ISTANBUL TECHNICAL UNIVERSITY ★ INFORMATICS INSTITUTE

LINEAR INTERFERENCE ALIGNMENT IN COGNITIVE RADIO NETWORKS

M.Sc. THESIS

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Applied Informatics Department

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JUNE 2018

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ

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Hakan ALAKOCA, a M.Sc. student of ITU Informatics Institute student ID 708151027 successfully defended the thesis entitled “LINEAR INTERFERENCE ALIGNMENT IN COGNITIVE RADIO NETWORKS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my mom and grandma,

FOREWORD

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I hope you enjoy your reading.

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ABBREVIATIONS

AF	: Amplify and forward
AWGN	: Additive white Gaussian noise
BER	: Bit error rate
CSI	: Channel state information
CR	: Cognitive radio
CRN	: Cognitive radio networks
DF	: Decode and forward
IA	: Interference alignment
LTE	: Long term evolution
MIMO	: Multiple-input Multiple-output
MISO	: Multiple-input Single-output
MMSE	: Minimum mean square error
MRC	: Maximum ratio combining
MRT	: Maximum ratio transmission
PDF	: Probability density function
PU	: Primary user
QoS	: Quality of Service
RF	: Radio frequency
SIMO	: Single-input Multiple-output
SINR	: Signal-to-interference noise ratio
SISO	: Single-input Single-output
SNR	: Signal-to-noise ratio
SU	: Secondary user
SVD	: Singular value decomposition
UWB	: Ultra-wide band
ZF	: Zero Forcing
3G	: Third generation
3GPP	: Third generation partnership project
4G	: Fourth generation

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LINEAR INTERFERENCE ALIGNMENT IN COGNITIVE RADIO NETWORKS

SUMMARY

Multi-input multi output (MIMO) systems are still developing via substantial research effort in the literature and leading telecommunication industry. MIMO communications that is a solution as countering fading and deep fade effect in wireless communication, presents spatial diversity of the system and increases data rates. Yet, the effective operation of MIMO systems depends on the design of the pre-coding and post-coding matrices.

Cognitive radio networks, which have been proposed for a long time in the literature, are still being developed. The communication of two different types of users is achieved on the principle that they are based on the use of different kinds of techniques as a solution to the spectrum scarcity. Primary users are allocated as licensed users, besides secondary users are considered as unlicensed users in cognitive radio networks. Overlay, underlay and interweave techniques are among the outstanding techniques in the literature. It is essential to minimize interference components that occur between the primary users and the secondary users so that these techniques can work effectively.

Interference alignment (IA) is a remedy for eliminating interference components due to the interference channel in MIMO networks. There are many variants for IA in the literature and linear interference alignment technique is the most frequently used due to its applicable approach. In the IA method using the MIMO network structure, the interference components are aligned in a specific direction by using the precoding and interference suppression matrices. However, the destruction of these interference components is accompanied by operative signal processing implementation. Additionally, IA technique has also known harmonious structure for CR networks.

In this thesis, the interference alignment performance of a MIMO CR network is examined in the presence of multiple secondary users. In the proposed architecture, it is assumed that linear IA is used at the primary system to alleviate the interference between primary and secondary networks. Although linear IA can surpass the interference in CR considerably, interference leakages may occur due to fast fading channel. Herein, we derive the closed-form outage probability expression considering the interference leakage occurred in the primary system. The results which are validated with Monte-Carlo simulations show that interference leakages can deteriorate both system performance and diversity gains considerably.

Furthermore, precoder and interference suppression matrix design is covered using the IA technique with MIMO zero-forcing receiver structure. Precoder and interference suppression matrix is designed considering the presence of a single primary user and two secondary users in the wireless environment. Sum rate performances and bit error rate performances are presented for both primary users and secondary users with respect to the number of antennas and distance.

BİLİŞSEL RADYO AĞLARINDA
DOĞRUSAL GİRİŞİM HİZALAMA

ÖZET

Çoklu giriş-çoklu çıkış sistemleri literatürde ve telsiz haberleşme endüstrisinin öncüleri tarafından geliştilmeye açıktır. Telsiz haberleşme sistemlerinde kablosuz ortamdan kaynaklı sönümlemelerin etkisinin ve derin sönümlemelerin etkisinin azaltılması için MIMO sistemler sıklıkla kullanılmaktadır. Günümüzde WCDMA, LTE ve 802.11 WLAN gibi geniş bantlı kablosuz haberleşme ağ standartlarında sıklıkla yer almaktadır. MIMO sistemlerin verimli çalışabilmesi için çoklu antenlerin girişiminden kaynaklı iç girişim değerlerinin yok edilmesi gerekmektedir. Bunun sağlanması için MIMO sistemlerde gönderilecek işaret bir önkodlayıcı matrisi ile çarpılmakta, daha sonra telsiz MIMO haberleşme kanalından geçmekte ve en sonunda bir son kodlayıcı matrisi ile çarpılarak alınmaktadır. Yüksek performansta MIMO sisteminin çalışması için ön kodlayıcı ve son kodlayıcı matris tasarımlarının doğru yapılması gerekmektedir; aksi taktirde çok anten yapısı kullanılması dolayısıyla iç girişim değerlerinin yok edilememesi verimlilik noksanlığına neden olmaktadır. Ayrıca MIMO ağlarında alınan işaret için literatürde çeşitli işaret algılayıcıları önerilmiştir. Bunlardan sıfıra zorlama ve minimum ortalama karesel hata tabanlı algılayıcılar basit yapılarından ötürü sıklıkla tercih edilmektedir.

Bilişsel radyo ağları literatürde uzun zaman önce önerilmesine rağmen güncelliğini hala sürdürmektedir. Spektrum kıtlığı ve frekans tahsisi konuları telsiz haberleşmedeki hali hazırda bulunan problemler arasında yer almaktadır. Bilişsel radyo ağlarında kaynak kullanımına göre iki farklı kullanıcı türünün olmasına işaret edilmiştir. Bunlar sırasıyla lisanslı kullanıcılara tahsis edilmiş birincil kullanıcılar ve lisanssız olan ikincil kullanıcılardır. Birincil kullanıcılar ikincil kullanıcılara nazaran performans açısından öncelikli olarak düşünülmüştür. Bu duruma göre birincil kullanıcının performansını etkilemeyecek aynı zamanda ikincil kullanıcların da ortam içinde verimli bir şekilde haberleşmelerinin sağlanması için literatürde üç ana teknik önerilmiştir. Bunlar sırasıyla, üstüne serme, altına serme ve araya karışma teknikleridir. Üstüne serme tekniğinde, ikincil kullanıcı birincil kullanıcının haberleşmesini kuvvetlendirecek şekilde röle veya işaret kuvvetlendirme vazifelerini yerine getirebilir. Burada amaç birincil kullanıcıların haberleşmesini daha iyi duruma getirmektir. İkincil kullanıcılar, birincil kullanıcılar ile aynı ortamda haberleşirler. Ancak ikincil kullanıcının gücü kendi iletimini gerçekleştirmede ve birincil kullanıcıya yardım etme ile paylaştırılır. Altına serme tekniğinde ikincil kullanıcılar birincil kullanıcılara mukayesen spektral maske denilen eşik değerinde daha düşük güçte iletim yaparlar. Buradaki ana sorun ikincil kullanıcılardan kaynaklı girişim değerlerinin birincil kullanıcılara olan etkisidir. Birincil kullanıcıların verimli haberleşebilmeleri için bu girişim değerlerinin azaltılması gerekmektedir. Araya karışma tekniğinde ise, ikincil kullanıcılar çevrelerinde bulunan spektrumları sezerek birincil kullanıcıların yer almadığı boş frekans bantlarına yerleşirler. İletimlerini bu boş frekans bantlarından

yaparak bu frekansın sahibi olan birincil kullanıcıların ortamda bulunması durumunda ise, ikincil kullanıcılar yeniden bulunduğu frekans bölgesini değiştirir. Böylelikle boş frekans bantlarının verimli bir şekilde kullanılması sağlanır. Benzer şekilde yan bantlarda olması durumunda bile oluşan komşu kanal girişimi birincil kullanıcıların performansını olumsuz yönde etkileyecektir. Kısacası, birincil ve ikincil kullanıcılar arası girişimin engellenmesi bu farklı türden tekniklerin verimli çalışmasına önemli bir adım teşkil edecektir.

Girişim hizalama (IA) tekniği MIMO kanallarda oluşan girişim bileşenlerinin yok edilmesine dayanan bir yöntemdir. Literatürde pek çok farklı türü bulunan girişim hizalama tekniklerinin arasından en yaygın olarak kullanılanı doğrusal girişim hizalama tekniğidir. IA tekniği MIMO ağ yapısı ile uyumlu olup, çalışma prensibi olarak girişim kaynaklarının aynı doğrultuya gelecek şekilde hizalanması ile bunların sıfır uzayına gelecek şekilde ön kodlayıcı matrislerinin ve girişim baskılama matrislerinin tasarlanması yolunu kullanır. Girişim bileşenlerinin hizalanması işlemi güçlü işaret işleme tekniklerinin de kullanılmasını beraberinde getirmektedir. Bununla ilgili kanal durum bilgilerinin de aynı şekilde alıcı yapılarına entegre edilmesi gerekmektedir. Buna ek olarak, girişim hizalama yönteminin CR ağları için uygunluğu da girişim bileşenlerinin yok edilmesi yönüyle literatürde vurgulanmaktadır.

Tezde ilk olarak, MIMO CR ağlarında girişim hizalama performansına yer verilmektedir. Önerilen mimaride tek kullanıcıya sahip bir birincil kullanıcı çifti ve çok sayıda ikincil kullanıcının birlikte yer aldığı bir sistem düşünülmüştür. İkincil kullanıcıların sayılarının artışıyla, birincil kullanıcıların MIMO ağlardaki performansının düşüşü gözlemlenmektedir. Bununla birlikte, yanlış girişim hizalamadan kaynaklı girişim kaçaklarının varlığında sistem performansı hızlı değişen kanallarda servis dışı kalma olasılıkları bakımından ifade edilmiştir. Bununla ilgili birincil alıcı düğümünde gözlemlenen işarete dair servis dışı kalma olasılığının kapalı formu matematiksel derivasyonlarla elde edilmiş ve çeşitli parametreler bakımından incelenerek Monte-Carlo benzetim sonuçlarıyla örtüştüğü gözlemlenmiştir. Artan ikincil kullanıcı sayısı birincil kullanıcının sistem performansını belirgin bir şekilde negatif yönde etkilemiştir. Buna benzer olarak, yanlış girişim hizasından kaynaklı girişim kaçakları modellenerek, bunların artışının servis dışı kalma olasılığına olan etkisi irdelenmiştir. Bunların yanında çeşitlilik kazancının getirmiş olduğu performans artışı farklı anten verici ve alıcı anten sayıları için gözlemlenmiştir. Bununla beraber MIMO iletimde veri iletim eşik değerleri bakımından servis dışı kalma olasılıkları farklı durumlar göz önüne alınarak incelenmiştir.

Birinci ve ikinci kullanıcıların ortamda aynı anda bulunsalar dahi birbirlerine girişim oluşturmadan haberleşmesi IA yöntemi ile gerçeklenmiştir. İkinci kısımda, ön kodlayıcı ve girişim baskılama matrisi tasarımı, MIMO sıfır-zorlama alıcı yapısı ile IA tekniği kullanılarak yer verilmiştir. Ön kodlayıcı ve girişim baskılama matrisi, telsiz ortamdaki tek bir birincil kullanıcı ve iki ikincil kullanıcının varlığını göz önünde bulundurarak tasarlanmıştır. Birincil ve ikincil kullanıcılar için oluşturulacak ön kodlayıcı matrisleri, girişimi oluşturan işaretlerin alt uzaylarını eşit düzeyde germesi baz alınarak oluşturulur. Daha sonra bununla ilgili güç bileşenlerine ait değerler tekil değer ayrıştırma neticesindeki elde edilen matrislere dair MIMO kapasitedeki maksimizasyona dayanmaktadır. Maksimizasyon algoritması olarak toplam veri iletimini optimize etmeye çalışan su-dolumu (water-filling) algoritması yöntemiyle gerçekleştirilmiştir. Toplam veri iletim performansları ve bit hata oranı performansları, hem birincil kullanıcılar hem de ikincil kullanıcılar için, farklı anten sayıları ve uzaklık bakımından sunulmaktadır.

1. INTRODUCTION

Increasing numbers of high-speed internet access, video calls, online video, voice/data services and terminals compatible with these applications in communication technologies have triggered a striking growth in global data traffic in recent years. Meeting the rising demand for broadband communication is possible through the provision of fair and secure service quality to end users, the provision of a wide coverage area, and wireless communication technologies. Mobile data traffic is increasing dramatically over the last years as mobile devices have become prevalent. To meet the ever increasing demand for high quality, ubiquitous mobile communications, 3rd Generation Partnership Project's (3GPP) and Long Term Evolution (LTE) technology have been emerged [1–3]. On the other hand, according to the report of the Federal Communications Commission (FCC), it is stated that in different geographical regions, spectrum is used between %15 and %85 distributed, and spectrum gaps still exist. However, it is anticipated that the increase in mobile data traffic will also occupy the above-mentioned spectrum gaps [4, 5]. Even though 3GPP and LTE-Advanced have brought potential gains, scarce and underutilized spectrum can not compensate the demand [5]. Cognitive radio (CR) has just emerged as a paradigm to solve this problem of spectrum scarcity. CR technology allows licensed primary users (PU) with legal usage rights and priorities to use the same frequency spectrum with non-licensed secondary users (SU) [6, 7]. Hence, spectrum sharing is one of the important/compelling issues that stand out in CR networks.

In CR networks, the overall spectrum efficiency can be enhanced by using the well-known spectrum sharing techniques [7]: In the underlay method, the secondary user (SU) transmits its information simultaneously with the primary user (PU) as long as the interference between SU and PU receiver is within a predefined threshold. In the overlay approach, SU helps PU by sharing its resources and in return, PU allows SU to communicate. In the interweave technique, SU can use the bandwidth of PU if

PU is not active. In this model, SU should have perfect spectrum sensing features to analyze the spectrum [8, 9].

Interference alignment (IA) is an important approach for CR to recover the desired signal of the PU or SU by utilizing precoding and linear suppression matrices of the channel matrix, which consolidates the interference beam or matrix into a single subspace in order to eliminate it. There are various IA techniques to provide interference-free communication in CR networks. In linear IA technique, arguably the most practical one, the channel matrix is assumed to be perfectly known at the transmitter and receiver side of PU [10–13]. In the literature, linear IA is adopted in CR interference channels in [14–17] and the references therein. In [14], adaptive power allocation schemes are considered for linear IA-based CR networks where the outage probability and sum rate were derived. In [15], adaptive power allocation was studied for linear IA-based CR using antenna selection at the receiver side. [16] enhances the security of CR networks by using zero-forcing precoder. Moreover, in [17], a similar work was proposed to improve the overall outage performance of the interference channel by using power allocation optimization. These studies have shown that interference management is a critical issue to be handled in all multi-user wireless networks. Motivated by the above works, in this study, we examine the impact of interference leakage for multi-input multi-output (MIMO) CR networks with multiple SUs. Specifically, a closed-form outage probability expression is derived to provide the performance of the primary system.

1.1 Literature Review

In order to exploit the advantages of cognitive radio networks and to improve the transmission capabilities of secondary users, MIMO structures could be used. In MIMO systems, multiple antennas are used in the transceiver pairs that are in communication to provide spatial diversity. These multiple antennas are used to transmit and receive multiple copies of each different signal due to the nature of fading channels [18]. Studies in [19–22] MIMO based cognitive radio networks are examined. On the other hand, as in MIMO systems, relay-assisted communication of relay terminals as collaborative agents is presented as a remedy to improve the transmission performance of the secondary users. There are two main techniques in the literature: Amplify and Forward (AF) and Decode and Forward (DF) [23–29]. In the AF technique, relaying the scaled version of the transmitted signal is relayed. Besides, the signal from the source is decoded by the relay and sent to the destination by using DF technique. Although MIMO and relay-assisted transmission offer countless advantages to secondary users, the biggest obstacle for reliable communications in cognitive networks is interference. In particular, the interference between PUs and SUs studied in overlay and underlay CRNs, has become one of the open issues in the literature. A new technique called interference alignment, which can guarantee the desired service quality at the same time when the interference is controlled in the PU transmission, is able to maintain the spectrum free of interference from each user and is given as an important approach/solution model for CR networks [30]. Interference alignment (IA), a recently proposed intervention management technique for more efficient use of existing wireless network resources, is one of the most effective methods of attenuating interference, achieving maximum degrees of freedom (DoF) and maximum capacity in wireless interference channels, and has been the subject of extensive work [10–12, 30–33].

In the IA method, precoders of all transmitters are designed such that the unwanted signal in each receiver is aligned in a single subspace and the desired signal is aligned in a separate subspace. Linear interference alignment method in cognitive radio networks has been studied frequently in the literature in recent years [14–17, 34–43].

In IA-based CR networks, the sub-limited spectrum sharing model is presented at [14]. Here, power budgeting algorithms are proposed to maximize the total data rate for SU and closed-form equations for the outage probability are derived. Study in [15] using the antenna selection method, the system performance for the primary network is increased and the data rates are analyzed. [16] and [17] discuss different power optimization methods, and the outage probability is calculated when the interference is perfectly aligned. In this study, the effect of interference leakage system performance on both MIMO-based CR networks and multiple secondary users was investigated using both analytical and simulation approaches. In [34] opportunistic communication has been addressed, and simultaneous wireless information and power transmission has been proposed in IA-based communication networks. Another opportunistic approach, which increases secondary user transmission and output capacities, is to use [35], using frequency domain diversity with the existing frequency spectrum in CR networks. A MIMO CR network with a relay was designed and used for IA to increase the available degree of freedom [36]. A practical IA algorithm, which can optimize the degree of freedom of the secondary users by minimizing the initiative of the primary user, is studied in [37]. Resource allocation approaches to optimize CR network performance covered studies in [38–41]. Interference leakage in IA are given in [42, 43]. In [42], an algorithm minimizing interference leakage is proposed. Study in [43], analyzes computational complexity in MIMO systems in order to minimize interference leakage.

