

**DESIGN AND PERFORMANCE ANALYSIS OF
RELAY-BASED COOPERATIVE OVERLAY
COGNITIVE RADIO NETWORKS**



Ph.D. THESIS

Said Abdelmoneim Abdelwahab EMAM

Department of Electronics and Communication Engineering

Telecommunication Engineering Programme

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**Said Abdelmoneim Abdelwahab EMAM
(504122304)**

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Thesis Advisor: Prof. Dr. Mehmet Ertuğrul ÇELEBİ

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**RÖLE TABANLI İŞBİRLİKLİ
ÜSTÜNE SERME BİLİŞSEL RADYO
AĞLARININ TASARIMI VE BAŞARIM ANALİZİ**

DOKTORA TEZİ

**Said Abdelmoneim Abdelwahab EMAM
(504122304)**

Elektronik ve Haberleşme Mühendisliği Anabilim Dalı

Telekomünikasyon Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Mehmet Ertuğrul ÇELEBİ

MAYIS 2018

Said Abdelmoneim Abdelwahab EMAM, a Ph.D. student of ITU Graduate School of Science Engineering and Technology, student ID 504122304, successfully defended the thesis entitled “DESIGN AND PERFORMANCE ANALYSIS OF RELAY-BASED COOPERATIVE OVERLAY COGNITIVE RADIO NETWORKS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Mehmet Ertuğrul ÇELEBİ**
Istanbul Technical University

Jury Members : **Prof. Dr. Hasan Ümit AYGÖLÜ**
Istanbul Technical University

.....
Assoc. Prof. Dr. Ertuğrul BAŞAR
Istanbul Technical University

.....
Assoc. Prof. Dr. Ali Emre PUSANE
Boğaziçi University

.....
Asst. Prof. Dr. Eylem ERDOĞAN
Istanbul Medeniyet University

Date of Submission : **20 April 2018**

Date of Defense : **24 May 2018**





To Mom, Mai, and Sama,



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ABBREVIATIONS

5G	: Fifth Generation
AF	: Amplify and Forward
ANC	: Analog Network Coding
APM	: Amplitude and Phase Modulation
AS	: Antenna Selection
AWGN	: Additive White Gaussian Noise
BC	: Broadcast Channel
BER	: Bit Error Rate
BEP	: Bit Error Probability
BS	: Base Station
BPSK	: Binary Phase Shift Keying
bpcu	: bit per channel use
b/s/Hz	: bit/second/hertz
CR	: Cognitive Radio
CDF	: Cumulative Distribution Function
COAS	: Capacity Optimised Antenna Selection
CSI	: Channel State Information
D2D	: Device-to-Device
DF	: Decode and Forward
DF-SUP	: Superposition based DF
DF-XOR	: XOR-based DF
EDAS	: Euclidean Distance Optimised Antenna Selection
FDM	: Frequency Division Multiplexing
GSM	: Generalized Spatial Modulation
ICI	: Inter-Channel Interference
iid	: independent and identically distributed
LC-EDAS	: Low Complexity EDAS
MIMO	: Multiple Input Multiple Output
MAC	: Medium Access Control
ML	: Maximum Likelihood
M-PSK	: M-ary Phase Shift Keying
NOMA	: Non-Orthogonal Multiple Access
OMA	: Orthogonal Multiple Access
OSA	: Opportunistic Spectrum Access
PBS	: Primary Base Station
PDF	: Probability Density Function
PDMA	: Pattern Division Multiple Access
PEP	: Pair-wise Error Probability
PLNC	: Physical-Layer Network Coding

PR	: Primary Receiver
PT	: Primary Transmitter
PU	: Primary User
QAM	: Quadrature Amplitude Modulation
QLC-EDAS	: Quadrature LC-EDAS
QoS	: Quality of Service
QPSK	: Quadrature Phase Shift Keying
QSM	: Quadrature Spatial Modulation
SBS	: Secondary Base Station
SCMA	: Sparse Code Multiple Access
SEP	: Symbol Error Probability
SER	: Symbol Error Rate
SIC	: Successive Interference Cancellation
SIMO	: Single-Input Multiple-Output
SINR	: Signal to Interference Noise Ratio
SISO	: Single-Input Single-Output
SM	: Spatial Modulation
SNR	: Signal to Noise Ratio
SqED	: Squared Euclidean Distance
SR	: Secondary Receiver
SSK	: Spatial Shift Keying
ST	: Secondary Transmitter
SU	: Secondary User
TAG	: Transmit Antenna Grouping
TAS	: Transmit Antenna Selection
TDM	: Time Division Multiplexing
TSAS	: Tree Search based Antenna Selection
V2V	: Vehicle-to-Vehicle
V-BLAST	: Vertical Bell Laboratories Layered Space-Time

