \tag{3.5}$$

P_n=**Noise Power**

SINR$_p$=**Signal-to-interference-plus-noise ratio of Primary Receiver**

Up-link

The Up-link equation for Fig.3.1 system model is as follows:

$$y_{up} = \sqrt{P_u}H_uS_u + \sqrt{P_d}\mathbf{H}_{ds}\mathbf{p}S_d + n \tag{3.6}$$

y_u = **Up-link signal**

P_u = **Up-link transmit power**

H_u = **Up-link channel**

S_u = **Up-link transmit symbol**

$\mathbf{H}_{ds}$ = **S-BS transmit and receive antennas channel(self-interference channel)**

$\mathbf{p}$ = **precoding matrix**

The Up-link is the communication link where the secondary transmitter transmits to the receiver antennas on the S-BS. The first part of the equation, $\sqrt{P_u}H_uS_u$, is the desired Up-link signal from the secondary transmitter. $\sqrt{P_d}\mathbf{H}_{ds}\mathbf{p}S_d$ is the interference caused by self-interference from the transmit antenna on the S-BS transmitting simultaneously for Down-link, which in turn, causes self-interference to the transmit antenna on the S-BS. This interference is again shown in Fig.3.1 as a dotted line. Meanwhile, the same precoding matrix generated, $\mathbf{p}$, is used to cancel the interference. The equations of SINR for the Up-link is as follows:

$$\mathrm{SINR}_{up} = \frac{P_u|H_u|^2}{P_d|\mathbf{H}_{ds}^T\mathbf{p}|^2 + P_n} \tag{3.7}$$

SINR$_p$=Signal-to-interference-plus-noise ratio of Receiver antenna on S-BS

Down-link

The Down-link equation is as follows:

$$y_d = \sqrt{P_d}\mathbf{H}_{dd}\mathbf{p}S_d + n \tag{3.8}$$

y_d **= Down-link received signal**

$\mathbf{H}_{dd}$ **= Down-link channel(from transmit antenna on S-BS to secondary receiver)**

This Down-link channel is the channel in which the transmit antenna transmits to the secondary receiver, causing interferences to the other two communication links. Here, the received signal at the secondary receiver does not face interference from both the primary and secondary transmitter. As a result, the precoding matrix was used instead to boost the performance of the link by the multiplication to the desired channel denoted by $|\mathbf{H}_{dd}^T\mathbf{p}|^2$ in Eq.3.9. The SNR for the Down-link is shown by the following equation:

$$\mathrm{SNR}_d = \frac{P_d|\mathbf{H}_{dd}^T\mathbf{p}|^2}{P_n} \tag{3.9}$$

SNR$_p$=Signal-to-noise ratio of Secondary Receiver

3.4. Channel Knowledge

Channel states can be categorized into two categories. The 'instantaneous channel state information' is a short-term channel state information where current conditions of the channel are known. On the other hand, the 'statistical channel state information' is a long-term channel state information where the statistical condition of the channel is known and the channel's characteristics can be described by fading and the average channel gain. Here, one of the more popular methods of training sequence (or pilot sequence) method can be used to estimate the channel state. This is done by sending known signals across the channel. The channel matrix **H** will be estimated based on the signal received at the receiver as the original signal sent was known. The pilot sequence (known signal) is represented by $p_1, ..., p_N$ where the vector p_i will transmit across the channel. Therefore, the received signal y_i will be:

$$y_i = Hp_i + n_i \tag{3.10}$$

where n denotes the noise. Since the received signal $\mathbf{Y}$=$y_i, ..., y_N$, with pilot sequence, $\mathbf{P}$=$p_i, ..., p_N$ and noise, $\mathbf{N}$=$n_i, ..., n_N$, the equation can be rewritten as:

$$Y = HP + N \tag{3.11}$$

Therefore, with the knowledge of $P = p_i$ and Y, the channel H can be estimated[43]. The estimated channel, as stated earlier, will remain the same throughout the transmission. Work in [44] looks into acquiring channel state for MIMO systems. They have achieved better channel estimation performance by using sequential channel estimation scheme along with Kalman filter. This project will not be focused on acquiring the channel state. Instead this project will assume to have achieved acquisition of the channel state during the transmission period.
In this project Rayleigh channels are generated by adding two Gaussian functions. Rayleigh distribution assumes that real and imaginary parts of the complex number responses are modeled using independent and identically distributed equal variance zero-mean Gaussian processes. This is so that the amplitude of the response comprises of the sum of the two processes. This method is adopted from [45]. Fig.3.2 shows the code in Matlab used to simulate the channels used in the project where x denotes the no. of receiver antenna(s) and y denoting no. of the transmit antenna(s). For example in the case of PU channel (x,y) will be (1,1) with the primary transmitter and receiver having 1 antenna each. Meanwhile, the Down-link channel where there's 3 transmit antenna at the S-BS and 1 receiver antenna at the secondary receiver (x,y) will be (1,3).

```
h=sqrt(1/2)*(randn(x,y)+1i*randn(x,y)); %Rayleigh Fading