In the literature, different IA techniques are foreseen for CR networks:

Linear Interference Alignment Method: It is the case that the alignment process for the signal space is performed by the linear pre-coding approach which is primarily described in [10–12,31,32]. It is expected that the number of variables does not exceed the number of equations in a linear interference alignment, which is considered to be a simple and practical method with a large number of transmitter and receiver antennas in the system model. In this model it is assumed that the transmitter knows the channel state information. Considering M transmit antennas and N received antennas with K users MIMO interference channel, $(M \times N, d)^K$, a proper system could be designed with respect to a transmitted data stream which is described as $d \leq (M+N)\,/\,(K+1)$, where d is denoted as achieved DoF ratio.

Distributed Interference Alignment Method: Distributed interference alignment model is based on repetitive approach and local channel information [33, 44–46]. In this solution, reducing the minimum weighted average mean square error generated by using the two-way communication and channel reciprocity model (exchange of transmit-receive roles) are used. In this technique, only local channel information needs to be known at each transmitter and receiver node. In other words, it is assumed that each user on the receiver side is aware of the channel with the transmitter counterpart. It is also envisaged that the covariance matrix generated by the use of additive white Gaussian noise (AWGN) and interference from other users is known. Here, as in the CR network approach, each receiver tries to avoid interference from undesired transmitters.

Ergodic Interference Alignment Method: In case of fading communication channels, the entire interference is automatically reset when we assume that the transmitter generates the same symbol for the two-channel status information and the receiver adds the received information to each other [47, 48]. It is also known that in the opportunistic IA method, a serial code is added to each successive channel state matrices to reset the interference via natural method. In this way, it is observed that the ergodic interference alignment method is quantized, the ergodically accepted channel state information is quantized, a complementary channel state matrix is formed for each channel state matrix, and the interference is completely eliminated. This method is called the ergodic interference alignment method because it is assumed that the channel is ergodic. Thus, it is a recommended method for ergodic channel construction on the assumption that channel information and complementary channel information are generated equally. Although this method is applicable to Rayleigh fading channels, Rician channel does not give satisfactory results. In many types of fading channels where channel information is not generated symmetrically, the main assumption on ergodicity fails, and therefore is not universally accepted.

Blind Interference Alignment Method: The blind IA technique is a technique in which delayed or quantized channel coefficients can be applied in situations where the receiver is unknown but the receiver information is known to different receivers. In this technique, it is assumed that the fading block occurs with damping, that is, the damping remains constant at certain time and frequency intervals. In this method, it is possible to align the interference for different receivers based on the channel's autocorrelation function, without the presence of channel state information [49, 50].

Subspace Interference Alignment Method: Unlike traditional methods, the interference is aligned in multi-dimensional subspaces. In this technique, the vector Y, $\sqrt{Y}+1$ dimensional vector alignment, increases the number of entrants free of interference and the degrees of freedom [51].

Retrospective Interference Alignment Method: In this model, it is foreseen that the channel status information is perfectly known and used with delay. It is assumed that the channel is independent and evenly distributed isotropic [52].

Lattice Interference Alignment Method: This interference alignment method, based on the proposal that the code-words can solve solely from the sum of the lattice points in cases where they can not be solved in a one-to-one manner, is proposed for static Gaussian interference channels [53, 54].

1.2 Problem Statement & Hypothesis

CR is a sensitive techniques, which signals can be easily deteriorated due to interferer users. Therefore, the interference components causes the receiver nodes to transmit erroneous data and not to use the channel capacity efficiently. The interference of the SUs to the PU and the interference of the SUs to other existed SUs adversely affect the network performance significantly and it is possible to minimize this adverse effects by the interference alignment method via MIMO configuration. CR technique can be capable to utilize the spectrum efficiently as long as the interference between PU and SU is perfectly aligned as shown in Figure 1.1.

1.3 Contributions

Motivated by the above works and problem statement, in the first part of the thesis, we examine the impact of interference leakage on MIMO CR networks with multiple SUs. Performance of primary network is investigated under interference leakage via outage probability functions in MIMO configurations. Closed form outage probability expression is expressed in a presence of leakage occurred in the primary network. In

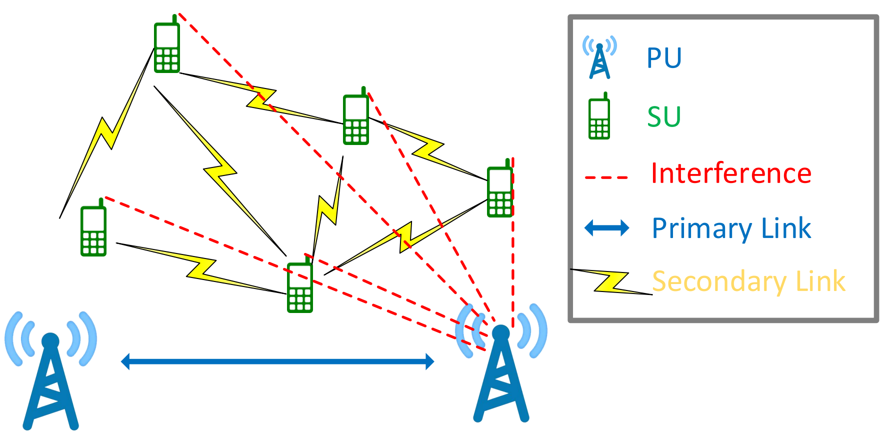

Figure 1.1 : Illustration of the primary link between the PU pair and interference links generated by SUs.

the second part of the thesis, pre-coding and post-coding matrix design is covered in MIMO fashion. In a proposed scenario, data rate performance of receiver nodes of PU is investigated under two SUs. Furthermore, sum rate performance of SUs is handled with a similar approach.

1.4 Thesis Organization

The outline of this thesis is organized as follows. First, principles of CRNs is covered with 5G requirements in Chapter 2. Also, background material used in this thesis is presented in Chapter 3. System performance of IA primary networks in a presence of multiple SUs in MIMO CRNs under leakage is covered in Chapter 4. Precoding and interference suppression matrix design a single PU and two SU transceiver case examined via data rate performance is given in Chapter 5. Eventually, conclusions and future works are presented in Chapter 6.

2. COGNITIVE RADIO NETWORKS

Being main source of wireless communications, the spectrum usages is licensed by telecommunication regulation authorities considering emerging technologies and user demands. Development of wireless technologies progressively and extensive user demands lead to require much more frequency band which is naturally a scarce source. Also, frequency allocation of licensed users may cause spectral collapse. Experimental studies is realized by regulatory authorities have expose that allocated frequency bands and radio spectrum are utilized deficiently. Frequency bands, which are rarely used at a specific time and frequency intervals, even it has mostly available, can be leased for an unlicensed secondary user group under specific conditions. CR concept requires a software defined radio transceiver platform, that is adopted and automated its fundamental parameters for communication.

Massive number of devices will communicate to one another in everywhere providing seamless quality of experience (QoE). 5G cellular networks offer to communicate with zero latency real-time applications, many systems and services. Moreover, the enhanced data transmission and reception will be ensured by supporting zero latency over a high speed radio link. In order to achieve this requirement set the scope of 5G cellular networks also bring the a new emerging advantages, methodologies and technologies such as device-to-device (D2D) communications, full duplex radio communications, software defined networks (SDN), energy efficient heterogeneous networks, and CRNs. Open issues still occurs due to increasing number of mobile devices and the bandwidth requirement for large amounts of data transmission. As a solution, development continues of the new emerging technologies and infrastructures in addition to the existing technology. To meet the growth and to provide fast and ubiquitous internet access, several promising technologies have been developed. Regarding with the deployment of the 5G wireless communication systems, the corresponding this growth in the demand for wireless radio spectrum resources will be appeared. Unfortunately, it is obvious that this issue will cause a severe shortage of spectrum resources. Thus, the solutions for spectrum utilization has been attracting attention appearing in the literature in recent years [55–57].

One of the candidate for handling the problem of spectrum shortage is the CRNs which will be a key technology for 5G networks. CRN has been attracted considerable interest as it can cope with the spectrum under-utilization phenomenon. The efficient usage of the limited spectrum is important for mobile applications like mobile gaming, video calling, and mobile video streaming. As aforementioned above, CRNs can remedy this problem by allowing the secondary (unlicensed) users to share the same spectrum band with the primary (licensed) users. CRNs is a promising solution for delivering the aforementioned voice and data services, providing quality of service, and overcoming the problem of spectrum limitation in 5G cellular networks. At the moment, the spectrum usage is assigned for the specific services with limited bandwidth based on the regulatory policy. This means that the unlicensed users will not be able to use the licensed frequency bands. However, the licensed spectrum have been reported for its' inefficient use [58]. CRNs also allows the unlicensed users to exploit the unused frequency bands dynamically without causing harmful interference to the licensed users. For this reason, it has been proposed to improve spectral utilization and efficiency.

In CRNs, there are two different user groups on the radio: primary users are the original users who own it and have priority rights over the licensed band. Secondary user devices are capable to sense the occupied or available frequency bands around them, to perceive the working environment, intelligent and dynamic setting of operating communication parameters. Secondary users use the licensed band under certain circumstances having CRs that perform their own communications. Secondary users can increase performance of primary users or at least could not effect the performance of primary users adversely in CRNs. Using spectrum cycle described in Figure 2.1, users are able to use spectrum proactively. Main functionalities of CRNs are summarized below.

- CR are proficient devices with RF front-end to sense and detect licensed frequency bands of licensed users in their spectrum. (Spectrum sensing approach)

- CR determine the best frequency band for communication. (Spectrum management)
- Handling access coordination with unlicensed users is provided in CR. (Spectrum sharing)
- When licensed user starts to use its frequency band, another available frequency band is selected by the unlicensed user. (Spectrum mobility)

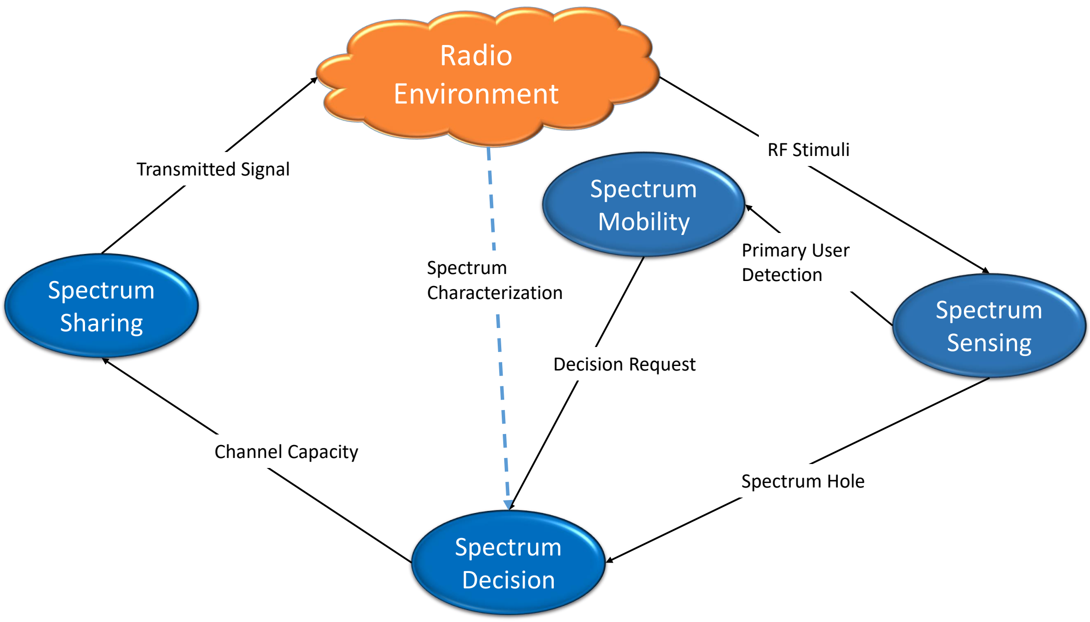

Figure 2.1 : Spectrum cycle mechanism in CRN.

2.1 Spectrum Sensing

Spectrum sensing is an effective spectrum awareness process used to analyze available frequency bands around secondary users calculating usage statistics of the primary and secondary networks. In this process, the secondary users are able to get available frequency bands and its operating parameters. Hence, spectrum usage is optimized via spectrum holes of licensed users. Spectrum holes are described in Figure 2.2. Furthermore, spectrum utilization in CRNs is given in Figure 2.3.

Various spectrum sensing techniques have been proposed in the literature. If secondary users have an information about primary users, optimum spectrum sensing is achieved via matching filtering. Existence of primary users are determined with respect to the received primary signal correlation using matching filtering technique. Thus, signal-to-noise ratio is maximized. This filtering technique presented shortens sensing

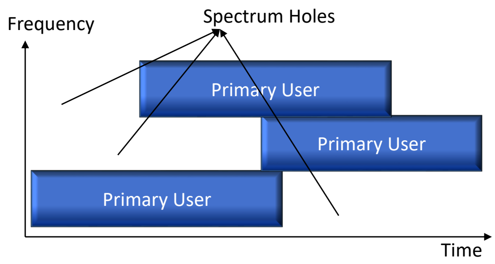

Figure 2.2 : Spectrum holes in a wireless networks.

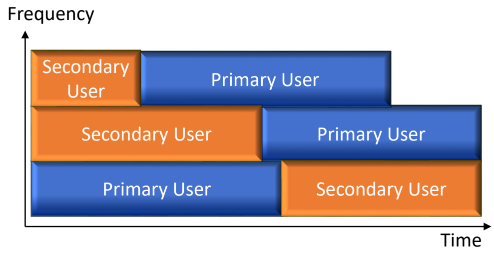

Figure 2.3 : Spectrum sharing in CRNs.

time interval with a satisfactory performance, yet it could not be used when there is no signal information about primary users in secondary nodes. The energy detection is the most widely used spectrum sensing technique. Observed signal energy is compared with a threshold value by the energy sensor, then determined presence of primary users. The energy detection sensor is easy to implement. Besides, it does not require prior knowledge of primary users signals like proposed in matching filtering technique, whereas it has limited performance due to unknown nature of additive noise channel. Performance of sensing is not reliable under specific signal-to-noise ratio value, which is defined as SNR wall. SNR wall may be decreased via pre-knowledge of primary users signals, however it may not be completely eliminated. In addition, additive noise or signals from other users in the environment could be misdetected as primary users. Feature detector is a technique for distinguishing between additive noise and licensed users. It makes use of the cyclostationarity properties of the signals, besides it can work at low signal-to-noise ratio conditions. Apart from these techniques, there are other spectrum sensing schemes proposed in the literature.

2.1.1 Spectrum sharing

Spectrum sharing can be examined from three directions: network architecture, access behavior, and access techniques.

2.1.2 Network architecture

If spectrum allocation for unlicensed users is managed via a single framework, the network architecture is centralized. However, such an implementing infrastructure due to the cost of installation, each user is responsible for accessing the spectrum with distributed network architecture.

2.1.3 Access behavior

Access behavior of the unlicensed user could in a cooperative or non-cooperative structure. Using cooperative access method, unlicensed users cooperate with each other to increase system performance. Centralized network architectures are generally modeled as cooperative access behavioral. Spectrum allocation among licensed and unlicensed users can be easily coordinated. Besides, secondary users have specific purpose and target for a communication in contrast to cooperative behavior. Therefore, non-cooperative access methods may be used by secondary users among them.

2.1.4 Access techniques

There are three different access techniques in CRN proposed the literature: Underlay, interleave and overlay. These techniques could be used as separately or mixed in an adaptively manner.

2.1.4.1 Underlay technique

Secondary users can communicate simultaneously under the condition that interference coming from secondary users to primary users must be restricted by a specific threshold level. This threshold level is determined considering a specific constraint defining by spectral mask which is power spectral density limitation for secondary users. Therefore, interference due to secondary users can be restricted at the primary nodes. Main description of this paradigm is demonstrated in Figure 2.4.

Instead of deciding on the intrinsic value of the interferences, such that the interference of the primary user's receiver to the power spectral density remains below the noise value. The secondary signal spread of the secondary user can be restored subsequently. In fact, this technique lie under spread spectrum techniques and ultra-wide band (UWB) communications. In addition, secondary users can communicate below

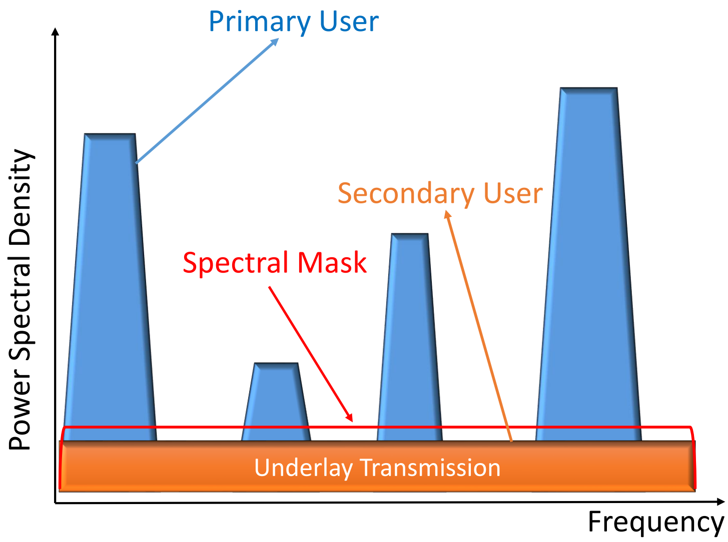

Figure 2.4 : Underlay concept in CRN

interference threshold value via adjusting transmission power level. However, this interference restriction may be so stringent by primary users that secondary users may be able to communicate at short distances at low data rates. It is difficult to determine the accurate value of the interference generated by the secondary users in the receivers of the primary users. Also, the main problem is that secondary users can adjust their transmission power in accordance with the power constraint.