SYMBOLS

$\mathbb{CN}(\mu, \sigma^2)$	: Circularly symmetric complex Gaussian random variable with mean μ and variance σ^2 , having independent Gaussian distributed $N(\mu, \frac{\sigma^2}{2})$ real and imaginary parts with mean μ and variance $\frac{\sigma^2}{2}$
$E\{\cdot\}$	: The Expectation operation
$f_X(\cdot)$	: Probability density function of random variable X
$F_X(\cdot)$	: Cumulative distribution function of random variable X
$Pr(\cdot)$	: Probability of an event
$Q(\cdot)$	: The Gaussian Q -function
$\Gamma(\cdot)$	: The Gamma function
$ x $	: Absolute value of a complex number x
$\ \mathbf{x}\ $	: The L_2 -norm of a vector $\mathbf{x}$
$\lfloor x \rfloor$	: The floor operation of the real number x
$\binom{N}{k}$	: The binomial coefficient
$\Re\{\cdot\}$	: The real part of a complex number
$(\cdot)^H$	: Hermitian transpose of a vector or matrix
$(\cdot)^*$	: Conjugate of a complex number
$\oplus$	: The XOR operator
α	: Power splitting factor
β	: Frequency splitting factor
W	: Total Bandwidth
U_i	: User i
M	: APM constellation size
x_i	: Unit power signal
h_i	: Channel coefficient
y_i	: Received signal
n_i	: Additive white Gaussian noise
C_{SM}	: The capacity of an SM system
$\mathbf{D}$	: $N_t \times N_t$ Euclidean distance matrix
$\mathbf{D}_I$	: $N_{t1} \times N_{t1}$ upper triangular sub-matrix generated from $\mathbf{D}$ by extracting the rows and columns equal to the elements of I
I_{ED}	: The optimum transmit antennas subset
$\mathcal{O}(\cdot)$	: Complexity order
A, B, C, D	: Network nodes (Ch3)
h_{ij}	: The channel coefficient between nodes i and j , $\forall i, j \in \{A, B, C, D\}$
d_{ij}	: The normalized distance between nodes i and j , with respect to the distance between the primary users A and B ($d_{AB} = 1$)
ν	: The path-loss exponent
$ h_{ij} $	: The channel amplitude
γ_{ij}	: Exponentially distributed random variables $\gamma_{ij} = h_{ij} ^2$ with parameters d_{ij}^ν

Γ_{ij}	: The SINR to decode the message of node i at node j
I_{ij}	: The maximum average mutual information between node i and node j $\forall i, j \in \{A, B, C, D\}$
R_{pt}	: The target rate for PUs
R_{st}	: The target rate for SUs
P_{OUT-i}^j	: The outage probability of node i to decode the message of node j
η_p, η_s	: The SNR at PU and SU in a single user scenarios, with $\eta_p = \frac{P_p}{\sigma^2}$ and $\eta_s = \frac{P_s}{\sigma^2}$
P_t	: Total transmit power
P_p	: Primary signal power
P_s	: Secondary signal power
N_p	: Transmit antennas at PT
N_t	: Transmit antennas at ST
N_{t1}	: Number of selected transmit antennas to be used for SM for PR
N_{t2}	: Number of transmit antennas for SM for SR
N_r	: Receive antennas at ST
N_{r1}	: Receive antennas at PR
N_{r2}	: Receive antennas at SR
N_a	: Number of active antennas
N_s	: Possible enumerations of transmit antenna subsets
$\mathbf{y}$	: Received signal vector
$\mathbf{B}, \mathbf{H}, \mathbf{G}$	: Channel matrices
σ_h^2, σ_g^2	: Channel variances
σ_n^2	: Noise variance
$\mathbf{H}_I$	: The channel matrix between the transmit antennas of the I^{th} subset at ST and the receiving antennas of SR
$\mathbf{h}_j$	: The j^{th} column of the channel matrix $\mathbf{H}$
$\mathbf{h}_{(j)}$	: The j^{th} column of $\mathbf{H}$ with the new ordering
$\mathbf{n}$	: Noise vector
γ	: A chi-square random variable with $2N_{r1}$ degrees of freedom
γ_{min}	: The minimum of two chi-square random variables
γ_{Max}	: The maximum of N_s γ_{min} random variables
$\tilde{\mathbf{n}}$	: The interference plus noise vector
$PEP_{PR}^{(i)}$	: The instantaneous PEP at PR
$PEP_{PR}^{(i)EDAS}$	: The instantaneous PEP at PR using EDAS
$\overline{PEP}_{PR}$	: The average PEP at PR
$\overline{PEP}_{PR}^{EDAS}$	: The average PEP at PR using EDAS
$SEP_{PR}^{(i)}$	: The instantaneous SEP at PR
$\overline{SEP}_{PR}$	: The average SEP at PR
d_{minQAM}^2	: The minimum-SqED of the QAM constellation