```

Figure 3.2: Rayleigh Fading Simulation

In designing practical systems, it is reasonable to acknowledge that the channel knowledge will not be perfect and could result in self-interference channel (SIC) estimation error. This leads to degraded performances to the system illustrated in Chapter 4's simulation results. The SIC estimation error formula used is shown in the Eq.3.12, where the power of δH is varied to show how performance reduces as the interference power increases.

$$\mathbf{H}_{RR} = \mathbf{H}_{00} + \delta\mathbf{H} \tag{3.12}$$

$\mathbf{H}_{RR}$=Real Channel State Information

$\mathbf{H}_{00}$=Estimated Channel used for generation of precoding matrix

$\delta\mathbf{H}$=SIC estimation error

3.5. Precoding Matrix Generation and Degree of Freedom

This system model revolves around the generation of the precoding matrix that was used to cancel interference levels and if applicable, boost performance of communication links. As shown previously in Fig.3.1, S-BS contains 4 antennas overall; 3 for transmission and 1 for receiving. With 3 transmission antennas and 1 receiving antenna, the channel generated will have a 3X1 matrix characteristic. There are two interference channels that need to be suppressed; the one caused by the 3 transmit antennas on the S-BS to the primary receiver, and the other being the self-interference from the 3 transmit antennas to the receiver antenna. Therefore, the generation of the precoding matrix will use these interference channels' knowledges to generate a matrix which 'nulls' out the interference channels. Additionally, in the case where there exists an available DoF(s), it will be used to boost the SINR of the Down-link channel in Fig.3.1. As channels are randomly simulated using Matlab, the precoding matrix generated will be different for each channel's instances and would only hold for that particular period of time where the channels remain constant.

The precoding matrix generated at the S-BS contains 3 DoF(s). However, there are only 2 DoF(s) remaining as one is required to be used for the Down-link transmission. The 3 DoF(s) reasonates from the fact that there are 4 antennas selected (3 transmit, 1 receive), where they are used to either cancel interference or boost a particular link's performance which is a second priority and only if there is DoF(s) remaining. The Eq.3.13 shown below was used to generate the precoding matrix and is adopted from [46]. The channel that is desired to be boosted is denoted by **H** where S represents a matrix that is orthonormal to the interference levels. Works in [47] looks into beamforming in Space Division Duplexing(SDD) where eigenmode transmission in MIMO systems are examined under SDD, in which interference is canceled by utilizing null space of interference channels. In this project, a similar method of generating precoding matrix in [46] was used, with the difference being the generation of a decoding matrix for the purpose of Spatial Multiplexing to cancel nearest interferers with and without Channel state information at the transmitter. Transmission capacity of Ad-hoc networks containing multiple antennas were analyzed in [48], where the transmitter uses eigen multimode-beamforming and the receiver uses partial-zero forcing to suppress interferenes using spartial receive degrees of freedom (SRDOF). The following equation for generation of precoding matrix was developed with assistance from reading upon the following works mentioned in this section. However, the difference is that the precoding matrix generated is specific to the proposed model in Fig.3.1.

$$\mathbf{p} = \frac{\mathbf{H} * SS^T}{|\mathbf{H} * SS^T|} \tag{3.13}$$

p = precoding matrix

H=Desired boosted channel

S=basis of null space of the canceled interferers

As stated before the precoding matrix was used to cancel the interference levels. Fig.3.3 shows the Eq.3.13 in Matlab where h1 denotes the Interference Channel from S-BS to primary receiver, h2 denoting the S-BS self-interference channel (from transmit antenna to receiver antenna) and h4 is the desired boosted transmission link(Down-link). The precoding matrix was then used to cancel out the interference levels h1 and h2, this is shown in Fig.3.4 where the precoding matrix was multiplied with the interference channels with Matlab returning extremely small numbers for each case which are close to zero and essentially and effectively cancelling out the interferences. This precoding matrix was used in all links shown earlier in the equations of Primary User, Up-link and Down-link. As mentioned before there're 3 DoFs available in the system model with 1 requiring for the Down-link transmission. Leading to the particular system model proposed the 2 remaining DoFs were used to cancel out h1 and h2 in the FD mode. On the other hand in HD mode only 1 interference level is required to be suppressed leaving 1 DoF to be used to boost the Down-link(more information in Chapter4). The full actual codes used in Matlab can be accessed in the Appendix A.

```
s=null([h1 h2]');
p=(h4*s*s')/(norm(h4*s*s'));
```

Figure 3.3: Precoding Matrix canceling code

```
Command Window
>> p*h1

ans =

  -1.5613e-17 + 2.0817e-17i

>> p*h2

ans =

   2.0817e-17 + 1.1102e-16i

fx >>
```

Figure 3.4: Precoding Matrix canceling out interferences

Chapter 4

Evaluation and Comparison to Half-Duplex

4.1. Project Originality

Matlab was used in all of the simulations carried out in the project due to its reliability as well as how it is trusted by many researchers evident from where many have used it as a primary tool for their works in wireless communications, such as in[49][50][51]. Matlab codes developed for simulations shown in the project is accessible in the Appendix section. The FD-CRN Beamforming Design was proposed by the author. Despite the design requiring adoption of techniques for zero-forcing and precoding from [46] as well as the general concept from [41], it has to be specifically tailored towards the proposed model. Therefore, all codes used for the simulations and equations for communication links are original and developed by the author specifically for the proposed model.