2.1.4.2 Overlay technique

In this technique, secondary users have pre-knowledge about primary user's signals and use primary user signals to improve the performance of both user classes. The secondary user may use the primary signal to destroy the interference that the primary user has generated on its own receiver. On the other hand, the secondary user can perform its own transmission while improving the performance of the primary user by cooperating with the primary user. The various configurations that the secondary user uses in cooperating with the primary user and the appropriate protocols are proposed in the literature. For instance, the secondary user can transmit both signals via power sharing method. For this, the secondary transmitter can use part of its own power for the primary user while the remaining part can use it for transmission its own data. The priority in the communication will be the primary user, so the secondary user will spend most sources for primary user. If the primary receiver can be adjusted to decode secondary user's signal with its own signal, it may eliminate interference caused by the secondary signal. In this way, it can improve its performance by increasing its own data rate even without increasing its data rate, and at the same time the secondary user also benefits from the frequency band.

2.1.4.3 Interweave technique

Interweave technique proposed as an initial concept for CR. It is intended that secondary users will be able to capture these spectrum holes when they are left blank by the primary users of the licensed spectrum. In this technique, secondary users can perform transmissions over time, frequency or space dimensions only when primary users do not use them. Thus, the interference generated by primary users is reduced to the lowest level. Secondary users control the transmissions of primary users in time, frequency and space dimensions to find spectrum holes. The fundamental difficulty of this transmission technique is that the secondary user's ability to detect the spectral gaps is important due to the transmission behavior of the primary user can change over time and geographic location.

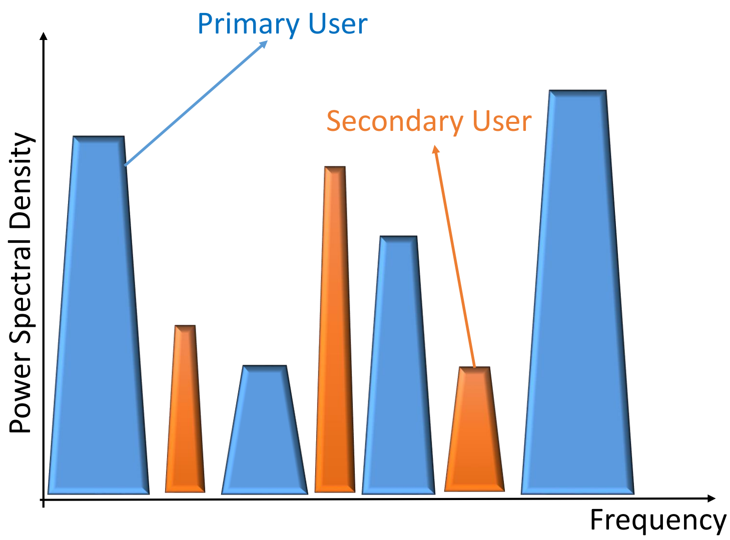

Figure 2.5 : Interweave technique in CRN.

3. BACKGROUND MATERIALS

In this chapter, background materials used in this thesis are presented. First, fading in wireless communications and wireless transmission diversity techniques are covered as a fading effect solution. Furthermore, different transmission techniques considering antenna configurations are also mentioned. Eventually, basic material of linear detector design and interference alignment are addressed for the better comprehension of the thesis.

3.1 Fading in Wireless Communication and Diversity

In wireless communication channels, there are two main distorting factors along with additive noise: interference and fading. Interference is caused when multiple users in a radio environment share the same transmission environment. There are three basic reasons for fading. Path-loss occurs due to weakening of the signal depending on distance and increases as the distance increases between the receiver and transmitter pair. Shadowing is caused by scattering objects, which blocks the transmitted signal. Multi-path fading is due to the time-varying nature of the channel. The transmitted signals which are diffracted, scattered, and/or reflected by the objects in the radio environment, reach the receiver in different directions and at different times. When these signals are received at different amplitudes and phases, fluctuations occur in the amplitude of the signal power. This fluctuation in the amplitude is called multi-path fading. In Figure 3.1, the effects of path loss, shadowing, and multi-path fading on the power of the signal are given with respect to distance.

While any channel between the receiver and the transmitter results in a strong fading at a certain time instant, there may be another channel which is independent of this channel having a higher instantaneous signal-to-noise ratio. With diversity techniques, it is ensured that multiple copies of a signal are transmitted to the receiver from statistically independent channels causing different fading effects; so that each copy is subject to different fading and the likelihood that all of them will undergo a strong

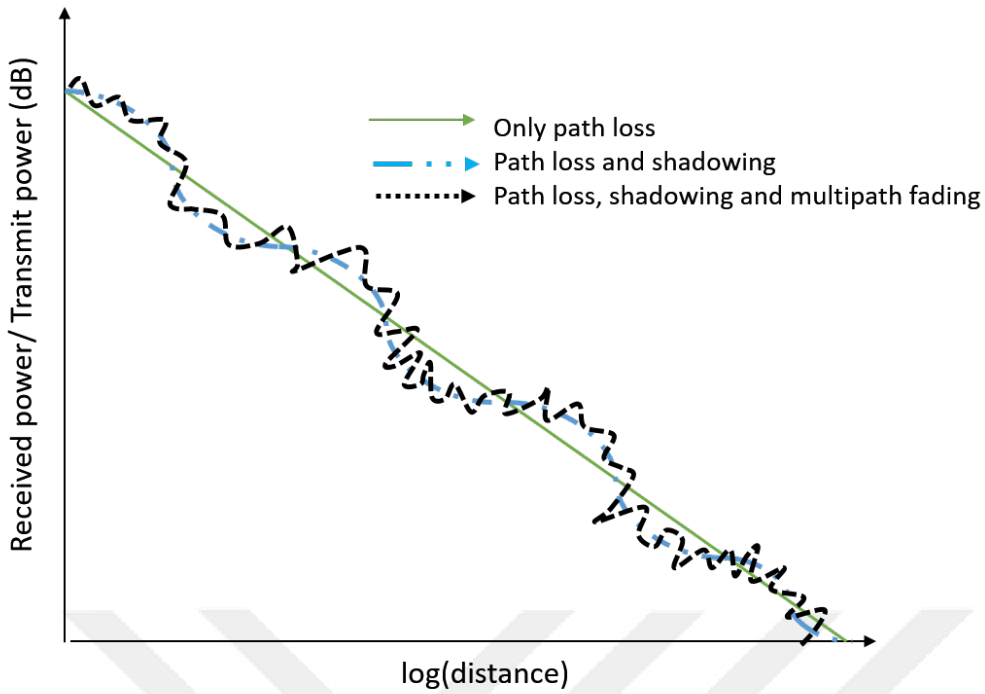

Figure 3.1 : The effects of path-loss, shadowing and multi-path fading on the amplitude of the received signal

fading at the same time, is reduced; therefore, reliability increases. There are three basic methods of diversity: Time diversity, frequency diversity, and space diversity. The signals are transmitted to the receivers in different time periods in time diversity, which can be obtained via coding and interleaving. The coded symbols are transmitted over in different time slots so that the different parts of the code words undergo different fading effects.

In case of frequency diversity, the signals are transmitted to the receiver by different frequency bands. In addition to more bandwidth and transmission power, receiver requirements with the same number of channels constitute the disadvantages of frequency diversity.

In space diversity, statistically independent channels are created by using multiple antennas at the receiver and/or transmitter. This diversity technique, also known as multiple-input multiple-output (MIMO) systems, provides higher bandwidth and channel reliability as well as increased transmission rate and coverage utilizing the same bandwidth and transmission power. Single-input single-output (SISO) systems using single antennas in receivers and transmitters, single-input multiple-output (SIMO) systems, multiple input single-output (MISO) systems using multiple antennas in receivers with single antennas can also be handled by the MIMO concept.

Diversity order is used in as a performance indicator wireless communication systems. The achievable diversity order, d, with fixed transmission rate can be expressed with

$$d = -\lim_{SNR \to \infty} \frac{\log P_e(SNR)}{SNR} \tag{3.1}$$

where P_e indicates as the bit error rate of a system. For a simplicity, correlation between BER and diversity order can be described as,

$$P_e(SNR) \propto SNR^{-d}. \tag{3.2}$$

In brief, due to the aforementioned aspects usage of multiple antenna systems create an advantage for BER performance. In addition, MIMO systems are used in many standards including IEEE 802.11n (Wi-Fi), HSPA + (3G), IEEE 802.16 WiMAX and LTE (Long Term Evaluation) (4G) standards.

3.2 Communication Systems with Respect to Antenna Configurations

Various communication system designs are employed with respect to different antenna configurations. This section briefly summerizes the single-input single-output (SISO) systems, multi-input single-output (MISO) systems, single-input multi-output (SIMO) systems and multi-input multi-output (MIMO) Systems.

3.2.1 Single input single output (SISO) systems

Conventional radio systems are designed via SISO configuration. In these systems, Input signal transmitted over the channel with a single antenna to be received by a single antenna. Conventional SISO radio system is described in Figure 3.2.

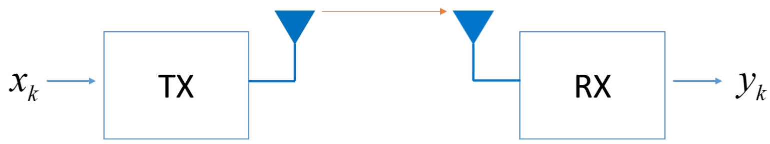

Figure 3.2 : Conventional SISO channel model.

Received signal is expressed as

$$y_k = hx_k + n_k, \tag{3.3}$$

where, y_k, h, x_k and n_k are defined as the received signal, channel coefficient, transmitted signal, and noise term, respectively. When the channel is assumed to be time-invariant, then the capacity of the conventional radio system is given as,

$$C_{SISO} = \log_2(1 + SNR_{SISO}), \tag{3.4}$$

where SNR_{SISO} is defined as the SNR of the signal power and noise power

$$SNR_{SISO} = \frac{P|\mathbf{h}|^2}{\sigma_N^2}, \tag{3.5}$$

where σ_N^2 is the noise power of the noise component n_k. Furthermore, average transmit power of transmitted signal component is restricted to be less than transmission power, P.

3.2.2 Multi input single output (MISO) systems

Communication over MISO systems, which is given in Figure 3.2, is handled with several antennas at the transmitter side and a single antenna at the receiver side.

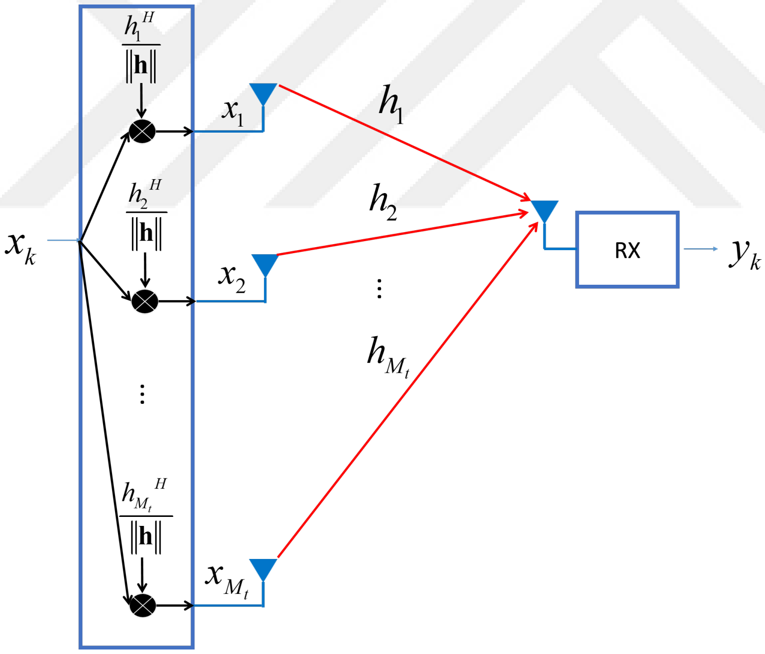

Figure 3.3 : MISO channel model

In MISO systems transmit beamforming is used for maximizing the capacity of the system. So as to achieve capacity of the channel, channel state information is known at the receiver node. Number of transmit antennas is given as M_t. Received signal through a time-invariant channel is given as,

$$y_k = \mathbf{h}_i^H \mathbf{x}_{k_i} + n_k, \tag{3.6}$$

where y_k is the received signal, $\mathbf{h}_i$ is the channel coefficient vector for all transmit antenna $\mathbf{h}_i = [h_1, h_2 \cdots h_{M_t}]$, $\mathbf{x}_{k_i}$ is the transmitted signal vector from each i^{th} transmit antenna $\mathbf{x}_{k_i} = [x_{k_1}, y_{x_2} \cdots x_{k_{M_t}}]$ and n_k is the noise component on the receiver node. Via transmit beamforming technique, transmitter symbols for each antenna are pre-processed and normalized before transmission, then multiplied with a complex coefficient which is the inversed phase of the fading channel. Transmit signal formed each antenna is determined as,

$$\mathbf{x}_{k_i} = \frac{h_i^H}{||\mathbf{h}||}\bar{\mathbf{x}}_{k_i} \tag{3.7}$$

where $\bar{\mathbf{x}}_{k_i}$ is the transmitted symbol vector after feedback channel. After transmit beamforming (3.6) is re-expressed as

$$y_k = ||\mathbf{h}_i||\mathbf{x}_{k_i} + n_k. \tag{3.8}$$

SNR expression is determined as

$$SNR_{SIMO} = \frac{P|\mathbf{h}|^2}{\sigma_N^2}. \tag{3.9}$$

Furthermore, system capacity using multi transmit antennas in time-invariant channel is expressed as follows.

$$C_{MISO} = \log_2(1 + SNR_{MISO}). \tag{3.10}$$

3.2.3 Single input multi output (SIMO) systems

In a SIMO system, communication is operated via single transmitter and multi-antenna receiver. SIMO system model is given in Figure 3.4.

Transmitted symbols are transmitted over the multi-antenna received channels. Number of received antenna is given as N_r. The received signal with time-invariant channel is described as,

$$\mathbf{y}_{k_i} = \mathbf{h}_i x_k + \mathbf{n}_{k_i}, \tag{3.11}$$

where $\mathbf{y}_{k_i}$ is received signal vector from each i^{th} antenna $\mathbf{y}_{k_i} = [y_{k_1}, y_{k_2} \cdots y_{k_{N_r}}]$, $\mathbf{h}_i$ is the channel coefficient vector for all antenna $\mathbf{h}_i = [h_1, h_2 \cdots h_{N_r}]$, x_k is the transmitted signal and $\mathbf{n}_{k_i}$ is the noise component vector for all received antennas $\mathbf{n}_{k_i} = [n_{k_1}, n_{k_2} \cdots n_{k_{N_r}}]$. At the receiver node, combination of the each receive antenna must be handled with

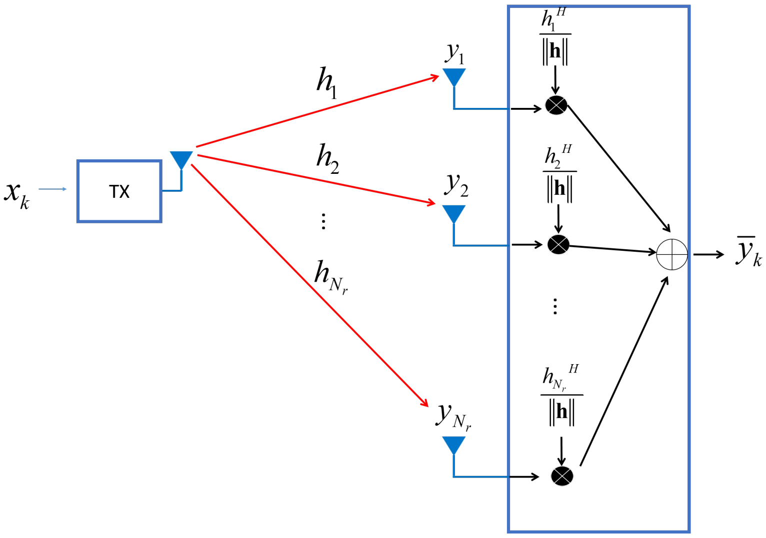

Figure 3.4 : SIMO channel model

a proper method. In order to maximize SNR, maximum ratio combining (MRC) post-processing method, could be used in [59]. SNR in the presence of the channel $\mathbf{h}_i$, is expressed as,

$$SNR_{SIMO} = \frac{P|\mathbf{h}|^2}{\sigma_N^2}. \tag{3.12}$$

Also, capacity of SIMO system in time-invariant channel is described as,

$$C_{SIMO} = \log_2(1 + SNR_{SIMO}). \tag{3.13}$$

It is seen above equations, capacity of SIMO and MISO systems are equal when channel coefficients are known at the receiver node.

3.2.4 Multi input multi output (MIMO) systems

Multiple antennas are used at the same time at both transmitter and receiver side. Transmission over MIMO channel is handled by pre-processing and post-processing operations. MIMO channel model is described in Figure 3.5. Number of transmit and receive antennas are given as M_t and N_r, respectively. Transmitted symbols are transmit over the $N_r \times M_t$ sized channel matrix, $\mathbf{H}_{k_{ij}}$.