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DESIGN AND PERFORMANCE ANALYSIS OF RELAY-BASED COOPERATIVE OVERLAY COGNITIVE RADIO NETWORKS

SUMMARY

As the rapid growth of wireless communications to meet the fast growing demand for supporting an increasing number of advanced wireless applications and services, the availability of the radio spectrum becomes extremely scarce. In addition, several studies reported that most of the allocated spectrum is not efficiently utilized. To deal with such a problem, cognitive radio (CR) was proposed as a promising technology for boosting the utilization of the radio spectrum, since it could efficiently resolve the spectrum scarcity versus under-utilization dilemma. In CR networks, unlicensed secondary users (SUs) are allowed to use/share the radio spectrum licensed for primary users (PUs) when they are inactive/active, without degrading the performance of the PUs. Research on CR has been divided into three main spectrum-sharing paradigms: interweave, underlay, and overlay. In the interweave paradigm, SUs are allowed to use the spectrum only when PUs are inactive. In the underlay paradigm, SUs are allowed to share the spectrum with PUs with an acceptable levels of interference at PUs' receivers. Throughout this thesis we consider the third paradigm, the overlay model, in which SUs are assumed to be smart and capable of cooperatively maintain or improve the communication between PUs while also gaining access to the spectrum for their own communication.

For further increasing the efficient utilization of the scarce spectrum, various modulation and multiple access techniques have been recently proposed such as spatial modulation (SM) and non-orthogonal multiple access (NOMA). NOMA exploits the power domain and SM exploits the spatial domain to efficiently improve the spectrum utilization and the network capacity. SM was proposed as a spatial multiplexing technique that effectively remove inter-channel interference (ICI) and inter-antenna synchronization in multiple input multiple output (MIMO) systems; by allowing only one transmit antenna to be activated at any time interval (i.e., only one radio frequency chain at any transmit interval). SM increases the spectral efficiency by utilizing the active antenna index for conveying information besides the usage of conventional amplitude and phase modulation (APM) techniques. For further enhancement in the performance of SM, transmit antenna selection (TAS) schemes were proposed for SM systems; specifically capacity optimized antenna selection (COAS) and Euclidean distance optimized antenna selection (EDAS). EDAS was shown to outperform COAS but with increased complexity.

On the other hand, NOMA is a promising spectral efficient multi-user access candidate for 5G systems. NOMA supports multiple users within the same time/frequency/code resource block but with different power levels that significantly improves the spectral efficiency over conventional orthogonal multiple access (OMA) schemes. In a two-user scenario, NOMA allocates higher power to the user with poor channel gain and less power to the user with better channel gain. The user with better channel gain

uses successive interference cancellation (SIC) for signal detection while the user with the poor channel gain uses direct decoding considering the signal for the other user as interference. The performance of NOMA can be improved by using user-pairing, i.e., by pairing the users with more distinctive channel gains with each other.

Various researchers have investigated SM in overlay CR networks, where they considered using SM at a secondary transmitter that uses the APM technique to relay the symbol of a primary transmitter while using the antenna index to transmit its own message to a secondary receiver. The application of NOMA in CR networks has also attracted many researchers to investigate problems related with outage probability, capacity analysis, energy efficiency and power allocation schemes to further improve the system performance.

In this thesis, we study the combination of NOMA, SM, and TAS schemes in overlay CR networks. Joining NOMA and SM altogether increases the spectral efficiency of the network by exploiting the power and spatial domains. The use of TAS schemes improves the quality of service provided for the primary receiver and enhances the energy efficiency of the system.

We first started by applying NOMA in overlay CR networks in both the uplink and downlink with single antenna users. In chapter 3, we propose a two-way two-phase spectrum sharing protocol for the overlay CR paradigm using NOMA and physical layer network coding (PLNC). In our proposed protocol, not only the SU (working as a relay) maintains the two-way transmission between the PUs, it also establishes a two-way transmission with the other SU that results in higher spectral efficiency and hence improved system capacity over other protocols proposed in literature. Closed form expressions for the outage probabilities for both PUs and SUs have been derived and validated through Monte Carlo simulations.