4.2. Simulation Description

The PU and SU's in FD mode throughputs are evaluated using transmission rates. Individually each PU and SU performances were analyzed to see how their performances downgraded with greater interferences resulting from self-interference channel(SIC) estimation error. The FD-CRN's transmission rate is also compared with HD-CRN. The SINR and SNR were found and used to generate the transmission rates for each link using equations previously stated in Chapter 3. There will be 4 case scenarios shown below in Table1. This performance analysis will only focus on the case where both the PU and SU are ON in the 'underlay' case.

Primary User	ON	ON	OFF	OFF
Secondary User	ON	OFF	ON	OFF

Table1:PU and SU state

In the analysis of the primary receiver's SINR and transmission rate, the power of transmission from the primary transmitter was varied from 1dB to 20dB, whilst the S-BS's power will be set to 1W. The noise power is also set to 1dB for every simulated link. In the analysis for the SU, the power of the Up-link and Down-link is set to be equal, and will vary from 1dB to 20dB. The power of the interference generated is set to 1W or 0dB from the transmission antenna to the receiver antenna. The noise power level will remain the same. The SU power is set to be the same for both Up-link and Down-link. In the simulations, the transmission rate (of information) will be measured when varying the transmit power. Assumptions were made that there is no interference generated from the PU transmitter to the SU receiver, and from the SU transmitter directly to the SU receiver without passing through the S-BS. This is due to long distances and additional shielding that makes the interference negligible.

The reasoning behind comparing HD with FD is that most existing systems today use HD, so it has been used as a control variable to compare the proposed technologies. When comparing FD-CRN and HD-CRN, in the case where there is a SIC estimation error, the power of the interference channel is set to 1W or 0dB. This is due to emerging technologies of acquiring channel states such as [52], where the authors came up with a new method of estimating the channel state for MIMO systems. Another example is [53], in which the author proposed an eigenvalue decomposition based approach to estimate the channel state. Taking this into consideration, it is reasonable to assume that the estimated channel state can be found and that the value would be equal or extremely close to the real channel.

In the simulations, Rayleigh block fading has been used to generate the channels, whilst noise power is set to 1dB. The reasoning behind deciding upon Rayleigh fading is due to the fact that it is seen to be a reasonable model for signal propagation in heavily built up urban environment; which is the type of environment where if the model were to be employed it is most likely in congested urban areas. Regarding the number of antennas on the S-BS, there are 3 for transmission and 1 for reception(see Fig.3.1). The Channels are constructed using Matlab random functions, which generated Gaussian functions that follows the Rayleigh Distribution shown in Chapter 3. Rayleigh Block fading was used for the simulations as it is a reasonable model for simulating the effects of heavily built-up urban environments on radio signals[54] - a place where FD-CRNs would most likely be employed due to a large number of users. Moreover, it has been used in numerous works regarding wireless communications. On top of that, the reasoning behind using block fading was the need for generating a precoding matrix. Moreover, as the channel is stable, interference cancellation can be made throughout the transmission. However, in reality, this is not likely to be the case. Therefore, the generated precoding matrix must be able to be re-generated in real time throughout the transmission to maximize the throughputs. When generating the precoding matrix for simulations, a 'null' function in Matlab was used to find the orthonormal matrix that could cancel out the interference channels, which would then be inputted into equation 3.13 shown in Chapter 3. Other equations in Chapter 3 were also input into Matlab to generate SINR and SNR values for each link.

4.3. Simulation Results and Performance Analysis

4.3.1 Primary User

Fig.4.1 shows the PU rate, with its transmission varying from 1 to 20dB. This is when the CRN system model is in the FD mode. It shows the 7 scenarios with different levels of SIC estimation error. The figure shows in all cases that the performance (transmission rate) increases with increasing transmit power. As expected, the perfect interference cancellation case performed the best as compared to other cases where there exists SLC estimation error. This is then followed by other cases, with the best performers being from the case where there is the least interference power, and the worst where the SIC estimation error is greatest. However, the reduction in performance between the perfect and imperfect SIC conditions is far more significant than the reduction in performance resulting from increased interference power (in the imperfect SIC condition).