At the receiver node, received signals can be expressed as,

$$\mathbf{y}_{k_i} = \mathbf{H}_{k_{ij}} \mathbf{x}_{k_j} + \mathbf{n}_{k_i} \tag{3.14}$$

where $\mathbf{y}_{k_i}$ is given as received signal vector from each i^{th} antenna $\mathbf{y}_{k_i} = [y_{k_1}, y_{k_2} \cdots y_{k_{N_r}}]$, $\mathbf{H}_{k_{ij}}$ is the channel coefficient matrix between transmitter and receiver. Also, $\mathbf{x}_{k_i}$ is

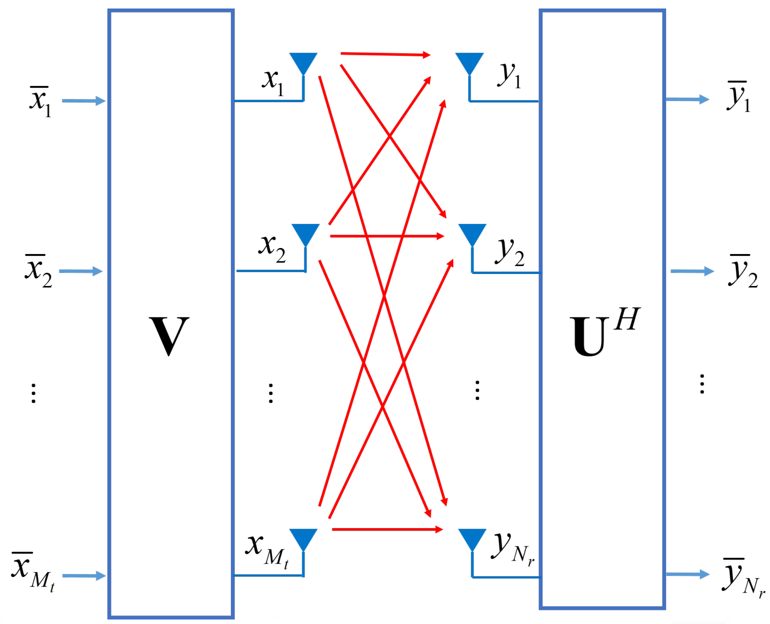

Figure 3.5 : MIMO channel model

transmitted signal vector from each j^{th} transmit antenna $\mathbf{x}_{k_j} = [x_{k_1}, x_{k_2} \cdots x_{k_{M_t}}]$ and $\mathbf{n}_{k_i}$ is the noise vector on the receiver node.

As indicated above, MIMO channel model is depends pre and post processing operations. Pre-processing matrix and post processing matrix is defined as $\mathbf{V}$ and $\mathbf{U}$, respectively. In order to determine pre-processing and post-processing matrix via singular value decomposition of channel matrix, $\mathbf{H}_{k_{ij}}$ is given as

$$\mathbf{H}_{k_{ij}} = \mathbf{U}\boldsymbol{\Lambda}\mathbf{V}^H, \tag{3.15}$$

where $\mathbf{U}$ is an $N_r \times N_r$ sized unitary matrix and $\mathbf{V}$ is an $M_t \times M_t$ sized unitary matrix. $\boldsymbol{\Lambda}$ is given as $N_r \times M_t$ sized diagonal matrix constituted with decreasingly non-negative singular values, λ_k. Rank of the channel matrix, $\mathbf{H}_{k_{ij}}$ is determined as $\text{rank}(\mathbf{H}_{k_{ij}}) \leq \min(N_r, M_t)$. Energy description of the channel can be expressed as,

$$\text{trace}(\mathbf{H}_{k_{ij}}\mathbf{H}_{k_{ij}}^H) = \sum_{j=0}^{M_t}\sum_{i=0}^{N_r} |h_{k_{ij}}|^2 = \sum_{l=0}^{r_H} \lambda_i^2. \tag{3.16}$$

$\bar{\mathbf{x}}_k$ is defined for transmitted signal before pre-processor. After pre-processing operation signal send through over the wireless channel. Before the post processing, transmitted signals can be expressed as,

$$\mathbf{H}_{k_{ij}}\mathbf{x}_k = \mathbf{U}\boldsymbol{\Lambda}\mathbf{V}^H\mathbf{V}\bar{\mathbf{x}}_k = \mathbf{U}\boldsymbol{\Lambda}\bar{\mathbf{x}}_k. \tag{3.17}$$

Received signal at the antenna input $\mathbf{y}_{k_i}$, is passing through post-processing blocks operated via $\mathbf{U}^H$, then $\bar{\mathbf{y}}_{k_i}$ is obtained as desired signal. Equivalent relationship can be described as,

$$\bar{\mathbf{y}}_{k_i} = \mathbf{\Lambda}\bar{\mathbf{x}}_k + \bar{\mathbf{n}}_{k_i}, \tag{3.18}$$

where $\bar{\mathbf{n}}_{k_i}$ is post processed noise component given as $\bar{\mathbf{n}}_{k_i} = \mathbf{U}^H \mathbf{n}_{k_i}$. Each output of the pre and post processing operation, is given following below.

$$\bar{y}_{k_i} = \begin{cases} \lambda_k \bar{x}_{k_i} + \bar{n}_{k_i} & \text{for } k = 1, 2, \cdots, r_H \\ \bar{n}_{k_i} & \text{for } k = r_H + 1, r_H + 2, \cdots, N_r \quad \text{when } r_H \leq N_r \end{cases} \tag{3.19}$$

In summary, signals transmitted over each independent eigen-channel, SNR of the each eigen-channel which is given as γ_k can be expressed as,

$$\gamma_k = \frac{\lambda_k}{\sigma_N^2}. \tag{3.20}$$

While P_k is given as transmit power term for each eigen-channel, $\sum_{k=1}^{r_H} P_k \leq P$ is provided with P is defined as average transmit power. The MIMO channel capacity is expressed as,

$$C_{MIMO} = \max \sum_{i=1}^{r_H} \log_2(1 + P_k \frac{\lambda_k}{\sigma_N^2}) \quad \text{subject to } \sum_{i=1}^{r_H} P_k \leq P. \tag{3.21}$$

Besides, with respect to water filling algorithm [60] the capacity of the time-invarient MIMO system can be re-expressed as,

$$C_{MIMO} = \max \sum_{i=1}^{r_H} \log_2 \det |\mathbf{I} + \frac{1}{\sigma_N^2} \mathbf{H}\mathbf{R}_{xx}\mathbf{H}^H|, \tag{3.22}$$

where $\mathbf{R}_{xx}$ is given as covariance matrix.

3.3 Detector Design for MIMO Systems

Detector design in MIMO systems is the challenging operation in contrast to SISO or SIMO systems due to spatial interference simultaneous from multi transmit and receive antennas. In order to eliminate this interference advanced signal processing techniques must be used in transmitter and receiver nodes. Linear detectors mostly used which are based on low complex architecture to estimate transmitted signals. ZF detector and MMSE detector are covered in this chapter as linear detectors in MIMO systems.

3.3.1 ZF detector

The ZF detector eliminates interference terms coming from other inter-channels. So as to solve desired signal components $\mathbf{\Upsilon}_{ZF}$ is used as a linear transformation matrix. $\mathbf{\Upsilon}_{ZF}$ which is defined as the pseudo-inverse of the channel matrix, can be expressed as,

$$\mathbf{\Upsilon}_{ZF} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H, \tag{3.23}$$

where $\mathbf{\Upsilon}_{ZF}$ is $N_t \times M_r$ sized matrix. Furthermore, $\mathbf{\Upsilon}_{ZF}\mathbf{H}$ matrix multiplication satisfies an $N_t \times N_t$ sized identity matrix, $\mathbf{\Upsilon}_{ZF}\mathbf{H} = \mathbf{I}$. Estimated symbols is indicated as $\hat{\mathbf{x}}_{ZF}$ at the receiver side can be obtained as follows.

$$\hat{\mathbf{x}}_{ZF} = \mathbf{\Upsilon}_{ZF}\mathbf{y}. \tag{3.24}$$

Furthermore, at high SNR performance of ZF detector is sufficient, yet under low SNR performance degradation occurred due to increasing of the noise variance.

3.3.2 MMSE detector

Mean square error between estimated vector and transmitted vector is minimized via MMSE detector. Linear transformation matrix which is given as $\mathbf{\Upsilon}_{MMSE}$ is a solution to minimize as following below.

$$\min_{\mathbf{\Upsilon}_{MMSE}} E[||\mathbf{x} - \mathbf{\Upsilon}_{MMSE}\mathbf{y}||^2] \tag{3.25}$$

In order to solve this minimization problem $\mathbf{\Upsilon}_{MMSE}$ is determined as,

$$\mathbf{\Upsilon}_{MMSE} = (\mathbf{H}^H\mathbf{H} + \sigma_N^2\mathbf{I})^{-1}\mathbf{H}^H \tag{3.26}$$

where $\mathbf{I}$ matrix is selected as a $N_t \times N_t$ sized identity matrix. Furthermore, estimated symbols at the output of the detector can be given as,

$$\hat{\mathbf{x}}_{MMSE} = \mathbf{\Upsilon}_{MMSE}\mathbf{y}. \tag{3.27}$$

BER performance of MMSE detector is better according to ZF detector considering entire rang of SNR. However, MMSE detector require knowledge of noise variances which is indicated as σ_N^2 at the oppose of ZF detector. On the other hand, similar to ZF detector performance degradation is occurred increasing receive antennas, N_t.

BER performance of BPSK modulated signal via ZF detector and MMSE detector is presented in Figure 3.6. Number of transmit and receive antennas as selected as $M_t = 2$, $N_t = 2$ in simulation and theoretical results. It can be seen that 3 dB BER performance improvement when switching from ZF to MMSE detector. Simulation results and theoretical analyses are matching as SISO system in ZF detector, yet in the system there is no diversity gain due to increase data rate. As indicated as above, transmit beamforming technique (MRT) in MISO systems and receive beamforming technique (MRC) in SIMO systems can bring diversity gain, however comparing to MIMO system data rate is decreased as half of it.

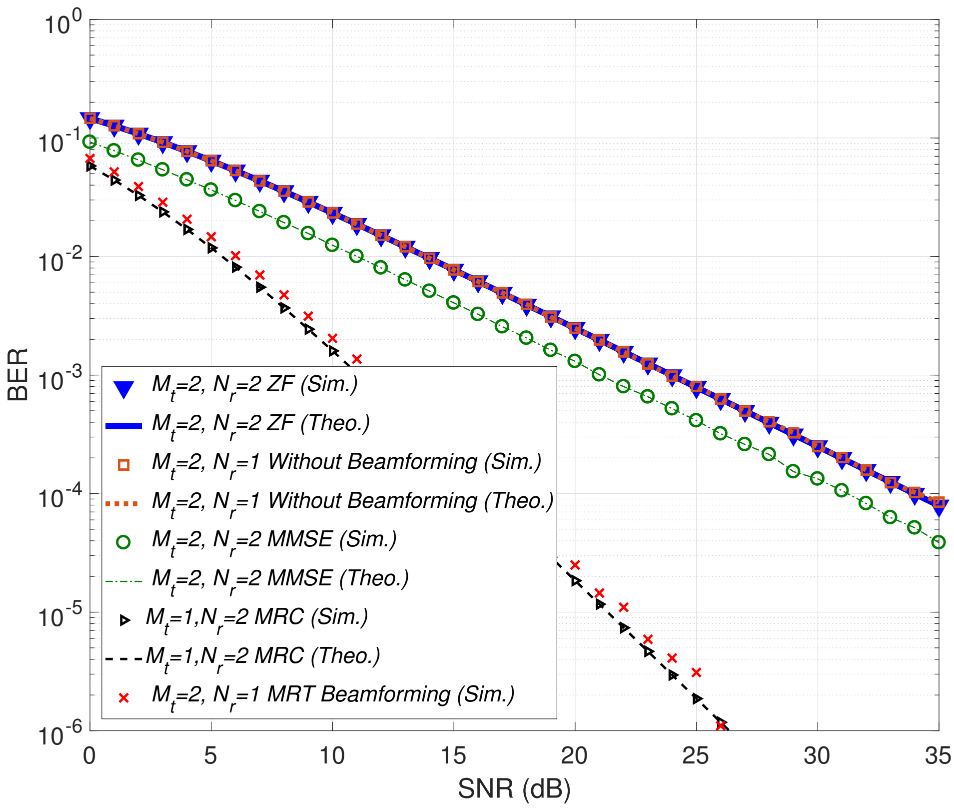

Figure 3.6 : BER performance of ZF and MMSE detectors according to transmit/receive diversity.

4. INTERFERENCE ALIGNMENT IN MIMO CRNs

4.1 Purpose

IA require sophisticated signal processing techniques both in transmitter and receiver side. Specifically this processing techniques also require robost processing hardware tools, yet in some cases hardware tools is not sufficient to constitute precoding and interference suppression matrices. It is caused interference leakage in the receiver side. Impact of interference leakage for MIMO CR networks with multiple SUs is covered in this chapter in order to observe the effects due to hardware inefficiency.

4.2 Linear Interference Alignment

MIMO systems could be used with multi-user case which is described as Figure 4.1. A set of users from 1 to K, which can be one or multi-antennas are decoded by a single destination. However, multi-user MIMO systems with multi receiver, traditional receiver architecture could not decode transmitted signals at the desired level due to infra-interference which is coming from other users. Interference alignment is used in multi-user MIMO case in order to overcome this issue.

Each user transmitter desire to communicate its pair via sending d_s data streams. Let x_u denoted as particular user in the network. Received signal at the each u^{th} user receiver can be obtained as,

$$\mathbf{y}_u = \mathbf{U}_u^H \mathbf{H}_{uu} \mathbf{V}_u \mathbf{x}_u + \sum_{j=1, j \neq u}^{K} \mathbf{U}_u^H \mathbf{H}_{uj} \mathbf{V}_j \mathbf{x}_j + \mathbf{U}_u^H \mathbf{n}_u. \tag{4.1}$$

where $\mathbf{U}_{uu}^H$ is the suppression matrix for each u^{th} receiver. Also, $\mathbf{V}_u$ and $\mathbf{V}_j$ are denoted for precoding matrices of desired symbols and interference symbols, respectively. Main purpose of IA is eliminate the interference term [61] which is indicated as $\sum_{j=1, j \neq u}^{K} \mathbf{U}_{uu}^H \mathbf{H}_{uj} \mathbf{V}_u \mathbf{x}_j$ by determining precoding and suppression matrices. It is also seen that noise term component giving with $\mathbf{U}_{uu}^H \mathbf{n}_u$. Main procedure of IA is described by Figure 4.2. Interference signals are aligned each other into null space of $\mathbf{U}_u^H$.

The following conditions described as,

$$\mathbf{U}_u^H \mathbf{H}_{uj} \mathbf{V}_u = 0, \forall j \neq u, \tag{4.2}$$

$$\text{rank}(\mathbf{U}_u^H \mathbf{H}_{uj} \mathbf{V}_u) = d_s, \tag{4.3}$$

must be satisfied in order to perfect linear IA.

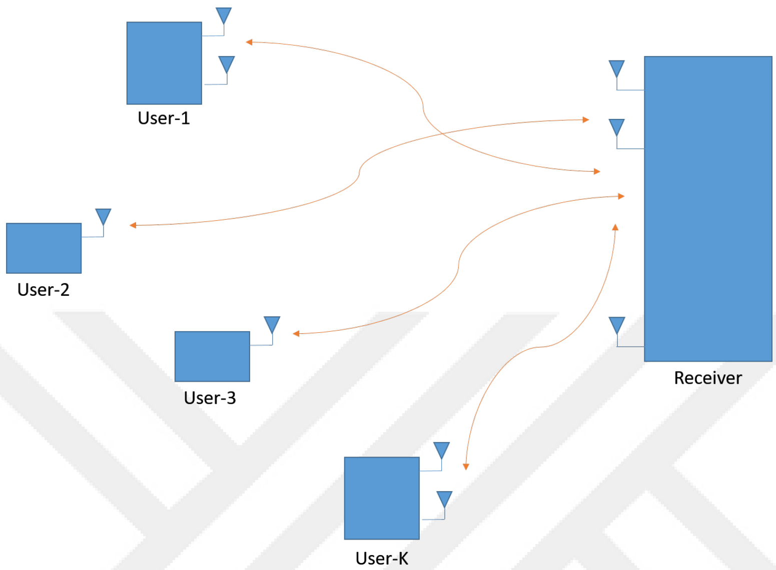

Figure 4.1 : Multi-user MIMO case with multi transmitter and a single receiver

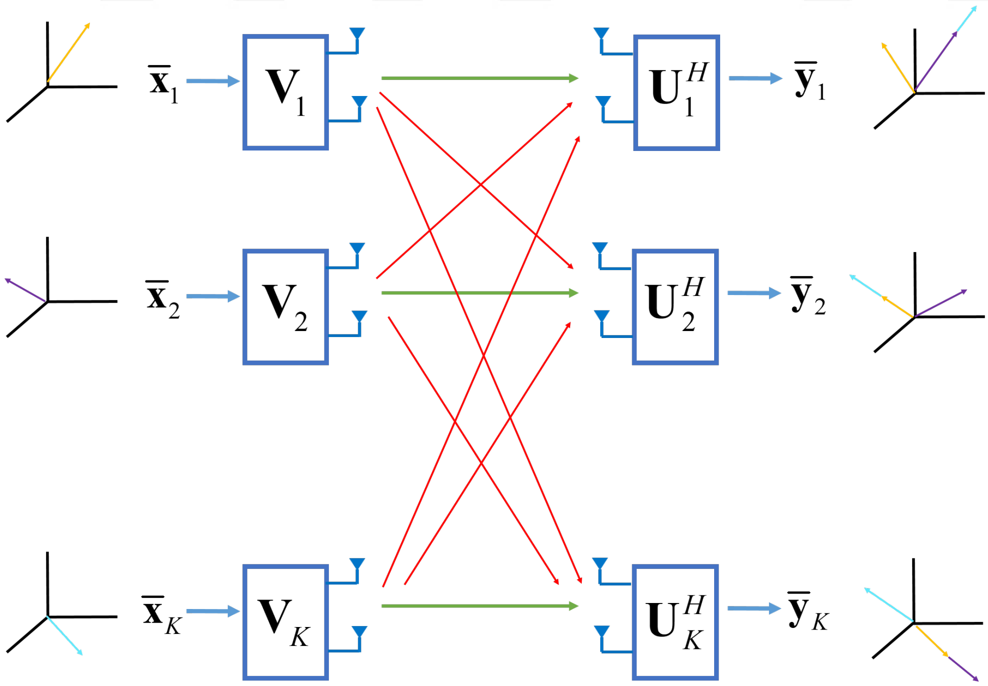

Figure 4.2 : IA structure for multi-user MIMO case.