In chapter 4, we studied the combination of NOMA and SM in overlay CR networks. We considered an overlay CR network that consists of multiple antennas primary transmitter (PT), primary receiver (PR), secondary transmitter (ST) and secondary receiver (SR). The proposed protocol allows ST to transmit simultaneously using NOMA and SM to both PR and SR. The usage of NOMA and SM increases the spectral efficiency for both PR and SR. With NOMA, SR uses SIC to detect the signal intended for PR and then cancels it to detect its own signal, while PR uses direct decoding to detect its own signal considering the intended signal for SR as an interference. This decreases the detection complexity considerably compared to the case without NOMA in which the detectors are required to jointly detect both SM symbols at each receiver. Furthermore, to provide higher quality of service (QoS) for PR, we considered the application of TAS schemes at ST in accordance with PR. We first considered the usage of COAS where ST assigns the antennas with highest channel gains with respect to PR for SM transmission toward PR. From PR's side, this will ensure that the primary symbol will be sent over one of the channels with high gain (with respect to PR) and the secondary symbol will be sent over one of the channels with low gain (with respect to PR), which will result in decreasing the secondary interference at PR – compared with the case without antenna selection (AS) – and therefore will enhance the performance of PR. On the other hand, from SR's side, the new ordering of the antennas of ST is still random with respect to SR and hence will not affect the performance of SR on the average. The performance of the proposed protocol is investigated through derivations

of upper bounds for the average symbol error probabilities (SEP) at PR and SR and validated through Monte Carlo simulations.

In chapter 5, we studied the combination of NOMA, SM and EDAS in overlay CR networks. Employing EDAS at ST in accordance with PR results in decreasing the SEP of PR significantly; since it selects the antenna subset that maximizes the minimum squared Euclidean distance for the SM constellation at PR. Similar to chapter 4, this will not deteriorate the performance of SR since re-ordering of the antennas at ST remains random with respect to SR. We evaluate the performance of the proposed protocol by derivation of an upper bound for the SEP of PR for the case of using BPSK for both PR and SR and selection of two transmit antennas from the transmit antennas at ST. Also we compare the performance of the proposed protocol with that of COAS and with that of without-AS through Monte Carlo simulations.

Finally, the use of NOMA and SM in CR increases the spectral efficiency and hence the system capacity by allowing more users to be serviced with higher data rates through the use of power and spatial domains. Introducing TAS schemes to NOMA-SM in overlay CR networks has been shown to improve the performance of the protocol for PR significantly without affecting the performance of SR, resulting in significant savings in the transmit power of the secondary transmitter that improves the energy efficiency of the network. It has also been shown that the performance of the proposed protocol CR-NOMA-SM with EDAS provides much more transmit diversity compared to CR-NOMA-SM with COAS; but with a trade-off of increased complexity which can be reduced by the use of low complexity EDAS algorithms.



RÖLE TABANLI İŞBİRLİKLİ ÜSTÜNE SERME BİLİŞSEL RADYO AĞLARININ TASARIMI VE BAŞARIM ANALİZİ

ÖZET

Telsiz iletişimin hızla artan büyümesi, artan sayıda gelişmiş telsiz uygulamalar ve servisler desteklemeye yönelik talebin artması nedeniyle, radyo spektrumunun kullanılabilirliği oldukça yetersiz olmaktadır. Ayrıca, birçok çalışma, spektrumun çoğunun verimli kullanılmadığını bildirmiştir. Böyle bir sorunu çözmek için, bilişsel radyo (cognitive radio – CR), radyo spektrumunun kullanımının artırılması için umut verici bir teknoloji olarak önerilmiştir. Bu teknoloji yetersiz kullanım karşısında spektrum kıtlığını etkili bir şekilde çözebilir. CR ağlarında lisanssız ikincil kullanıcıların (secondary users – SU) birincil kullanıcılar (primary users – PU) için lisanslanmış radyo spektrumunun kullanmasına veya paylaşmasına aktif veya aktif olmadıklarında PU'lerin başarımını düşürmeden izin verilir. CR ile ilgili araştırma üç temel spektrum paylaşım yaklaşımı ile sınıflandırılabilir: araya karıştırma (interweave), altına serme (underlay), ve üstüne serme (overlay). Araya karıştırma yaklaşımında, SU'lerin sadece PU'ler aktif olmadığında spektrumu kullanmalarına izin verilir. Altına serme yaklaşımında, SU'ların, PU'lerin alıcılarında kabul edilebilir bir girişim seviyesi ile spektrumları PU'ler ile paylaşmasına izin verilir. Üstüne serme yaklaşımında, SU'ların akıllı olmaları ve PU'ler arasındaki iletişimi işbirlikli olarak sürdürmeleri ya da geliştirebilmeleri ve aynı anda kendi iletişim için spektruma erişebildikleri varsayılmaktadır. Bu tez boyunca üstüne serme yaklaşımını ele alıyoruz.