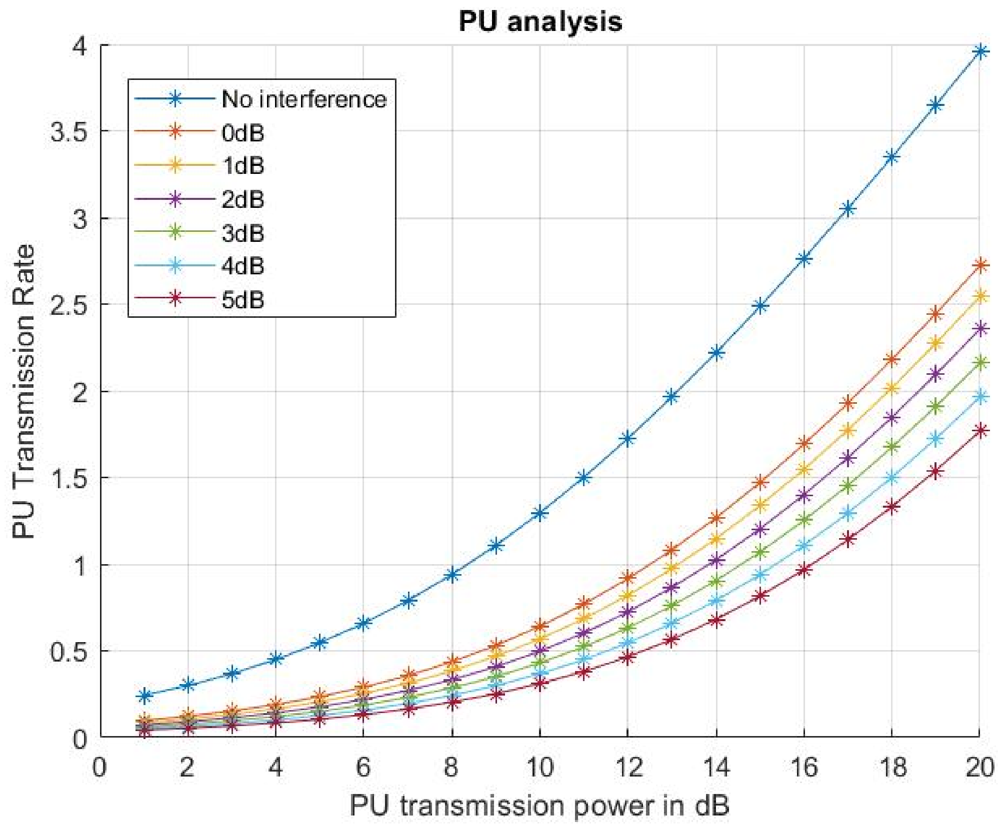

Figure 4.1: Primary User Analysis

4.3.2 Secondary User

For the SU's throughput analysis, the Up-link and Down-link were added together as they transmit simultaneously, forming the Secondary User. Similarly, the simulations represent when the CRN is operating in FD mode and showing 7 scenarios as with PU analysis. The Up-link experiences self-interference generated at the Secondary Base Station (S-BS), which is canceled out by the precoding matrix. Whereas the Down-link only experiences noise. Fig.4.2 shows the SU transmission. The power for both the Up-link and Down-link is set to be the equal to one another and varies from 1dB to 20dB. As expected, the case where there is no SIC estimation error outperformed the other cases. However, the difference in performance levels of when there exists perfect channel knowledge and when there is imperfect channel knowledge is not as large compared to the PU. This is due to the fact that SU consists of both Up-link and Down-link and are combined for analysis, with the Down-link not affected by any interference. In addition, up to a transmission power of approximately 5dB, there is no significant impact of SIC estimation error on the transmission rate of SU.