4.3 System Model

In this chapter, interference alignment-based CR network with single PU and multiple SUs are considered under Rayleigh fading channel as shown in Figure 4.3. Both PU and SU can operate with SISO and MIMO mode. The number of transmit and receive antennas of the PU is given by M_p and N_p, respectively. The transmit antennas of each SU is expressed as M_s. The received signal, at the end of the primary node implementing the linear IA technique is given as,

$$\mathbf{y}_p = \mathbf{U}_p^{\mathrm{H}}\mathbf{H}_{pp}\mathbf{V}_p\mathbf{x}_p + \sqrt{\alpha}\sum_{i=1}^{K}\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i} + \mathbf{U}_p^{\mathrm{H}}\mathbf{n}, \tag{4.4}$$

where x_p and x_{s_i} are denoted for transmitted signals from PU and the i-th SU (for $i = 1,2,...,K$), respectively. In addition, $\mathbf{H}_{pp}$ is defined as the matrix of channel coefficients between the PU pair and $\mathbf{H}_{ps_i}$ denotes the channel matrix coefficients between the primary receiver and the i^{th} secondary transmitter node. Leakage which is occurred by misalignment, is modeled similar to the study in [62]. The interference leakage parameter as defined as α $(0 \leq \alpha \leq 1)$ represents the status of the alignment. For instance, perfect alignment and perfect misalignment cases are demonstrated $\alpha = 0$ and 1, respectively. In the formulation precoding and interference suppression matrices are denoted by $\mathbf{V}$ and $\mathbf{U}$, respectively. The superscript $(\cdot)^{\mathrm{H}}$ is represented as the Hermitian operator and $\mathbf{n}$ is the zero mean unit variance ($\sigma_N^2 = 1$) circularly symmetric additive white Gaussian noise (AWGN) vector. The following conditions must be satisfied by using the linear IA technique for perfect interference alignment between PU and SUs.

$$\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i} = 0, \tag{4.5}$$

$$\mathrm{Rank}(\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i}) = d_s. \tag{4.6}$$

Each user transmits d_s data streams under slow fading channel assumption. Using the ideal linear IA techniques, (4.4) can be re-expressed as,

$$\mathbf{y}_p = \mathbf{U}_p^{\mathrm{H}}\mathbf{H}_{pp}\mathbf{V}_p\mathbf{x}_p + \mathbf{U}_p^{\mathrm{H}}\mathbf{n}, \tag{4.7}$$

as $\sum_{i=1}^{K}\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i}$ is set to zero.

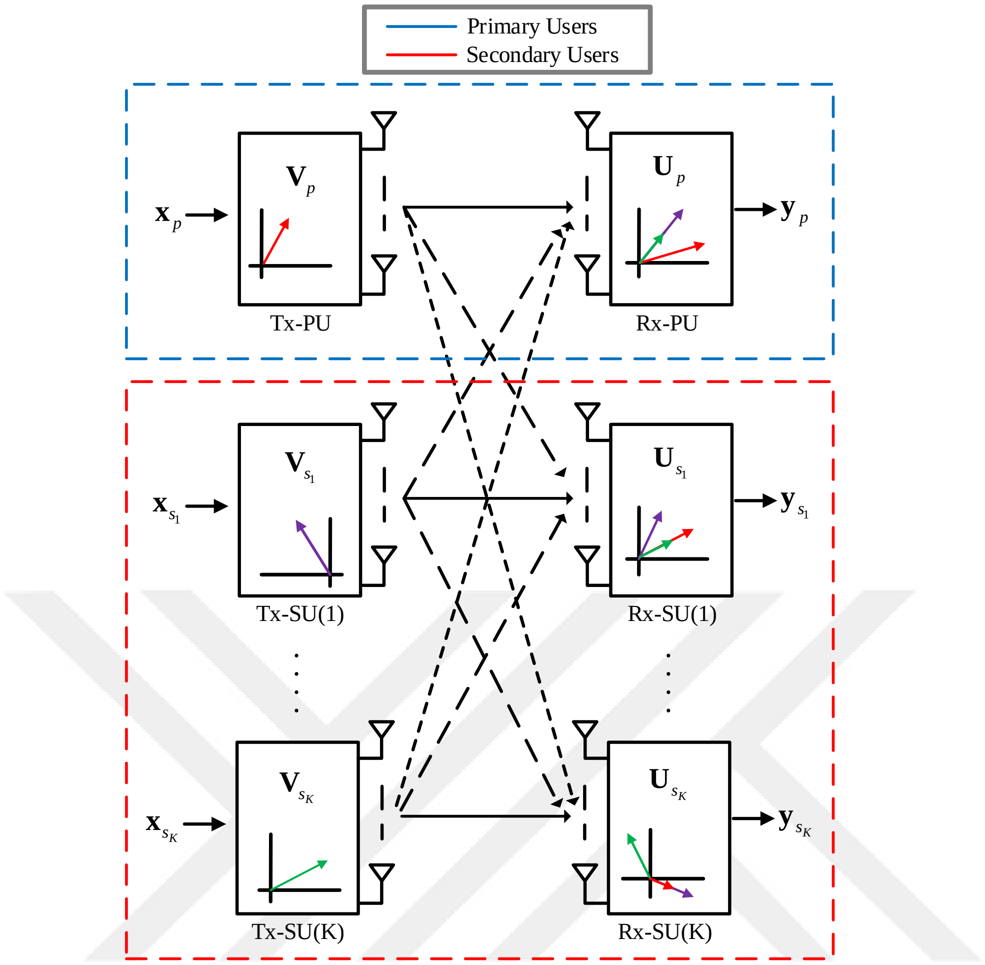

Figure 4.3 : IA-based CR network with single PU and K SUs sharing the spectrum.

4.4 Outage Probability Analysis

The channel capacity and outage probability are the most important factors which effect the quality of service (QoS) in wireless communication systems. The channel capacity can be obtained as

$$C = \log_2(1+\gamma_\tau) = \log_2\left(1+\frac{\gamma_1}{1+\gamma_2}\right), \tag{4.8}$$

where $\gamma_1 = \frac{P_1}{\sigma_N^2}|\mathbf{U}_p^{\mathrm{H}}|^2||\mathbf{H}_{pp}||^2|\mathbf{V}_p|^2$ is the signal-to-noise ratio (SNR) of the primary link. Besides, γ_2 can be expressed as $\gamma_2 = \frac{P_2}{\sigma_N^2}\sum_{i=1}^{K}||\mathbf{H}_{ps_i}||^2$. Squared Frobenius norm of the channel matrix is denoted by $||.||^2$. Transmit powers of the PU and SU are represented as P_1 and P_2, respectively. If linear IA perfectly eliminates the interference between SU and PU, then SNR of the interference channel, γ_2 becomes zero. Furthermore, precoding and linear suppression vectors are given as $|\mathbf{U}_p^{\mathrm{H}}|^2 = |\mathbf{V}_p|^2 = 1$. Though using multi-antennas in the primary nodes, in the presence of interference free communication, primary system works in the single-input and single-output (SISO) fashion [14]. Hence, the probability density function (PDF) of γ_1 can be expressed as $f_{\gamma_1}(\gamma) = \frac{1}{\bar{\gamma}_1}\exp(-\gamma/\bar{\gamma}_1)$ and the outage probability of the SISO system can be obtained as

$$P_{out} = \int_0^{2^{R_{th}}-1} f_{\gamma_1}(\gamma)d\gamma, \tag{4.9}$$

where R_{th} is the data rate threshold and $\bar{\gamma}_1 = \frac{P_1}{\sigma_N^2}$ denotes the average SNR of the primary system. By substituting $f_{\gamma_1}(\gamma)$ into (4.9), the outage probability can be obtained as,

$$P_{out} = 1 - \exp\Big(\frac{2^{R_{th}}-1}{\bar{\gamma}_1}\Big). \tag{4.10}$$

In the presence of interference, the primary system works in MIMO fashion and leakages may occur due to fast fading Rayleigh channel. To improve the performance of the primary system, we adopt maximum ratio transmission and maximum ratio combining at the transmitter node and receiver node respectively. Thereby, the end-to-end signal-to-interference noise ratio (SINR) of the primary system can be written as $\gamma_\tau = \frac{\gamma_1}{1+\gamma_2}$.

In the proposed system, all channels are modeled as independent and identically distributed Chi-squared distribution and the PDF of γ_1 can be expressed as

$$f_{\gamma_1}(\gamma) = \frac{\gamma^{M_pN_p-1}\exp\big(-\gamma/(\bar{\gamma}_1/M_p)\big)}{\Big(\frac{\bar{\gamma}_1}{M_p}\Big)^{M_pN_p}(M_pN_p-1)!}. \tag{4.11}$$

In addition, the PDF of γ_2 can be defined as

$$f_{\gamma_2}(\gamma) = \frac{\gamma^{KM_sN_p-1}\exp\big(-\gamma/(\alpha\bar{\gamma}_2/M_s)\big)}{\Big(\frac{\alpha\bar{\gamma}_2}{M_s}\Big)^{KM_sN_p}(KM_sN_p-1)!}, \tag{4.12}$$

where $\bar{\gamma}_2 = \frac{P_2}{\sigma_N^2}$ is the average SNR of the secondary system. Finally, the PDF of γ_τ can be written as,

$$f_{\gamma_\tau}(\gamma) = \int_0^\infty (x+1)f_{\gamma_1}((x+1)\gamma)f_{\gamma_2}(x)dx. \tag{4.13}$$

By substituting (4.11) and (4.12) into (4.13) then the with the help of [63, eq. 3.351.3] and after few manipulations, PDF expression of $f_{\gamma_\tau}(\gamma)$ is given as,

$$f_{\gamma_\tau}(\gamma) = \Delta\sum_{m=0}^{M_pN_p}\binom{M_pN_p}{m}(KM_sN_p+m-1)!\Big(\frac{\gamma M_p}{\bar{\gamma}_1}+\frac{M_s}{\alpha\bar{\gamma}_2}\Big)^{-KM_sN_p+m}. \tag{4.14}$$

Furthermore, collecting constant terms in (4.14), Δ is defined by

$$\Delta = \beta \gamma^{M_pN_p-1} \exp(-\frac{M_p\gamma}{\bar{\gamma}_1}). \tag{4.15}$$

Hereby, β is constituted as

$$\beta = \frac{\left(\frac{\bar{\gamma}_1}{M_p}\right)^{-M_pN_p} \left(\frac{\alpha\bar{\gamma}_2}{M_s}\right)^{-KM_sN_p}}{(M_pN_p-1)!\,(KM_sN_p-1)!}. \tag{4.16}$$

By using (4.9), the outage probability of the system can be expressed as under the specific boundary conditions given in Appendix A.1 ,

$$f_{\gamma_\tau}(\gamma) = \int_0^{\infty} \Delta \sum_{m=0}^{M_pN_p} \sum_{t=0}^{\infty} (-1)^t \binom{M_pN_p}{m} \binom{KM_sN_p+m+t-1}{t} \times (KM_sN_p+m-1)! \left(\frac{\gamma M_p}{\bar{\gamma}_1}\right)^t \left(\frac{M_s}{\alpha\bar{\gamma}_2}\right)^{KM_sN_p+m+t}. \tag{4.17}$$

4.5 Performance Evaluation

System performance of the cognitive radio network is demonstrated under interference leakage for Rayleigh fading channel by comparing the analytical results with computer simulations. For simplicity, power values of PU and SU are assumed as $P_1 = P_2 = \rho$ while noise power $\sigma_N^2 = 1$ in the performance evaluation.

Firstly, effect of the P_{out} performance for different R_{th} values is presented in Figure 4.4 and Figure 4.5. In SISO configuration, $\alpha = -30$ dB, $M_p = 1$, $N_p = 1$, $K = 1$, and $M_s = 1$ condition is considered. As a MIMO configuration, We take $\alpha = -20$ dB, $M_p = 2$, $N_p = 2$, $K = 5$, and $M_s = 1$. It can be seen from Figure 4.4 and Figure 4.5 that when R_{th} is increased from 1 to 4 bits/channel, the P_{out} performance is degraded. According to findings performance of P_{out} is better multi-antenna systems considering SISO counterpart. Increasing number of antennas could decrease effect of leakage keeping same R_{th} values, as expected. For instance, P_{out} performance SISO networks in $M_p = 1$, $N_p = 1$, $K = 1$, $M_s = 1$ and $\alpha = -30$ while $R_{th} = 1$ P_{out} performance values at 20 dB SNR is 1×10^{-2} level. However, P_{out} performance is observed as close to 1×10^{-4} level while $R_{th} = 1$ at 20 dB SNR with $M_p = 2$, $N_p = 2$, $K = 5$, $M_s = 1$ and $\alpha = -20$ dB. It is obvious that performance degradation due to increasing number of SUs and leakage can be decreased via increasing number of transmit/receive antennas of PUs, as expected.

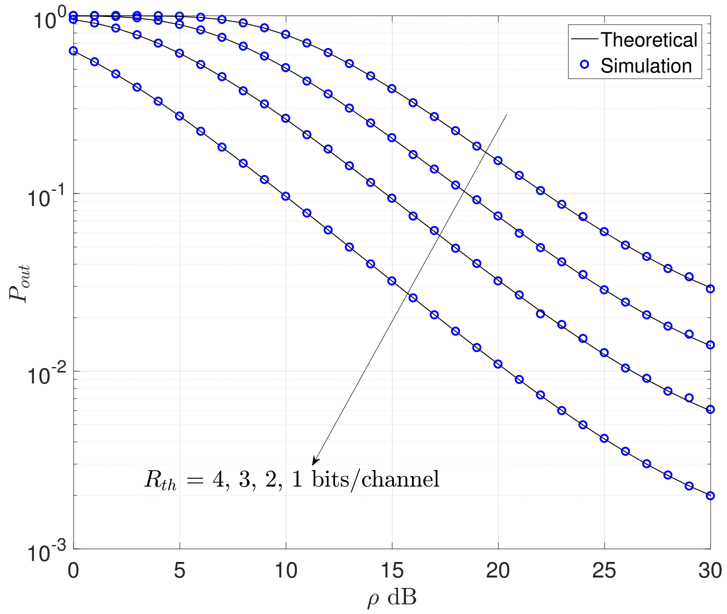

Figure 4.4 : P_{out} performance for different data rate threshold R_{th} when $\alpha = -30$ dB, $M_p = 1$, $N_p = 1$, $K = 1$ and $M_s = 1$.

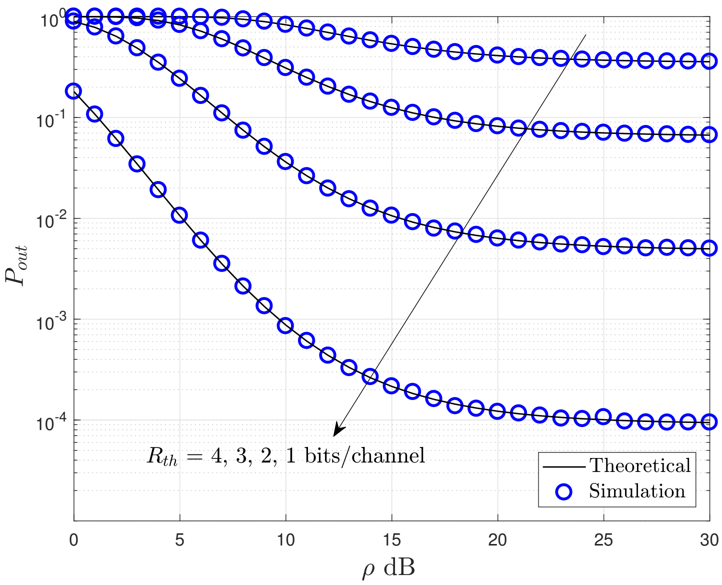

Figure 4.5 : P_{out} performance for different data rate threshold R_{th} when $\alpha = -20$ dB, $M_p = 2$, $N_p = 2$, $K = 5$ and $M_s = 2$.

Figure 4.6 depicts, the effect of interference leakage in SISO networks under $R_{th} = 1$ to bit/s/Hz and $K = 2$. When the interference leakage decreases, the outage probability is also observed to decrease. Furthermore, in Figure 4.7, the impact of the leakage coefficient, α on the outage probability performance is evaluated for $M_p = 2$, $N_p = 2$, $K = 1$, $M_s = 1$, and $R_{th} = 3$ bits/channel. As can be seen from the both two figures, when α is varied from -10 dB to -30 dB, the performance of the primary systems are enhanced.