Kıt spektrumun verimli kullanımını daha da artırmak için uzaysal modülasyon (spatial modulation – SM) ve ortogonal olmayan çoklu erişim (non-orthogonal multiple access – NOMA) gibi, çeşitli modülasyon ve çoklu erişim teknikleri önerilmiştir. SM ve NOMA, spektrum kullanımını ve ağ kapasitesini verimli bir şekilde geliştirmek için, sırasıyla uzaysal ve güç alanları kullanırlar. SM, çoklu giriş çoklu çıkış (multiple input multiple output – MIMO) sistemlerinde kanallararası girişim ve anten arası eşzamanlama sorununu etkin bir şekilde ortadan kaldıran uzaysal çoğullama tekniği olarak önerilmiştir. SM, her işaretleme aralığında sadece bir verici antenin aktif olmasına izin verir; yani her işaretleme aralığında sadece bir radyo frekans zinciri kullanılır. SM, klasik genlik ve faz modülasyonu (amplitude and phase modulation – APM) tekniklerinin kullanımının yanı sıra bilgi aktarımı için aktif anten indisini kullanarak spektral verimliliği artırır. SM'nin başarımını daha da artırmak için verici anten seçimi (transmit antenna selection – TAS) teknikleri önerilmiştir: özellikle kapasite en uygun hale getirmek için anten seçimi (capacity optimized antenna selection – COAS) ve Öklid uzaklığını en uygun hale getirmek için anten seçimi (Euclidean distance optimized antenna selection – EDAS).

Öte yandan, NOMA, 5G sistemleri için bir spectrum-verimli çoklu-kullanıcı erişim adayıdır. NOMA, aynı zaman/frekans kaynak bloğu ile ancak farklı güç seviyelerine sahip birden fazla kullanıcıyı destekler. Buda geleneksel ortogonal çoklu erişim (orthogonal multiple access – OMA) tekniklerine göre spektral verimliliği önemli

ölçüde artırır. İki kullanıcı bir senaryoda, NOMA, daha düşük kanal kazancı olan kullanıcıya daha yüksek güç ve daha iyi kanal kazancı olan kullanıcıya daha az güç ayırır. Daha iyi kanal kazancı olan kullanıcı, sinyal tespiti için ardışık girişim iptalini (successive interference cancellation – SIC) kullanırken, zayıf kanal kazancı olan kullanıcı, diğer kullanıcının sinyalini girişim olarak düşünür ve doğrudan sinyal kestirimi yapar. NOMA'nın başarımı, kullanıcı eşleştirmesi kullanılarak geliştirilebilir, diğer bir deyişle, kullanıcıların birbirleriyle daha farklı kanal kazanımlarını eşleştirir.

Çeşitli araştırmacılar, üstüne serme CR ağlarında SM'yi araştırdılar ve ikincil vericide SM'yi kullanmayı uyguladılar. İkincil verici, birincil vericinin sembolünü birincil alıcıya aktarmak için APM tekniğini kullanırken, kendi mesajını ise ikincil alıcıya iletmek için anten indisini kullanmıştır. NOMA'nın CR ağlarında uygulanması son zamanlarda, sistem başarımını daha da iyileştirmek için, kesinti olasılığı, kapasite analizi, enerji verimliliği ve güç tahsisi teknikleri ile ilgili sorunların araştırılması birçok araştırmacının ilgisini çekmiştir.

Bu tez çalışmasında, üstüne serme CR ağlarında NOMA, SM ve TAS tekniklerinin birleştirmesi amaçlanmaktadır. NOMA ve SM'nin birleştirmesi, güç ve uzaysal alanları kullanarak ağın spektral verimliliğini artırır. TAS tekniklerinin kullanımı birincil alıcıya sağlanan hizmet kalitesini (quality of service – QoS) artırmakta ve sistemin enerji verimliliğini artırmaktadır.

İlk olarak, NOMA'yı üstüne serme CR ağlarında hem yukarı yönlü bağlantı (uplink) hem de aşağı yönlü bağlantı (downlink) içerisinde tek anten kullanıcılarıyla uyguladık. Bölüm 3'te, NOMA ve fiziksel katman ağ kodlamasını (physical layer network coding – PLNC) kullanarak üstüne serme CR ağları için iki yönlü bir iki fazlı spektrum paylaşım protokolü önermekteyiz. Bu protokolün başlıca katkısı şudur: SU (bir röle olarak çalışan), PU'lerin arasındaki iki yönlü iletimi sürdürür ve diğer SU ile iki yönlü bir iletim oluşturur. Buda daha yüksek spektral verimlilik ve dolayısıyla geliştirilmiş sistemin kapasitesi literatürde önerilen bazı protokollere göre daha iyi sonuç verir. Bu çalışmada hem PU'ler hem de SU'lar için kesinti olasılıkları için kapalı biçim ifadeleri türetilmiş ve Monte Carlo bilgisayar benzetimleri yardımıyla değerlendirilmiştir.