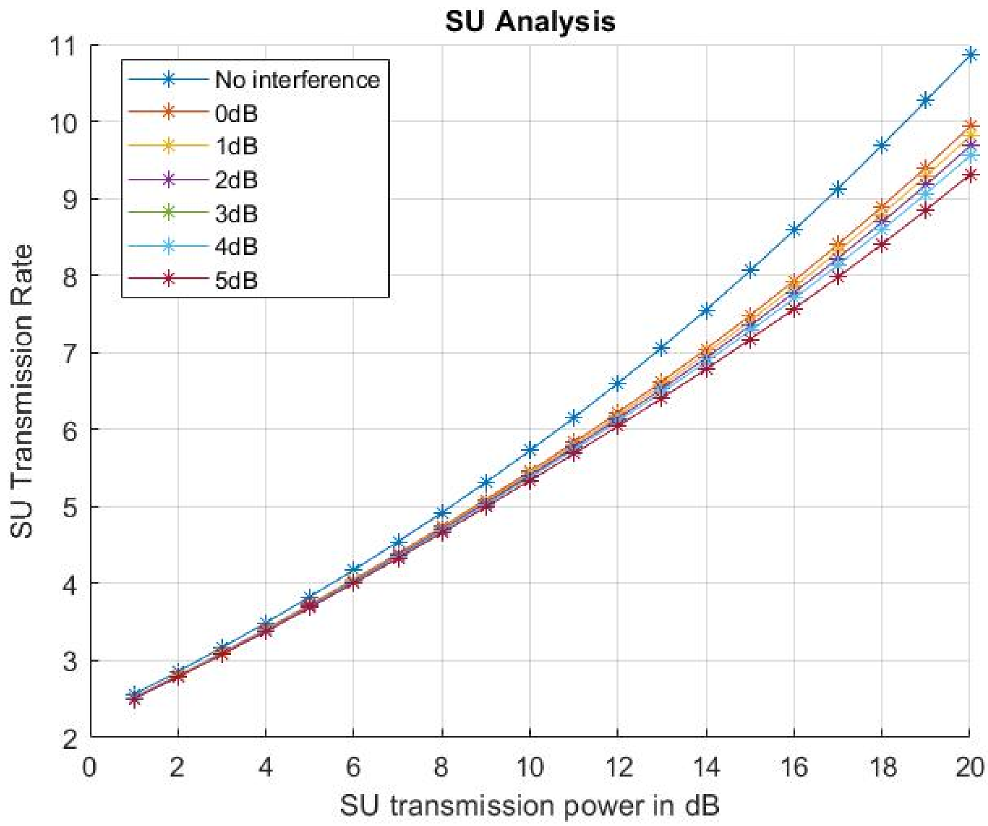

Figure 4.2: Secondary User Analysis

4.3.3 Full-Duplex vs Half-Duplex

The PU for both the HD and FD remains the same due to both facing the same level of interference. Meanwhile, the SU rate was halved in the simulations as HD mode requires double time slots compared to FD mode. This is due to the fact that the Up-link and Down-link are not happening simultaneously with there being a wait period for the Down-link as it waits for the Up-link to complete its transmission. As a result, one time slot will be used for Up-link whilst another is required for Down-link. Consequently, in the HD case, the precoding matrix now has to only negate the interference caused to the primary receiver, whilst FD also requires self-interference suppression at the S-BS. Therefore in the HD case, having 3 DoFs where 1 is used for transmission and another for negating interference caused to the primary receiver, there is one spare DoF which now can be used to boost the performance of the Down-link. On the other hand, although FD requires half the number of time slots as compared to HD, all 3 DoFs have been exhausted where 1 is used for transmission and the other 2 for canceling interference, which downgrades the performance of the Down-link of the SU.

Fig.4.3 shows the SU's throughput analysis for both FD and HD. Even with the usage of the precoding matrix to boost the Down-link's performance in the HD case, FD shows to be superior at every transmitting power. This is due to the fact that as it requires half the amount of time slots required for HD. In this case, the interference cancellation is assumed to be perfect because it is assumed that the channel state information acquired is perfect. Therefore, a precoding matrix based on that channel was generated. However, in reality, this might not be the case.

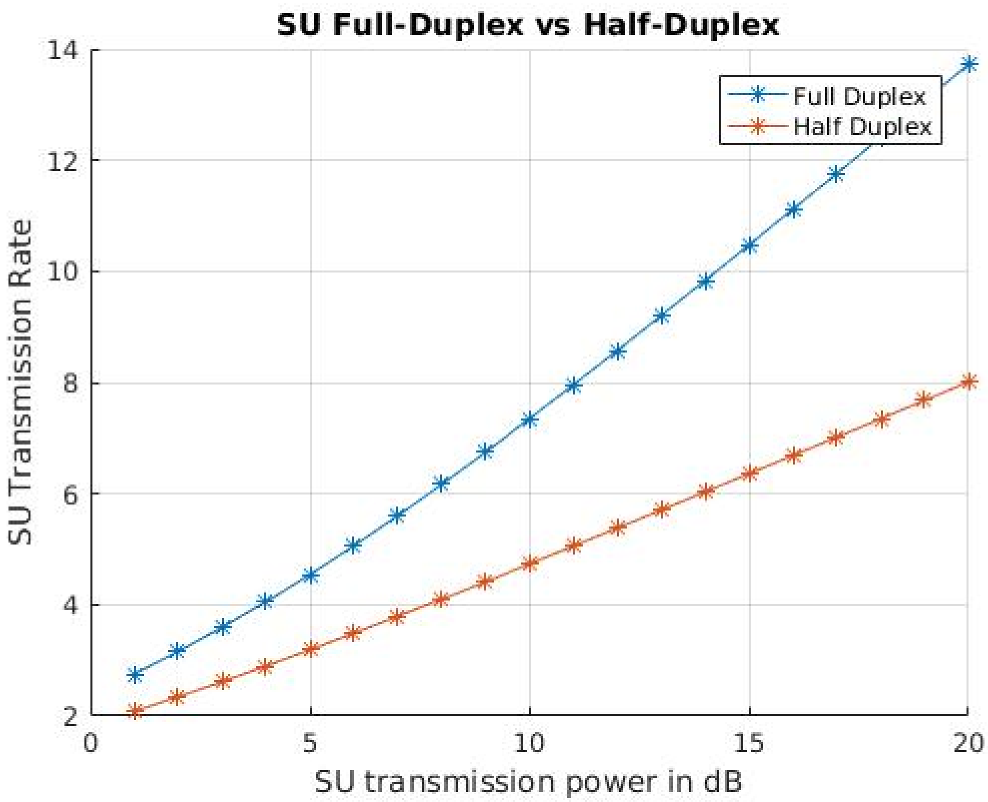

Figure 4.3: Secondary User Analysis with perfect cancellation

Fig.4.4 shows the same simulations that were ran in Fig.4.3. However, in this case, the difference is that the channel state information acquired is not exactly equal to the real channel state. In practical real life systems, the channel state acquired will not be exactly the same as the channel state and therefore the power of SIC estimation error of 1W is added to the simulations. Where the δH in Eq.3.12 is assigned a power of 1W. In this case, both the performances of PU and SU decreases compared to the perfect channel knowledge scenario. Moreover, FD does not always outperform HD. The simulations show that it now depends on the transmission power of the SU. Below 7.5dB, HD performs better than FD, whilst FD outperforms HD at 7.5dB and above. Both the HD and FD transmission rate is less than the previous case due to the inaccurate channel state information. In the ideal case where the channel estimation is perfect, Fig.4.3 is the ideal transmission rate. The better the channel estimation gets, the closer the FD curve in Fig.4.4 will get to the ideal case.