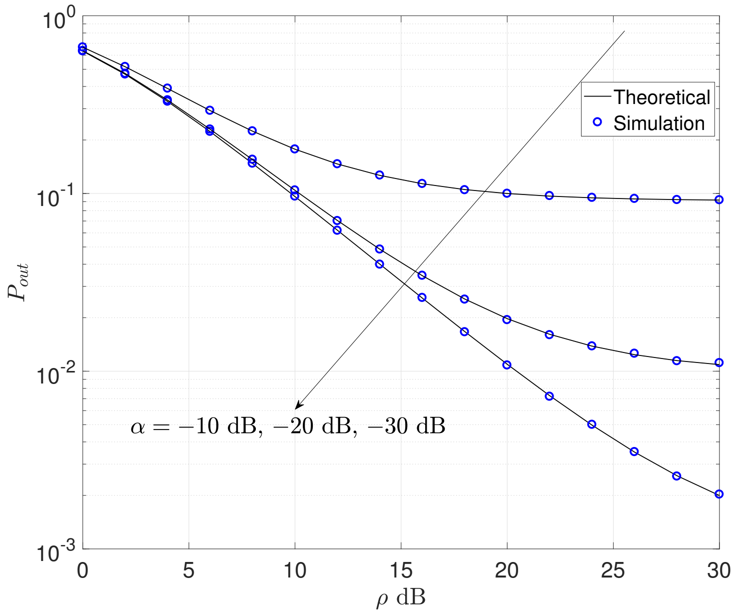

Figure 4.6 : P_{out} performance with varying SNR for different interference leakage values considering with $R_{th} = 1$ dB, $K = 2$, $M_p = 1$, $N_p = 1$ and $M_s = 1$.

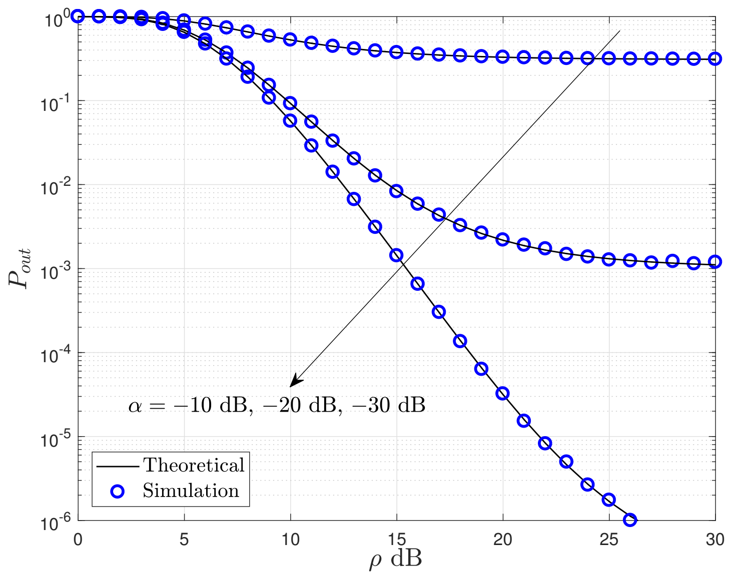

Figure 4.7 : P_{out} performance with varying SNR for different interference leakage values considering with $R_{th} = 3$ dB, $K = 1$, $M_p = 2$, $N_p = 2$ and $M_s = 1$.

The effect of number of secondary users on a SISO system performance is evaluated in Figure 4.8. α is taken as -30 dB, M_p, N_p, M_s and R_{th} are taken as 1, 1, 1, and 1 bits/s/Hz respectively. In Figure 4.9 we evaluate the MIMO configuration system parameters α, M_p, N_p, M_s and R_{th} are taken as -20 dB, 2, 2, 1, and 1 bits/channel respectively. It can be observed from the figures that increasing the number of SUs decreases the outage probability performance of the primary system considerably.

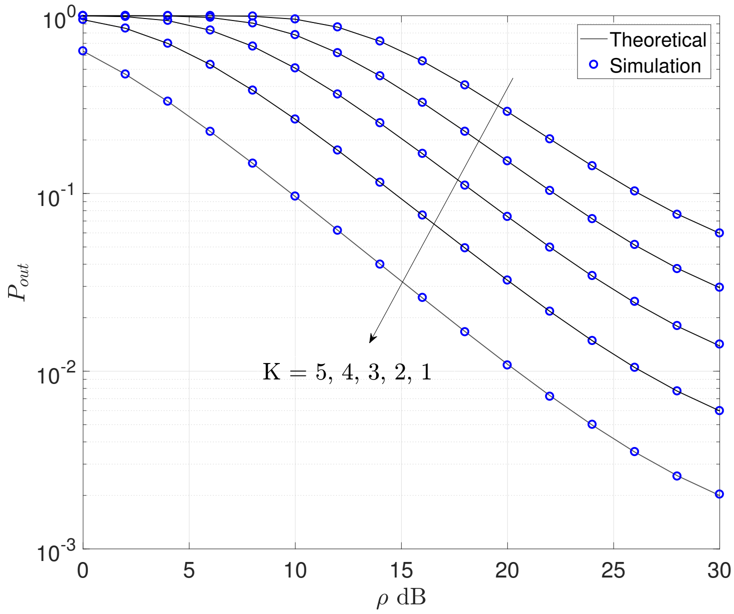

Figure 4.8 : P_{out} vs SNR when $\alpha = -30$ dB, $M_p = 1$, $N_p = 1$, $R_{th} = 1$ dB and $M_s = 1$.

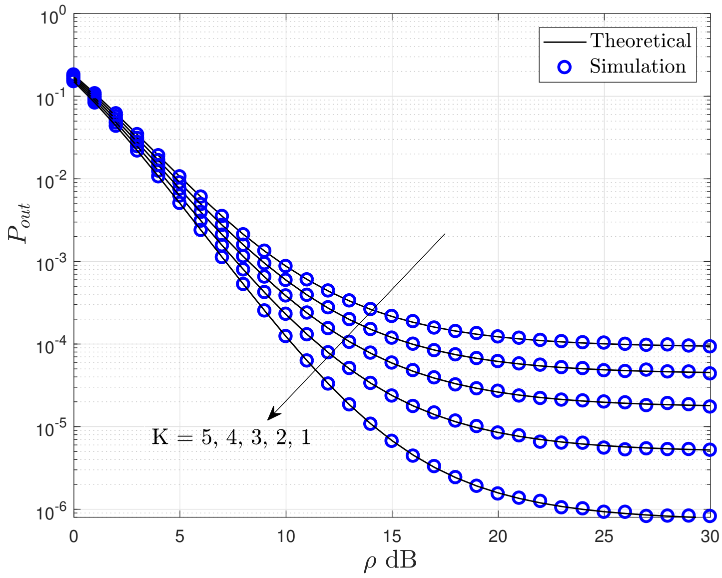

Figure 4.9 : P_{out} vs SNR when $\alpha = -20$ dB, $M_p = 2$, $N_p = 2$, $R_{th} = 1$ dB and $M_s = 1$.

In Figure 4.10, the impact of antenna diversity on the P_{out} performance is investigated for $\alpha = -10$ dB, $K = 2$ and $R_{th} = 1$ dB. It is observed from the figure that, when the number of antennas at the primary transmitter and receiver increases, the system performance enhances. Besides, the receiver diversity effect on the system performance is greater than the transmitter diversity, as expected.

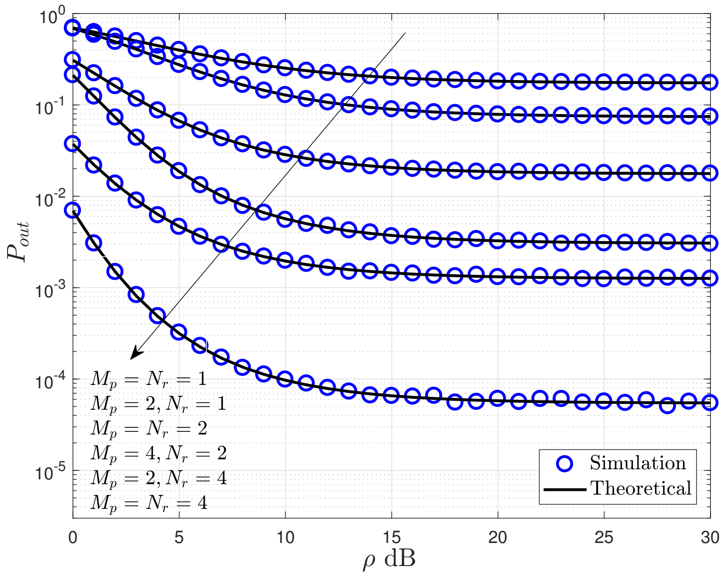

Figure 4.10 : The effect of antenna diversity on the outage probability performance considering with $\alpha = -10$ dB, $K = 2$ and $R_{th} = 1$ dB.

4.6 Conclusion

In this chapter, the system performance of linear IA on the MIMO CR network is investigated under interference leakage. To quantify the performance of the primary system under certain levels of interference leakage, the closed-form outage probability expression is derived for Rayleigh fading channel. In all analyses, the theoretical results match almost perfectly with the simulations, which confirm the accuracy of the derived expressions.

5. DESIGN OF MATRICES in MIMO CRNs

This chapter aims to present the basic signal processing algorithms used in matrix design for IA in MIMO networks. Interference due to interfering users can be minimized even perfectly eliminated via linear IA technique which collects the interference signals in a single subspace and provides the desired signal on the output. It is also noted that, both access techniques of CRN are sensitive to interference sources. Fundamental MIMO receiver structure is covered in previous sections, besides precoding and postcoding matrices referred as interference suppression matrix design in IA is demonstrated considering CRN. Water filling solution is a well-known method to increase MIMO system capacity [64]. Also linear precoder designs are already covered studies like [65–67]. IA method is used to eliminate interference components of both PUs and SUs in CRN.

5.1 System Model

In this chapter, MIMO interference alignment based CR network is considered with a single PU and multiple SUs. M_p and N_p are denoted as the number of transmit and receive antennas for PU, respectively. The transmit and receive antennas of each SU are given as M_s and N_s.

Each user transmits independent data streams to receiver nodes. Transmitted symbols from PU and SUs are denoted by x_p and x_{s_i}, respectively. Also, x_u is defined as a particular user selected within a combination set of primary user and secondary users describing by $\{x_u \mid x_u \in x_p, x_{s_i}\}$. All symbols of the users are generated independently and have a unit variance given with $E[x_u x_u^H] = \mathbf{I}_{q_s}$ where q_s is the number of data streams from user x_u. Channel coefficients and distance between the m^{th} transmitter and the n^{th} receiver can be represented as $\mathbf{H}_{nm}$ and d_{nm}, respectively. Network diagram of the proposed system is shown in Figure 5.1. Adjacent transmit and receive nodes are equally placed at d distance. Distance between each transmitter and receiver pair is also selected as d distance. Furthermore, path loss exponent is defined as v. Primary user

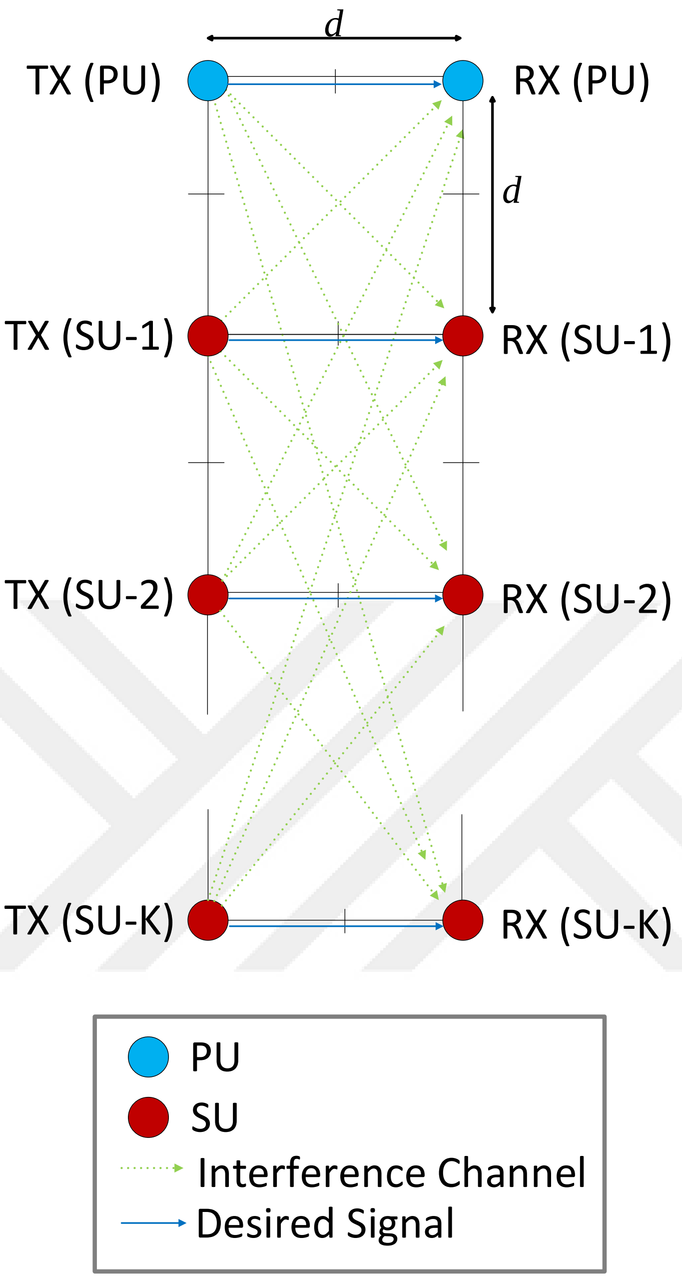

Figure 5.1 : CR based network diagram of the proposed system model. Adjacent transmit and receive nodes are equally placed at d distance.

power and each i^{th} secondary user's power are expressed as P_p and P_{s_i}, respectively. Received signal at the antenna input for primary receiver node which is denoted by $\mathbf{y}'_p$ is given as,

$$\mathbf{y}'_p = \sqrt{\frac{P_p}{1+d_{pp}^{v}}}\mathbf{H}_{pp}\mathbf{V}_p\mathbf{x}_p + \sum_{i=1}^{K}\sqrt{\frac{P_{s_i}}{1+d_{ps_i}^{v}}}\mathbf{H}_{ps_i}\mathbf{V}_{s_i}\mathbf{x}_{s_i} + \mathbf{n}_p, \tag{5.1}$$

where noise component for the primary user is denoted by $\mathbf{n}_p$. $\mathbf{H}_{pp}$ denotes for channel matrix coefficients between the primary transmitter and receiver pair. Besides, $\mathbf{H}_{ps_i}$ is the channel matrix coefficients between primary receiver and the i^{th} secondary transmitter. $\mathbf{V}_p$ stands for the precoding matrix with $M_p \times q_s$ for PU. Also, $N_p \times 1$ sized receiver signal vector, $\mathbf{y}'_p$, for PU is multiplicated with interference suppression matrix $\mathbf{U}_p^H$ with $q_s \times N_p$ sized used for symbol detection for PU. Received signal for PU, is given via,

$$\hat{\mathbf{x}}_p = \mathbf{U}_p^H \mathbf{y}'_p = \sqrt{\frac{P_p}{1+d_{pp}^v}} \mathbf{U}_p^H \mathbf{H}_{pp} \mathbf{V}_p \mathbf{x}_p + \sum_{i=1}^{K} \sqrt{\frac{P_{s_i}}{1+d_{ps_i}^v}} \mathbf{U}_p^H \mathbf{H}_{ps_i} \mathbf{V}_{s_i} \mathbf{x}_{s_i} + \mathbf{U}_p^H \mathbf{n}_p. \quad (5.2)$$

At the end of the i^{th} secondary node received signal can be expressed as,

$$\mathbf{y}'_{s_i} = \sqrt{\frac{P_{s_i}}{1+d_{s_i s_i}^v}} \mathbf{H}_{s_i s_i} \mathbf{V}_{s_i} \mathbf{x}_{s_i} + \sum_{j=1, j\neq i}^{K} \sqrt{\frac{P_{s_j}}{1+d_{s_i s_j}^v}} \mathbf{H}_{s_i s_j} \mathbf{V}_{s_j} \mathbf{x}_{s_j} + \sqrt{\frac{P_p}{1+d_{s_i p}^v}} \mathbf{H}_{s_i p} \mathbf{V}_p \mathbf{x}_p + \mathbf{n}_{s_i} \quad (5.3)$$

where $\mathbf{n}_{s_i}$ is denoted as the noise component for the i^{th} SUs. $N_s \times q_s$ sized precoding matrix for SUs is given by $\mathbf{V}_{s_i}$. Detected signal component multiplied by the $q_s \times N_s$ sized interference suppression matrix, $\mathbf{U}_{s_i}$, is given by,

$$\begin{aligned} \hat{\mathbf{x}}_{s_i} &= \mathbf{U}_{s_i}^H \mathbf{y}'_{s_i} \quad (5.4) \\ &= \sqrt{\frac{P_{s_i}}{1+d_{s_i s_i}^v}} \mathbf{U}_{s_i}^H \mathbf{H}_{s_i s_i} \mathbf{V}_{s_i} \mathbf{x}_{s_i} + \sum_{j=1, j\neq i}^{K} \sqrt{\frac{P_{s_j}}{1+d_{s_i s_j}^v}} \mathbf{U}_{s_i}^H \mathbf{H}_{s_i s_j} \mathbf{V}_{s_j} \mathbf{x}_{s_j} \\ &+ \sqrt{\frac{P_p}{1+d_{s_i p}^v}} \mathbf{U}_{s_i}^H \mathbf{H}_{s_i p} \mathbf{V}_p \mathbf{x}_p + \mathbf{U}_{s_i}^H \mathbf{n}_{s_i} \end{aligned}$$

where $\mathbf{U}_{s_i}^H \mathbf{H}_{s_i s_i} \mathbf{V}_{s_i} \mathbf{x}_{s_i}$ term is the desired signal component for SU. Furthermore, $\mathbf{U}_{s_i}^H \sum_{j=1, j\neq i}^{K} \mathbf{H}_{s_i s_j} \mathbf{V}_{s_j} \mathbf{x}_{s_j}$ terms are interference caused by the secondary network, whereas $\mathbf{U}_{s_i}^H \mathbf{H}_{s_i p} \mathbf{V}_p$ term is the interference caused by the primary network. To remove the interference terms following conditions,

$$\mathbf{U}_s^{\mathrm{H}} \mathbf{H}_{ps_i} \mathbf{V}_s \mathbf{x}_{s_i} = 0, \quad (5.5)$$

$$\mathrm{Rank}(\mathbf{U}_s^{\mathrm{H}} \mathbf{H}_{ps_i} \mathbf{V}_s \mathbf{x}_{s_i}) = q_s, \quad (5.6)$$

must be satisfied for the primary network. For the secondary network linear interference alignment conditions are given as,

$$\mathbf{U}_{s_i}^H \sum_{j=1, j\neq i}^{K} \mathbf{H}_{s_i s_j} \mathbf{V}_{s_j} \mathbf{x}_{s_j} + \mathbf{U}_{s_i}^H \mathbf{H}_{s_i p} \mathbf{V}_p \mathbf{x}_p = 0, \quad (5.7)$$

$$\mathrm{Rank}(\mathbf{U}_{s_i}^H \sum_{j=1, j\neq i}^{K} \mathbf{H}_{s_i s_j} \mathbf{V}_{s_j} \mathbf{x}_{s_j} + \mathbf{U}_{s_i}^H \mathbf{H}_{s_i p} \mathbf{V}_p \mathbf{x}_p) = q_s. \quad (5.8)$$

Also note that, channel information are assumed to be known both user classes for each transmitter and receiver.