Bölüm 4'te, üstüne serme CR ağlarında NOMA ve SM'nin birleştirmesi inceledik. Çoklu anten birincil verici (primary transmitter – PT), birincil alıcı (primary receiver – PR), ikincil verici (secondary transmitter – ST) ve ikincil alıcıdan (secondary receiver – SR) oluşan bir üstüne serme CR ağını ele almaktayız. Önerilen protokol ST'nin hem PR'ye hem de SR'ye NOMA ve SM kullanarak aynı anda iletmesine izin verir. NOMA ve SM'nin kullanımı hem PR hem de SR için spektral verimliliği artırır. NOMA ile, SR SIC kullanıp, PR'nin yönelen sinyalini çözüp alınan sinyalinden çıkarır, ve sonra kendi sinyalini çözer. PR ise kendi sinyalini çözmek için, SR'nin yönelen sinyali bir girişim olarak ele alarak, direkt çözme yapar. Bu, alıcıların her alıcıda her iki SM sembolünü ortak olarak algılamak zorunda olduğu NOMA'sız duruma kıyasla önemli ölçüde çözme karmaşıklığını azaltır. İlave olarak, PR için daha yüksek bir hizmet kalitesi (QoS) sağlamak için, PR'ye göre ST'de TAS tekniklerinin uygulanmasını önerdik. İlk olarak, ST'nin PR'ye SM iletimi için PR'ye göre en yüksek kanal kazancı olan antenleri atadığı COAS kullanımını değerlendirdik. PR tarafından, bu, birincil sembolün yüksek kazançlı kanallardan birinden (PR'ye göre) gönderilmesini ve ikincil sembolün düşük kazançlı kanallardan (PR'ye göre) gönderilmesini sağlayacaktır, ve PR'de ikincil girişiminin azalmasıyla sonuçlanacaktır. Buda AS olmayan durumla karşılaştırıldığında PR'nin başarımını artıracaktır. Öte yandan, SR tarafından, ST'nin

antenlerinin yeni sıralaması SR'ye göre hala rastgele olduğu için SR'nin başarımını ortalama olarak etkilenmeyecektir. Önerilen protokolün başarımı, PR ve SR'deki ortalama sembol hatası olasılıkları (symbol error probability – SEP) için üst sınırların türetilmesi yoluyla araştırılmış ve Monte Carlo bilgisayar benzetimleri yardımıyla değerlendirilmiştir.

Bölüm 5'te, üstüne serme CR ağlarında NOMA, SM ve EDAS yöntemlerinin birleşimini inceledik. PR'ye göre ST'de EDAS kullanımı, PR'nin SEP'inin azaltılmasında önemli ölçüde sonuç vermektedir; çünkü PR'deki SM simge kümesinin elemanları arasından en düşük Öklid mesafesini en büyükleyen anten alt-kümesini seçer. Bölüm 4'te görüldüğü gibi bu SR'nin başarımını ortalama olarak etkilemeyecektir, çünkü ST'deki antenlerin yeniden sıralaması, SR'ye göre rastgele kalır. PR ve SR için BPSK kullanılması ve ST'deki verici antenlerden iki verici anten seçimi için PR'nin SEP'i için bir üst sınırın türetilmesi yoluyla önerilen protokolün başarımını değerlendirdik. Ayrıca, önerilen protokolün başarımını COAS ve AS olmayan protokollar ile Monte Carlo bilgisayar benzetimleri yardımıyla karşılaştırdık.

Son olarak, CR'de NOMA ve SM'nin kullanımı, güç ve uzaysal alanların kullanımı yoluyla daha fazla veriyle daha fazla kullanıcıya hizmet verilmesini sağlar ve spektral verimliliği ve dolayısıyla sistem kapasitesini artırır. CR ağlarında NOMA-SM'ye TAS tekniklerinin uygulamalarının, PR protokolünün başarımını, SR'nin performansını etkilemeden önemli ölçüde iyileştirdiği gösterilmiştir. Bu da, ikincil vericinin iletim gücünde önemli bir tasarruf sağlayarak, ağın enerji verimliliğini artırır. Ayrıca önerilen protokol CR-NOMA-SM'nin EDAS ile başarımının, COAS ile CR-NOMA-SM'ye kıyasla çok daha fazla iletim çeşitliliği sağladığı gösterilmiştir, ama artan karmaşıklığın bir sonucu olarak, düşük karmaşıklığı EDAS algoritmaları kullanılarak azaltılabilir.