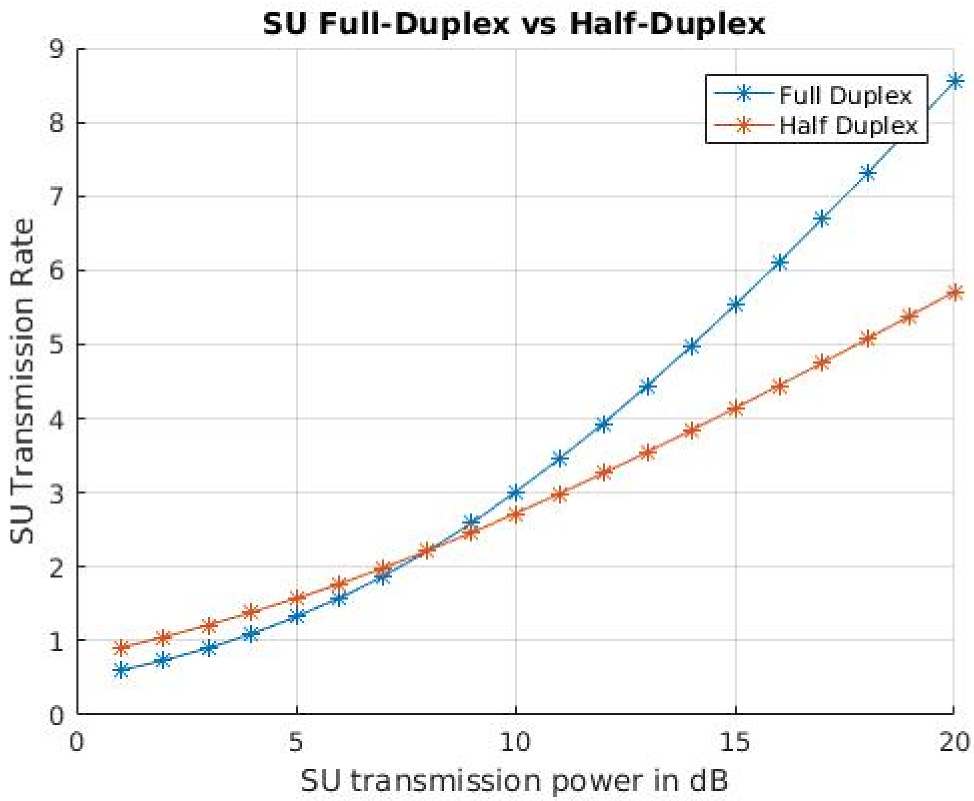

Figure 4.4: Secondary User Analysis with imperfect cancellation

4.4. Evaluation

In this Chapter, a way of incorporating FD into CRN is proposed. Given channel state knowledge, SU was able to transmit simultaneously with PU experiencing tolerable interference levels. The precoding matrix presents a great way to cancel out interference if the channel state is known. The model proposed allows a CRN in the 'underlay' paradigm to operate with FD mode, in which both PU and SU were able to transmit simultaneously at an acceptable information rate. Performance of the throughputs for both users reduces significantly with self-interference channel (SIC) estimation error. Therefore, a good channel state information is required.

When comparing it to the HD-CRN, only the throughput of the SU is analysed due to the PU's remaining the same for both modes. Compared to HD-CRN, the FD-CRN proposed outperforms it at every transmitting power when there is no self-interference channel (SIC) estimation error. However, when the δH(in equation 3.12) is added with a given power of 1W or 0dB, there exists imperfect interference cancellation of the precoding matrix at the S-BS, leading to HD outperforming the FD mode at certain transmit powers.

In both analyses, it can be said that the FD-CRN system model proposed will outperform the HD-CRN for both users with perfect or near perfect channel estimation state. In addition, it would present a lower latency due to FD allowing Up-link and Down-link to happen simultaneously for SU. The precoding matrix presents a way to cancel out self-interference and/or interference, as well as boost performances of desired links given the DoFs' availability.

Chapter 5

Conclusion and Future Work

5.1. Conclusion

Full-Duplex and Cognitive Radio Networks technologies have potential in improving spectrum utilization. Therefore, addressing an ongoing problem may rely on these technologies in the near future. Given FD's benefits of acheiving better spectral efficiency, it is reasonable to assume that when self-interference suppression is negated, FD would replace all HD in most systems. CRN, which is still a relatively new and promising concept, is therefore combined with FD. This is because in-band FD might become the new standard in wireless communications in the near future.