5.2 Precoder Design for 3-User MIMO Case

In this section, precoding design procedure for a single PU and two SUs with MIMO structure is covered in Figure 5.2. Antenna pairs of the primary and secondary users, i.e., M_p, N_p, M_s, N_s are equally selected as M antennas, also M is assumed to be even. Received signal components for PU and SUs from (5.1) and (5.3) are given as,

$$\mathbf{y}'_p = \sqrt{\frac{P_p}{1+d_{pp}^v}}\mathbf{H}_{pp}\mathbf{V}_p\mathbf{x}_p + \sqrt{\frac{P_{s_1}}{1+d_{ps_1}^v}}\mathbf{H}_{ps_1}\mathbf{V}_{s_1}\mathbf{x}_{s_1} + \sqrt{\frac{P_{s_2}}{1+d_{ps_2}^v}}\mathbf{H}_{ps_2}\mathbf{V}_{s_2}\mathbf{x}_{s_2} + \mathbf{n}_p, \tag{5.9}$$

$$\mathbf{y}'_{s_1} = \sqrt{\frac{P_{s_1}}{1+d_{s_1s_1}^v}}\mathbf{H}_{s_1s_1}\mathbf{V}_{s_1}\mathbf{x}_{s_1} + \sqrt{\frac{P_{s_2}}{1+d_{s_2s_2}^v}}\mathbf{H}_{s_2s_2}\mathbf{V}_{s_2}\mathbf{x}_{s_2} + \sqrt{\frac{P_p}{1+d_{s_1p}^v}}\mathbf{H}_{s_1p}\mathbf{V}_p\mathbf{x}_p + \mathbf{n}_{s_1}, \tag{5.10}$$

$$\mathbf{y}'_{s_2} = \sqrt{\frac{P_{s_2}}{1+d_{s_2s_2}^v}}\mathbf{H}_{s_2s_2}\mathbf{V}_{s_2}\mathbf{x}_{s_2} + \sqrt{\frac{P_{s_1}}{1+d_{s_2s_1}^v}}\mathbf{H}_{s_2s_1}\mathbf{V}_{s_1}\mathbf{x}_{s_1} + \sqrt{\frac{P_p}{1+d_{s_2p}^v}}\mathbf{H}_{s_2p}\mathbf{V}_p\mathbf{x}_p + \mathbf{n}_{s_2}. \tag{5.11}$$

Channel matrix coefficients from the m^{th} transmitter and the n^{th} receiver is given by $M \times M$ full matrix $\mathbf{H}_{nm}$. Users are able to transmits $\frac{M}{2} \times 1$ sized data stream. $\mathbf{x}_p$ is the transmitted data streams for PU, while $\mathbf{x}_{s_1}$ and $\mathbf{x}_{s_2}$ are transmitted data for SUs respectively.

So as to decode received signal components perfectly, precoders of the given system must satisfy following conditions.

$$\begin{aligned} \text{span}(\mathbf{H}_{ps_1}\mathbf{V}_{s_1}) &= \text{span}(\mathbf{H}_{ps_2}\mathbf{V}_{s_2}), \\ \text{span}(\mathbf{H}_{s_1p}\mathbf{V}_p) &= \text{span}(\mathbf{H}_{p_1s_2}\mathbf{V}_{s_2}), \\ \text{span}(\mathbf{H}_{s_2p}\mathbf{V}_p) &= \text{span}(\mathbf{H}_{s_2s_1}\mathbf{V}_{s_1}), \end{aligned} \tag{5.12}$$

where, span($\boldsymbol{\nu}$) demonstrate the spanned vector space by a column vector $\boldsymbol{\nu}$. After mathematical manipulations, precoding matrix for PU can be given as,

$$\text{span}(\mathbf{V}_p) = \text{span}(\boldsymbol{\zeta}\mathbf{V}_p). \tag{5.13}$$

Where $\boldsymbol{\zeta}$ is expressed as,

$$\boldsymbol{\zeta} = \mathbf{H}_{s_2p}^{-1}\mathbf{H}_{s_2s_1}\mathbf{H}_{ps_1}^{-1}\mathbf{H}_{ps_2}\mathbf{H}_{s_1s_2}^{-1}\mathbf{H}_{s_1p}. \tag{5.14}$$

Eventually, $\mathbf{V}_p$ is determined as,

$$\mathbf{V}_p = \begin{bmatrix} c_1 & c_2 & \dots & c_{\frac{M}{2}} \end{bmatrix} \tag{5.15}$$

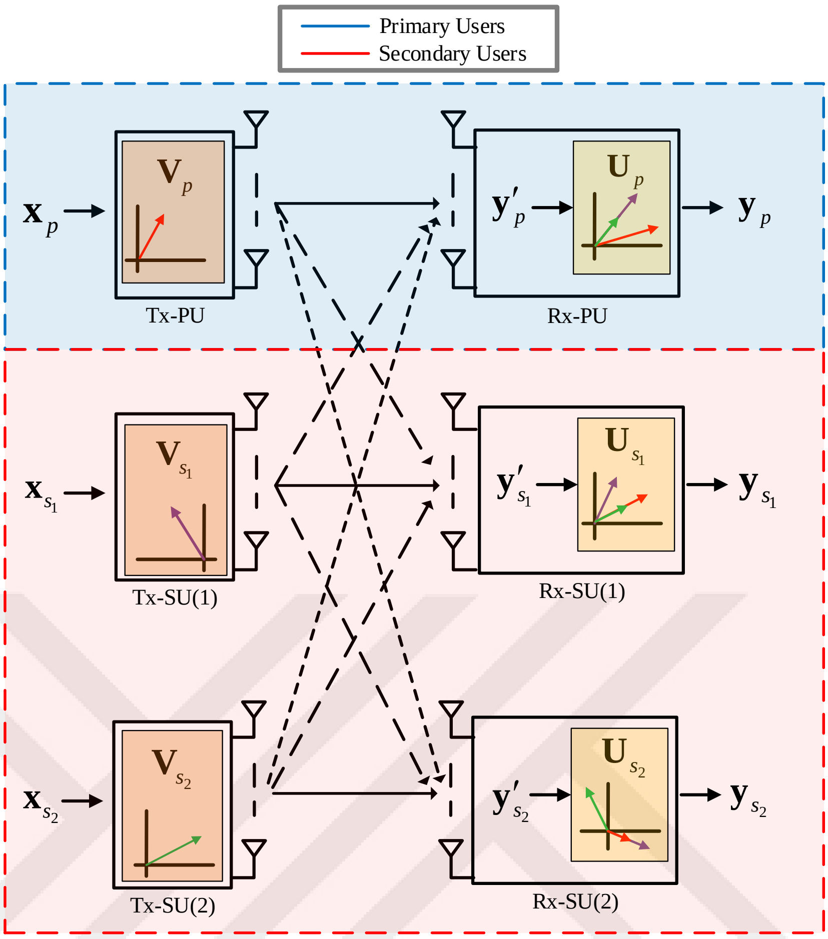

Figure 5.2 : A single PU and two SUs pair sharing the same spectrum. Each user is an interference source to another users.

where $c_1, c_2 \dots c_{\frac{M}{2}}$ are the eigenvectors of $\boldsymbol{\zeta}$. By using (5.13), $\mathbf{V}_{s_1}$ and $\mathbf{V}_{s_2}$ are determined as

$$\mathbf{V}_{s_1} = \mathbf{H}_{s_2 s_1}^{-1} \mathbf{H}_{s_2 p} \mathbf{V}_p, \tag{5.16}$$

and

$$\mathbf{V}_{s_2} = \mathbf{H}_{s_2 s_1}^{-1} \mathbf{H}_{s_1 p} \mathbf{V}_p. \tag{5.17}$$

5.3 Precoder Optimization Methods and Interference Suppression Matrix Design for ZF Decoder

After precoding components are obtained considering signal space components of each user, interference suppression matrix must be completed to eliminate interfering users. QR decomposition of the precoding matrix of each user is given as,

$$\mathbf{V}_u = \mathbf{Q}_u \mathbf{R}_u, \tag{5.18}$$

where u is a set of a single PU and two SUs transceiver pair, $u \in \{p, s_1, s_2\}$. Furthermore, $\mathbf{Q}_u$ is given for $M \times \frac{M}{2}$ sized orthonormal basis vector. $\mathbf{R}_u$ is denoted by $\frac{M}{2} \times \frac{M}{2}$ sized upper triangular matrix. First, precoder of each user must be modified considering zero-forcing detector. For the primary user,

$$\mathbf{V}_{z,p} = \mathbf{Q}_p \mathbf{Z}_p \tag{5.19}$$

where, $\mathbf{V}_{z,p}$, $\mathbf{Q}_p$ and $\mathbf{Z}_p$ are indicated for zero-forcing modified precoder for PU, orthonormal basis vector after QR decomposition for PU, and transmit power constraint matrix for PU, respectively. Using a similar approach for the SU, ZF precoder can be expressed as,

$$\mathbf{V}_{z,s_1} = \mathbf{Q}_{s_1} \mathbf{Z}_{s_1} \tag{5.20}$$

$$\mathbf{V}_{z,s_2} = \mathbf{Q}_{s_2} \mathbf{Z}_{s_2}. \tag{5.21}$$

For PU considering (5.9) received signal can be expressed as,

$$\mathbf{y}'_p = \sqrt{\frac{P_p}{1+d_{pp}^v}} \mathbf{F}_{pp} \mathbf{Z}_p \mathbf{x}_p + \sqrt{\frac{P_{s_1}}{1+d_{ps_1}^v}} \mathbf{F}_{ps_1} \mathbf{Z}_{s_1} \mathbf{x}_{s_1} + \sqrt{\frac{P_{s_2}}{1+d_{ps_2}^v}} \mathbf{F}_{ps_2} \mathbf{Z}_{s_2} \mathbf{x}_{s_2} + \mathbf{n}_p. \tag{5.22}$$

By the similar way, considering (5.10) and (5.11) the received signal for the SUs can be given as

$$\mathbf{y}'_{s_1} = \sqrt{\frac{P_{s_1}}{1+d_{s_1s_1}^v}} \mathbf{F}_{s_1s_1} \mathbf{Z}_{s_1} \mathbf{x}_{s_1} + \sqrt{\frac{P_{s_2}}{1+d_{s_2s_2}^v}} \mathbf{F}_{s_1s_2} \mathbf{Z}_{s_2} \mathbf{x}_{s_2} + \sqrt{\frac{P_p}{1+d_{s_1p}^v}} \mathbf{F}_{s_1p} \mathbf{Z}_p \mathbf{x}_p + \mathbf{n}_{s_1}, \tag{5.23}$$

$$\mathbf{y}'_{s_2} = \sqrt{\frac{P_{s_2}}{1+d_{s_2s_2}^v}} \mathbf{F}_{s_2s_2} \mathbf{Z}_{s_2} \mathbf{x}_{s_2} + \sqrt{\frac{P_p}{1+d_{s_2p}^v}} \mathbf{F}_{s_2p} \mathbf{Z}_p \mathbf{x}_p + \sqrt{\frac{P_{s_1}}{1+d_{s_2s_1}^v}} \mathbf{F}_{s_2s_1} \mathbf{Z}_{s_1} \mathbf{x}_{s_1} + \mathbf{n}_{s_2}, \tag{5.24}$$

where, $\mathbf{F}$ is defined as $M \times \frac{M}{2}$ sized effective channel matrix given by,

$$\mathbf{F}_{nm} = \mathbf{H}_{nm}\mathbf{Q}_{m}. \tag{5.25}$$

One of the interfering matrices can be choosen for elimination of these interference sources, and singular value decomposition (SVD) of the effective channel matrix is applied as follows.

$$\mathbf{F}_{nm} = [\mathbf{S}_{nm}^{(1)} \ \ \mathbf{S}_{nm}^{(0)}][\mathbf{\Lambda}_{nm} \ \ \mathbf{0}]^{T}[\mathbf{D}_{nm}^{H}], \tag{5.26}$$

where, $\mathbf{S}_{nm}^{(1)}$ is denoted for $\frac{M}{2}$ left singular vectors, besides $\mathbf{S}_{nm}^{(0)}$ is given for $\frac{M}{2}$ right singular vector components. Also, $\mathbf{\Lambda}_{nm}$ is a diagonal matrix and $\mathbf{D}_{nm}$ is a complex unitary matrix. $\mathbf{T}_u$ is defined for each user and it can be expressed considering (5.26) to eliminate interference term selected as, $\mathbf{T}_u = [\mathbf{S}_{nm}^{(0)}]^H$. Furthermore, block channel matrix, $\mathbf{B}_u$, can be determined considering, $\mathbf{B}_u = \mathbf{T}_u\mathbf{F}_{uu}$. SVD of the block channel matrix for each user $\mathbf{B}_u$ is denoted as $\mathbf{B}_u = \mathbf{S}_u\mathbf{\Lambda}_u\mathbf{D}_u^H$. Also, transmit power constraint matrix for each user, $\mathbf{Z}_u$, can be expressed as $\mathbf{Z}_u = \mathbf{D}_u\sqrt{\boldsymbol{\varepsilon}_u}$. Furthermore, $\boldsymbol{\varepsilon}_u$ indicates diagonal power matrix terms which is constituted with respect to water-filling optimization expressed by,

$$\max_{\boldsymbol{\varepsilon}_u} \log_2 \left|\mathbf{I} + \frac{1}{\sigma_N^2}\mathbf{V}_u\boldsymbol{\varepsilon}_u\right| \quad \text{subject to} \quad Tr(\boldsymbol{\varepsilon}_u) \leq P_u. \tag{5.27}$$

Also, interference suppression matrix and precoding matrix for each user can be determined as,

$$\mathbf{U}_u^H = \mathbf{S}_u^H\mathbf{T}_u \tag{5.28}$$

$$\mathbf{V}_u = \mathbf{Q}_u\mathbf{Z}_u = \mathbf{Q}_u\mathbf{D}_u\sqrt{\boldsymbol{\varepsilon}_u} \tag{5.29}$$

Eventually, estimated symbols for the PU can be expressed as,

$$\hat{\mathbf{x}}_p = \mathbf{U}_p^H\mathbf{y}_p' = \mathbf{D}_p\sqrt{\boldsymbol{\varepsilon}_p}\mathbf{x}_p + \mathbf{U}_p^H\mathbf{n}_p. \tag{5.30}$$

Also, estimated symbols for SUs can be written as,

$$\hat{\mathbf{x}}_{s_1} = \mathbf{U}_{s_1}^H\mathbf{y}_{s_1}' = \mathbf{D}_{s_1}\sqrt{\boldsymbol{\varepsilon}_{s_1}}\mathbf{x}_{s_1} + \mathbf{U}_{s_1}^H\mathbf{n}_{s_1}, \tag{5.31}$$

$$\hat{\mathbf{x}}_{s_2} = \mathbf{U}_{s_2}^H\mathbf{y}_{s_2}' = \mathbf{D}_{s_2}\sqrt{\boldsymbol{\varepsilon}_{s_2}}\mathbf{x}_{s_2} + \mathbf{U}_{s_2}^H\mathbf{n}_{s_2}. \tag{5.32}$$

Information rate of PU can be easily computed by,

$$R_p = \log_2|\mathbf{I} + \mathbf{B}_p\mathbf{Z}_p\mathbf{Z}_p^H\mathbf{B}_p^H(\sigma_N^2\mathbf{T}_p\mathbf{T}_p^H)^{-1}| \tag{5.33}$$

$$= \log_2|\mathbf{I} + \frac{1}{\sigma_N^2}\mathbf{V}_p\mathbf{D}_p^H\mathbf{Z}_p\mathbf{Z}_p^H\mathbf{D}_p\mathbf{V}_p^H|. \tag{5.34}$$

With a similar approach, information rate for the first SU can be expressed as,

$$R_{s_1} = \log_2 |\mathbf{I} + \mathbf{B}_{s_1}\mathbf{Z}_{s_1}\mathbf{Z}_{s_1}^H\mathbf{B}_{s_1}^H(\sigma_N^2\mathbf{T}_{s_1}\mathbf{T}_p^H)^{-1}| \tag{5.35}$$

$$= \log_2 |\mathbf{I} + \frac{1}{\sigma_N^2}\mathbf{V}_{s_1}\mathbf{D}_{s_1}^H\mathbf{Z}_{s_1}\mathbf{Z}_{s_1}^H\mathbf{D}_{s_1}\mathbf{V}_{s_1}^H|, \tag{5.36}$$

and the second SU is expressed as,

$$R_{s_2} = \log_2 |\mathbf{I} + \mathbf{B}_{s_2}\mathbf{Z}_{s_2}\mathbf{Z}_{s_2}^H\mathbf{B}_{s_2}^H(\sigma_N^2\mathbf{T}_{s_2}\mathbf{T}_{s_2}^H)^{-1}| \tag{5.37}$$

$$= \log_2 |\mathbf{I} + \frac{1}{\sigma_N^2}\mathbf{V}_{s_2}\mathbf{D}_{s_2}^H\mathbf{Z}_{s_2}\mathbf{Z}_{s_2}^H\mathbf{D}_{s_2}\mathbf{V}_{s_2}^H|. \tag{5.38}$$

5.4 Numerical Results

In this section, sum rate performances are evaluated for $M \times M$ MIMO networks in CRN with ZF-based detector. Numerical results are presented for a single PU and two SU pairs in the proposed system. Each primary transmitter and each secondary transmitters transmit with power constraints P_p and P_s, respectively. Furthermore, SNR expression for the PU is given by $\frac{P_u}{\sigma_N^2}$. Besides, SNR is defined as $\frac{P_s}{\sigma_N^2}$ for each SUs. Also, channel matrix for MIMO represented by $\mathbf{H}$ is consituted via Rayleigh fading coefficients, i.i.d. complex Gaussian distributed with zero mean and unit variance.