1. INTRODUCTION

1.1 Motivation

The 5G wireless networks are envisioned to be launched in the 2020s and are expected to support large-scale heterogeneous traffic and to provide ultra-high data rates, low latency, massive connectivity, ultra-high spectral efficiency and ultra-high energy efficiency [1, 2]. To meet these requirements, new key technologies of modulation and multiple access/spectrum sharing schemes are being explored for the 5G networks. Among these key technologies are non-orthogonal multiple access (NOMA), spatial modulation (SM), and cognitive radio (CR) networks [3–7].

CR is an effective technology that was proposed to enhance the efficient use of the congested scarce but under-utilized radio spectrum. CR could efficiently resolve the spectrum scarcity versus under-utilization dilemma caused by the fixed allocation of the spectrum by allowing secondary users (SUs) to opportunistically use or simultaneously share the licensed spectrum to primary users (PUs) [8–10].

Furthermore, to ensure the efficient utilization of the scarce spectrum, high spectral efficiency modulation and spectrum access techniques have been recently investigated such as spatial modulation (SM) [11] and non-orthogonal multiple access (NOMA) [12], which are multiplexing schemes that improves the spectrum utilization by utilizing the spatial and power domains, respectively. SM uses the indices of the transmitting antennas to convey information, besides the use of conventional amplitude and phase modulation (APM) techniques in multiple input multiple output (MIMO) systems, by allowing only one transmit antenna to be active at a time. SM has many advantages: it removes the inter-channel interference (ICI) and inter-antenna synchronization since it uses only one radio frequency chain at each transmission period, provides higher spectral efficiency compared to SISO and SIMO systems, and provides higher energy efficiency compared to other MIMO systems like V-BLAST [13]. On the other hand, NOMA allows multiple users to be multiplexed

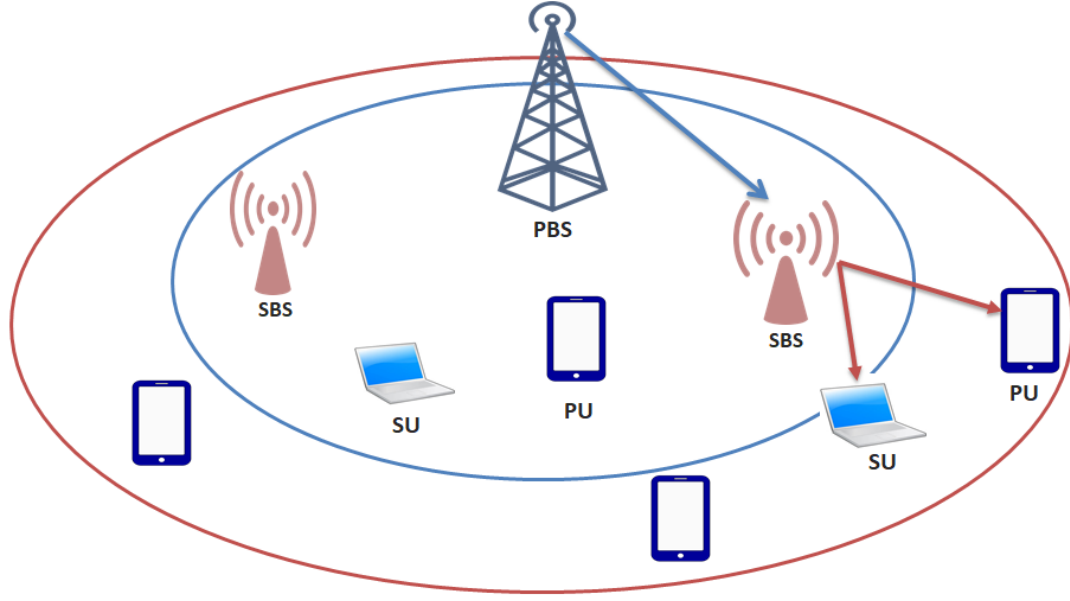


Figure 1.1 : Overlay CR network with secondary base station (SBS) that broadcasts data for the SUs.

simultaneously on the same channel by using superposition coding (using different power levels) at the transmitter and successive interference cancellation (SIC) at the receivers. NOMA is recognized as a promising multi-user access candidate for 5G systems, that can significantly improve the spectral efficiency over conventional orthogonal multiple access (OMA) schemes [14].