The main motivation behind the project to accommodate the increasing number of users is outlined in Chapter 1. Here, the current problem of inefficient spectrum usage is explored; in which FD and CR are potential solutions for these problems. The advantages and potentials of both technologies are explored in Chapter 2 where an in-depth literature review including other aspects of the technologies such as the state of the art, brief history, limitations and applications is also explored individually and combined. Chapter 3 presents a Beamforming design for FD-CRN in the 'underlay' case, which enhances spectral efficiency and is a proposed way to suppress interference for both users. The simulations of the Beamforming design produced using Matlab is then further evaluated in Chapter 4, where the FD-CRN model is compared to the HD-CRN model.

5.2. Future Work

Given the nature of both these technologies being rather new, many research paths can be taken in coming up with useful applications. As for combining FD and CRN, less assumptions will have to be made to simulate a more practical and realistic scenario to depict a real-life case. For example, realistically, channels would most likely not remain the same during transmission. Therefore, the precoding matrix generated would have to be regenerated. Other types of fading such as the Rican fading should also be taken into consideration if the system were to be employed in a real life scenario where there's a dominant line of sight between the transmitter and receiver as Rayleigh fading is most applicable when there's no dominant line of sight. In addition, modulation schemes such as coded and uncoded should also be taken into consideration, simulated and analyzed to see the optimal coded/uncoded(eg. BPSK, 4-PAM) systems.

The number of transmission and receiver antennas have to be explored to identify the optimal ratio for them, with all users and communication links taken into consideration. A higher number of antennas would lead to a greater challenge in generating the precoding matrix and would need ensuring that it contains enough Degrees of Freedom (DOFS) to cancel interference levels and boost the performance of desired throughput links. Results of other schemes of CRN(interleave and overlay) should be researched when it is incorporated with FD. This should then be compared to the 'underlay' case to identify the best combination FD-CRN type. The Channel state information estimation should also be incorporated into the simulations to see how accurate the channels estimation are. There should also be a way for the SU to sense PU interference levels so it can adjust its transmit power accordingly as PU experiencing high interference resulting from SU transmitting is not acceptable.

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Appendix A

Matlab Code for Simulations

A.1. Primary User Simulations Code

```
clear
h0=sqrt(1/2)*(randn(1,1)+i*randn(1,1)); %Primary Channel
h1=sqrt(1/2)*(randn(1,3)+i*randn(1,3)); %Interference Channel from s-bs to primary receiver
h2=sqrt(1/2)*(randn(1,3)+i*randn(1,3)); %S-bs self-interference channel(from transmit antenna to receiver antenna
h4=sqrt(1/2)*(randn(1,3)+i*randn(1,3)); %Downlink Channel
hx=sqrt(1/2)*(randn(1,3)+i*randn(1,3)); %Imperfect Channel
h1=transpose(h1)
h2=transpose(h2)        %making matrix aligh for multiplication
h4=transpose(h4)
s=null([h1 h2]')        %finding orthogonal space to null interference channels
p=(h4'*s*s')/(norm(h4'*s*s')) %generating precoding matrix
N0=1              %sound power
for i=1:20
sinr(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+N0) %generate SINR
c(i) = log2(1+sinr(i))                  %generate transmission rate
end
figure(1);
```

```
hold on;
i=1:20
a=plot(i,c,'-*'); M= 'No interference';

for i=1:20
sinr0(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+db2pow(0)*norm(hx)+
    N0)
c0(i) = log2(1+sinr0(i))
end
i=1:20
a0=plot(i,c0,'-*'); M0= '0dB'

for i=1:20
sinr1(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+db2pow(1)*norm(hx)+
    N0)
c1(i) = log2(1+sinr1(i))
end
i=1:20
a1=plot(i,c1,'-*'); M1= '1dB'

for i=1:20
sinr2(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+db2pow(2)*norm(hx)+
    N0)
c2(i) = log2(1+sinr2(i))
end
i=1:20
a2=plot(i,c2,'-*'); M2= '2dB'

for i=1:20
sinr3(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+db2pow(3)*norm(hx)+
    N0)
c3(i) = log2(1+sinr3(i))
end
```

```
i=1:20
a3=plot(i,c3,'-*'); M3= '3dB'

for i=1:20
sinr4(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+db2pow(4)*norm(hx)+N0)
c4(i) = log2(1+sinr4(i))
end
i=1:20
a4=plot(i,c4,'-*'); M4= '4dB'

for i=1:20
sinr5(i) = ((db2pow(i))*norm(h0)^2)/(abs(p*h1)^2+db2pow(5)*norm(hx)+N0)
c5(i) = log2(1+sinr5(i))
end
i=1:20
a5=plot(i,c5,'-*'); M5= '5dB'


title('PU analysis')
xlabel('PU transmission power in dB')
ylabel('PU Transmission Rate')
legend([a;a0;a1;a2;a3;a4;a5], M,M0,M1, M2, M3,M4,M5);
grid on;
```