Figure 5.3 illustrates MIMO performances in the presence of two interference channels caused by two secondary users in the system. BPSK modulated symbols are used as both PUs' and SUs' symbols. Moreover, distance among the nodes d, and the path loss exponent, v is taken as 1m and 4, respectively. Information rate of the PU which is indicated as R_p is given with respect to SNR covering with different $M \times M$ MIMO antenna configurations. As the SNR value increases, the average data rate also increases as expected. According to findings, when the M increases then R_p enhances.

Effect of the distance of the nodes d at the PU receiver is presented in Figure 5.4. Simulation is operated via BPSK modulated symbols, besides path loss exponent, v, is taken as 4 with 2×2 MIMO channels. Increasing distance from 0.25 m to 3 m adversely affects the performance of R_p. For instance, alteration distance from 0.25m to 2m effect R_p performance degradation from 9 bit/s/Hz to 5 bit/s/Hz at 30 dB SNR. However, when $d \geq 1$ this impact can be observed significantly due to the path loss model.

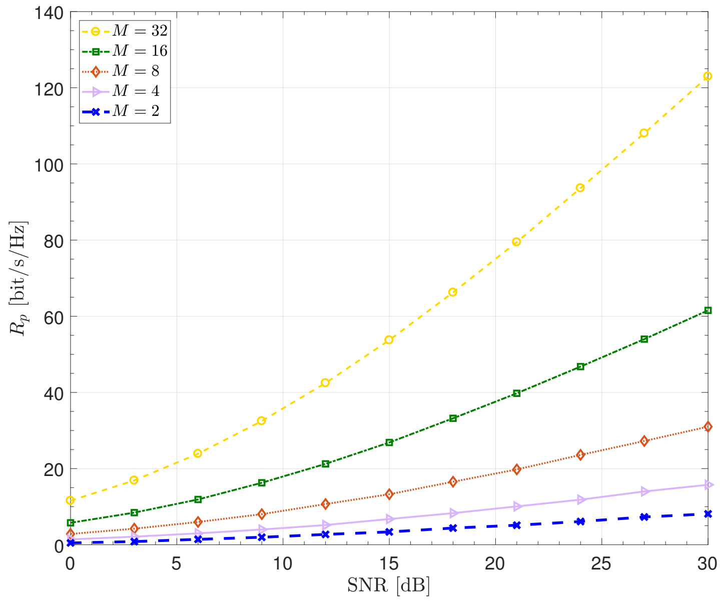

Figure 5.3 : Information rate for PU vs SNR with different $M \times M$ MIMO antenna configurations.

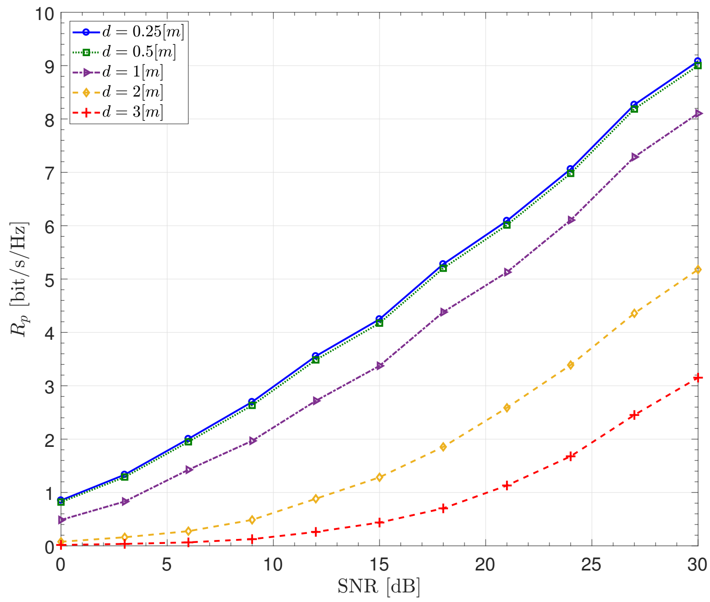

Figure 5.4 : Information rate for PU vs varying distance level from 0.25m to 3m.

Figure 5.5 presents information rate performances of the first SU with respect to the relative power of PU in the proposed system. Simulation is performed when $d = 1$ and path loss exponent is taken as $v = 4$. When secondary users' power P_s is equally selected to primary users' power, sum rate performances are increased with regards to lower power level of secondary users, as expected. Yet, at lower power values of SUs are evaluated corresponding relative power of PUs. Considering underlay CRNs, information rate of first SU, P_s, is evaluated approximately as 8.2, 7.1 and 5 bit/s/Hz at

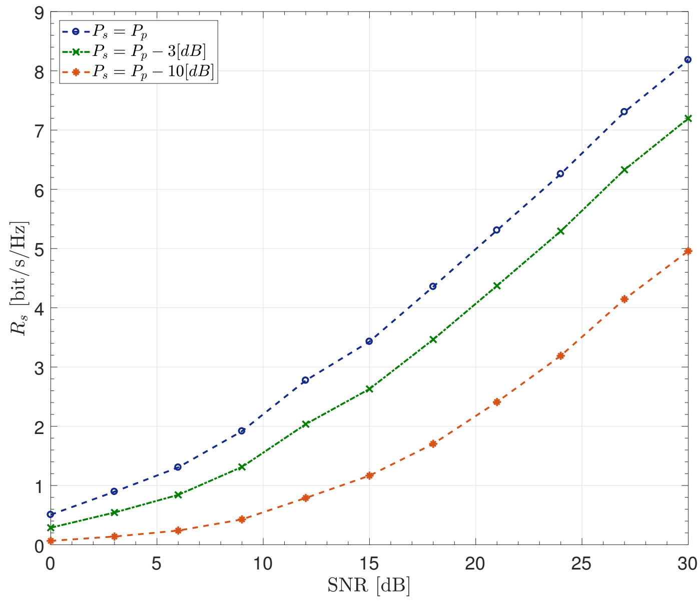

Figure 5.5 : Information rate performance of first SU corresponding to relative power of PU.

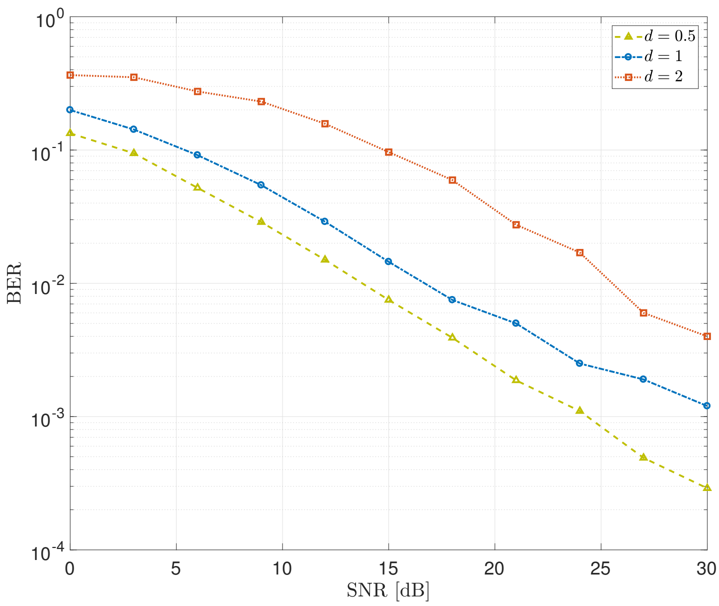

Figure 5.6 : BER performance of 2×2 MIMO system in a presence of two SUs transceiver pair with respect to distance.

30 dB SNR under while secondary users' power is taken as $P_s = P_p$, $P_s = P_p - 3$ and $P_s = P_p - 30$, respectively.

Figure 5.6 evaluates BER performances of first SU via 2×2 MIMO system considering a varying distance, d. It is observed that as the distance increases, the bit error performance decreases significantly. For instance, BER performance of first SU transceiver pair is observed as approximately 8×10^{-3}, 1×10^{-3} and 6×10^{-2} at 30 dB SNR distances with $d = 0.5$, $d = 1$ and $d = 2$, respectively.

5.5 Conclusion Remarks

In this chapter, sum rate and BER performances of a CRN with a single PU and two SUs pair are evaluated via numerical results. In order to reduce the effect of interference, linear IA is applied to aforementioned system. Furthermore, water filling performance is examined via linear IA technique considering different path loss, distance, and number of antennas. As the underlay CR aspects, information rate performance is also achieved with lower power than PU. Considering PUs' and SUs' BER performance is sufficient at low distance, yet increasing distance degrades network performance of both PU and SUs with regards to information rate and bit error performance.

6. CONCLUSIONS

The IA technique is based on the destruction of interference components occurring in MIMO channels. Among the interference alignment techniques that have many different types in the literature, the most widely used technique is the linear interference alignment technique. The IA technique is compatible with the MIMO network structure and uses the way that the interference sources are aligned in to beam same direction besides that the precoder matrices and the interference suppression matrices are designed to fit into nullspace of desired signal. However, the alignment of interference components is accompanied by the use of strong signal processing techniques. Channel status information related to this must be integrated in the receiver structures in the same way. In addition, the method of alignment of the enterprise is suitable for CR networks, which is emphasized in the literature because the interference components are eliminated.

In the thesis firstly, the performance of interference alignment in MIMO CR networks is given. A proposed architecture is a system in which a primary user pair with a single user and a large number of secondary users co-exist. As the numbers of secondary users increase, the performance of primary users in MIMO networks is observed to decrease. However, in the presence of interference leaks due to misalignment, system performance is expressed in terms of outage probability in fast fading channels. On the other hand, the outage probability function in the primary receiver node was obtained from closed form mathematical derivations and examined from various parameters and validated via Monte-Carlo simulation results. Increasing number of secondary users significantly affects the primary user's system performance in the negative direction. Similarly, interference leaks originating from misalignment are modeled and the effect of these increases on the likelihood of outage probability is examined. In addition to these, performance enhancements brought about by diversity gain have been observed for different antenna transmit and receive antenna counts. However, with regard to the data transmission thresholds in MIMO transmission, the outage probability have been examined in different situations.

In the second part of the thesis, the design of the precoder and interference suppression matrix is given using the MIMO zero-force receiving structure and the IA technique. The precoder and interference suppression matrix is constituted considering the system model which is in a presence of a single primary user and two secondary users in the CR network. As a numerical results, data rate transmission performances and bit error rate performances are covered considering primary and secondary users with respect to distance of the nodes.

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APPENDICES

APPENDIX A.1 : Derivation of the PDF expression for $f_{\gamma_\tau}(\gamma)$

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PDF expression of f_{γ_τ} can be derivated by subtituting (4.11) and (4.12) into (4.13),

$$f_{\gamma_\tau}(\gamma) = \int_0^\infty \frac{(x+1)(x+1)^{M_pN_p-1}\gamma^{M_pN_p-1}\exp(-\frac{\gamma(x+1)}{\bar{\gamma}_1/M_p})x^{KM_sN_p-1}\exp(-\frac{x}{\alpha\bar{\gamma}_2/M_s})}{\left(\frac{\bar{\gamma}_1}{M_p}\right)^{M_pN_p}\left(\frac{\alpha\bar{\gamma}_2}{M_s}\right)^{KM_sN_p}(M_pN_p-1)!\,(KM_sN_p-1)!}dx, \quad \textbf{(A.1)}$$

where M_p, N_p is denoted for number transmit antennas and receive antennas PU, respectively. M_s is given as number of transmit antennas for SU. K, α, $\bar{\gamma}_1$ and $\bar{\gamma}_2$ is denoted for number of secondary users, interference leakage parameter, average SNR of PU and average SNR of SU, respectively. After a few mathematical manipulations,

$$\begin{aligned} f_{\gamma_\tau}(\gamma) =& \beta \int_0^\infty (x+1)(x+1)^{M_pN_p-1}\gamma^{M_pN_p-1} & \textbf{(A.2)} \\ &\times \exp(-\frac{\gamma(x+1)}{\bar{\gamma}_1/M_p})x^{KM_sN_p-1}\exp(-\frac{x}{\alpha\bar{\gamma}_2/M_s})dx \\ =&\beta\gamma^{M_pN_p-1}\int_0^\infty (x+1)(x+1)^{M_pN_p-1} & \textbf{(A.3)} \\ &\times \exp(-\frac{\gamma(x+1)}{\bar{\gamma}_1/M_p})x^{KM_sN_p-1}\exp(-\frac{x}{\alpha\bar{\gamma}_2/M_s})dx \\ =&\Delta\int_0^\infty (x+1)^{M_pN_p}x^{KM_sN_p-1}\exp\left(\left(-\frac{\gamma M_p}{\bar{\gamma}_1}+\frac{M_s}{\alpha\bar{\gamma}_2}\right)x\right)dx, & \textbf{(A.4)} \end{aligned}$$

where β can be expressed as,

$$\beta = \frac{\left(\frac{\bar{\gamma}_1}{M_p}\right)^{-M_pN_p}\left(\frac{\alpha\bar{\gamma}_2}{M_s}\right)^{-KM_sN_p}}{(M_pN_p-1)!\,(KM_sN_p-1)!}. \quad \textbf{(A.5)}$$

Furthermore, Δ can be constituted as,

$$\Delta = \beta\gamma^{M_pN_p-1}\exp(-\frac{M_p\gamma}{\bar{\gamma}_1}). \quad \textbf{(A.6)}$$

Also, binomial expression of $(x+1)^{M_pN_p}$ term in (**A.4**) are following below.

$$(x+1)^{M_pN_p} = \sum_{m=0}^{M_pN_p}\binom{M_pN_p}{m}x^m. \quad \textbf{(A.7)}$$

(**A.4**) can be reexpressed as considering (**A.7**),

$$\begin{aligned} f_{\gamma_\tau}(\gamma) =& \Delta\int_0^\infty\sum_{m=0}^{M_pN_p}\binom{M_pN_p}{m}x^{KM_sN_p-1+m}\exp\left(\left(-\frac{\gamma M_p}{\bar{\gamma}_1}+\frac{M_s}{\alpha\bar{\gamma}_2}\right)x\right)dx \\ =&\Delta\sum_{m=0}^{M_pN_p}\binom{M_pN_p}{m}\int_0^\infty x^{KM_sN_p-1+m}\exp\left(\left(-\frac{\gamma M_p}{\bar{\gamma}_1}+\frac{M_s}{\alpha\bar{\gamma}_2}\right)x\right)dx. & \textbf{(A.8)} \end{aligned}$$

Besides, with the help of [63, eq. 3.351.3] (**A.8**) can be expressed as,

$$f_{\gamma_\tau}(\gamma) = \Delta \sum_{m=0}^{M_pN_p} \binom{M_pN_p}{m} (KM_sN_p + m - 1)! \left(\frac{\gamma M_p}{\bar{\gamma}_1} + \frac{M_s}{\alpha \bar{\gamma}_2}\right)^{-KM_sN_p+m}. \quad \textbf{(A.9)}$$

In order to achieve closed form expression of (**A.9**), binomial expression of $\left(\frac{\gamma M_p}{\bar{\gamma}_1} + \frac{M_s}{\alpha \bar{\gamma}_2}\right)^{-KM_sN_p+m}$ term must be completed. The binomial expansion of this negative exponential term is given as follows.

$$\left(\frac{\gamma M_p}{\bar{\gamma}_1} + \frac{M_s}{\alpha \bar{\gamma}_2}\right)^{-KM_sN_p+m} = \sum_{t=0}^{\infty} (-1)^t \binom{KM_sN_p + m + t - 1}{t} \times \left(\frac{\gamma M_p}{\bar{\gamma}_1}\right)^t \left(\frac{Ms}{\alpha \bar{\gamma}_2}\right)^{KM_sN_p+m+t}. \quad \textbf{(A.10)}$$

Where validation of (**A.11**) are restricted via $|\frac{\gamma M_p}{\bar{\gamma}_1}| < \frac{M_s}{\alpha \bar{\gamma}_2}$ condition. Under these conditions closed form expression of f_{γ_τ} are given below.

$$f_{\gamma_\tau}(\gamma) = \Delta \sum_{m=0}^{M_pN_p} \sum_{t=0}^{\infty} (-1)^t \binom{M_pN_p}{m} (KM_sN_p + m - 1)! \times \binom{KM_sN_p + m + t - 1}{t} \left(\frac{\gamma M_p}{\bar{\gamma}_1}\right)^t \left(\frac{Ms}{\alpha \bar{\gamma}_2}\right)^{KM_sN_p+m+t}. \quad \textbf{(A.11)}$$

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