A.2. Secondary User Simulations Code

```
clear
h3=sqrt(1/2)*(randn(1,1)+i*randn(1,1));
h1=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
h2=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
h4=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
hx=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
```

```
h1=transpose(h1)
h2=transpose(h2)
h4=transpose(h4)
s=null([h1 h2]')
p=(h4'*s*s')/(norm(h4'*s*s'))
N0=1


S=null([h1]')
B=(h4'*S*S')/(norm(h4'*S*S'))

for i=1:20
sinra(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+N0)
ca(i) = log2(1+sinra(i))
sinrb(i)=(db2pow(i)*norm(p*h4)^2)/N0
cb(i)= log2(1+sinrb(i))
c(i)=ca(i)+cb(i)
end
figure(1);hold on;
i=1:20
a= plot(i,c,'-*'); M='No interference';

for i=1:20
sinr0a(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+db2pow(0)*norm(
    hx)+N0)
c0a(i) = log2(1+sinr0a(i))
sinr0b(i)=(db2pow(i)*norm(p*h4)^2)/N0
c0b(i)= log2(1+sinr0b(i))
c0(i)=c0a(i)+c0b(i)
end
figure(1);hold on;
i=1:20
a0= plot(i,c0,'-*'); M0='0dB';
```

```
for iH=1:20
sinr1a(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+db2pow(1)*norm(
    hx)+N0)
c1a(i) = log2(1+sinr1a(i))
sinr1b(i)=(db2pow(i)*norm(p*h4)^2)/N0
c1b(i)= log2(1+sinr1b(i))
c1(i)=c1a(i)+c1b(i)
end
iH=1:20
a1= plot(iH,c1,'-*'); M1='1dB';

for iH=1:20
sinr2a(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+db2pow(2)*norm(
    hx)+N0)
c2a(i) = log2(1+sinr2a(i))
sinr2b(i)=(db2pow(i)*norm(p*h4)^2)/N0
c2b(i)= log2(1+sinr2b(i))
c2(i)=c2a(i)+c2b(i)
end
iH=1:20
a2= plot(iH,c2,'-*'); M2='2dB';

for iH=1:20
sinr3a(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+db2pow(3)*norm(
    hx)+N0)
c3a(i) = log2(1+sinr3a(i))
sinr3b(i)=(db2pow(i)*norm(p*h4)^2)/N0
c3b(i)= log2(1+sinr3b(i))
c3(i)=c3a(i)+c3b(i)
end
iH=1:20
a3= plot(iH,c3,'-*'); M3='3dB';
```

```
for iH=1:20
sinr4a(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+db2pow(4)*norm(
    hx)+N0)
c4a(i) = log2(1+sinr4a(i))
sinr4b(i)=(db2pow(i)*norm(p*h4)^2)/N0
c4b(i)= log2(1+sinr4b(i))
c4(i)=c4a(i)+c4a(i)
end
iH=1:20
a4= plot(iH,c3,'-*'); M4='4dB';

for iH=1:20
sinr5a(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+db2pow(5)*norm(
    hx)+N0)
c5a(i) = log2(1+sinr5a(i))
sinr5b(i)=(db2pow(i)*norm(p*h4)^2)/N0
c5b(i)= log2(1+sinr5b(i))
c5(i)=c5a(i)+c5b(i)
end
iH=1:20
a5= plot(iH,c5,'-*'); M5='5dB';

title('SU with interference')
xlabel('SU transmission power in dB')
ylabel('SU Transmission Rate')
legend([a;a0;a1;a2;a3;a4;a5],M, M0,M1, M2, M3, M4, M5);
grid on
```

A.3. Secondary User FD vs HD

```
clear
h3=sqrt(1/2)*(randn(1,1)+i*randn(1,1));
h1=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
```

```
h2=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
h4=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
hx=sqrt(1/2)*(randn(1,3)+i*randn(1,3));
h1=transpose(h1)
h2=transpose(h2)
h4=transpose(h4)
s=null([h1 h2]')
p=(h4'*s*s')/(norm(h4'*s*s'))
N0=1


S=null([h1]')
B=(h4'*S*S')/(norm(h4'*S*S'))


for i=1:20
sinr2(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+norm(hx)+N0)
c2(i) = log2(1+sinr2(i))
sinr3(i)=(db2pow(i)*norm(p*h4)^2)/N0
c3(i)= log2(1+sinr3(i))
c(i)=c2(i)+c3(i)
end
figure(1);hold on;
i=1:20
a1= plot(i,c,'-*'); M1='Full Duplex';

for iH=1:20
sinr2H(i) = ((db2pow(i))*norm(h3)^2)/(abs(h1'*p')^2+norm(hx)+N0)
c2H(i) = 0.5*log2(1+sinr2H(i))
sinr3H(i)=(db2pow(i)*norm(B*h4)^2)/N0
c3H(i)= 0.5*log2(1+sinr3H(i))
cH(i)=c2H(i)+c3H(i)
end
```

```
iH=1:20
a2= plot(iH,cH,'-*'); M2='Half Duplex';
title('SU Full-Duplex vs Half-Duplex')
xlabel('SU transmission power in dB')
ylabel('SU Transmission Rate')
legend([a1;a2], M1, M2);
grid on
```