Motivated by the advantages of the aforementioned key technologies and methods, in this thesis, we propose the integration of NOMA and SM in overlay CR networks. The overlay CR paradigm [15] can be considered as a spectrum-sharing scheme which is independent of the underlying wireless technology. It can be applied in a wide range of scenarios, for example, in cellular networks the cell-edge users often suffer from signal degradation, and some others experience different signal qualities due to shadowing and multi-path fading. To overcome such a problem, bi-directional relays are being deployed between the base station and the mobile users, which simply amplify and forward the signal they receive. These relays can be replaced by cognitive secondary base stations (cognitive relays) as shown in Figure 1.1, which cooperatively relays the data of the primary network and at the same time superimposes their own data to other SUs. Another example is shown in Figure 1.2, where the SUs act as relays as in device-to-device (D2D) communication.

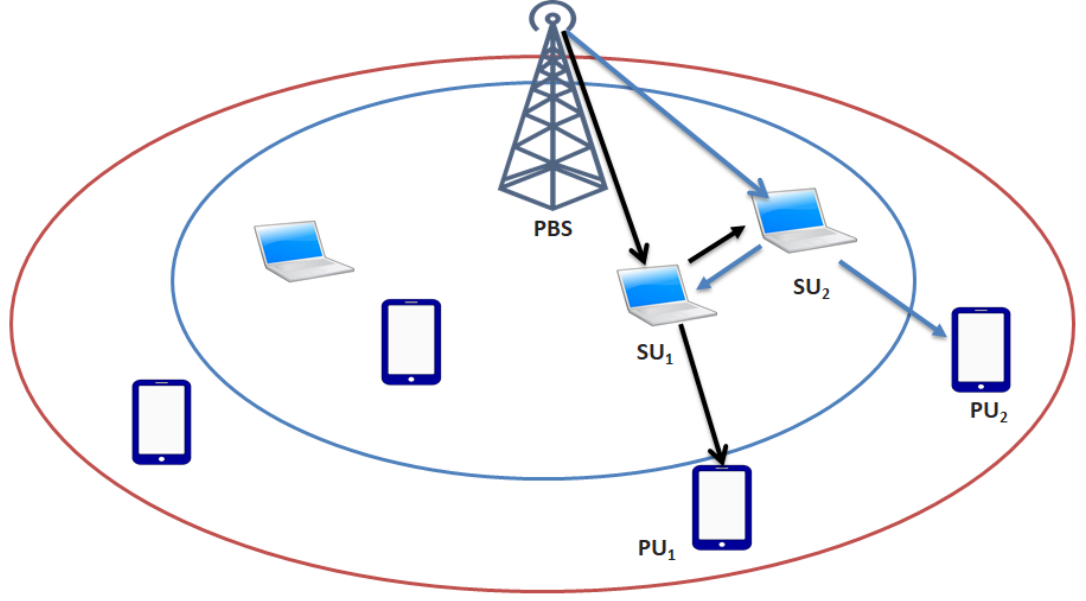


Figure 1.2 : Overlay CR network with device-to-device (D2D) communication.
(Transmission from the PBS to SU_1 and SU_2 can be done on different frequencies or different time slots).

In such cases NOMA and the overlay CR paradigm are well matched to each other. The usage of NOMA with overlay CR networks increases the system throughput, and the spectral efficiency for both the PUs and SUs with reduced detection complexity than the case without NOMA in which the detectors are required to jointly detect both symbols at each receiver. Using SM with NOMA in the overlay CR networks will provide further increase in the spectral efficiency for the users. Furthermore, the application of transmit antenna selection schemes at the cognitive relays with respect to the PUs is expected to further enhance the quality of service for the PUs and decrease the energy consumption by decreasing the transmit power at the relays.

1.2 Research Contributions

The contributions of this thesis are summarized as follows.

First, we proposed a two-way two-phase spectrum sharing protocol for overlay CR networks using NOMA and physical layer network coding (PLNC), where one of the SUs acts as a relay to assist the transmission between the PUs and at the same time allowing access for the SUs to the radio spectrum. The main contribution of this protocol is that the SU working as a relay to maintain the two-way transmission between the PUs, establishes a two-way transmission with the other SU, that results

in higher spectral efficiency and hence improved system capacity over other protocols proposed in literature. Closed form expressions for the outage probabilities for both PUs and SUs have been derived and validated through Monte Carlo simulations [16].

Second, We investigated the combination of NOMA and SM in overlay CR networks. The proposed protocol allows a secondary transmitter (ST) to transmit simultaneously to both a primary receiver (PR) and a secondary receiver (SR) using SM. Furthermore to provide more quality of service (QoS) for PR, we considered the application of capacity optimized antenna selection (COAS) scheme at ST in accordance with PR. Upper bounds on the average symbol error probabilities (SEP) at PR and SR have been derived [17].

Third, we studied the introduction of Euclidean distance optimized antenna selection (EDAS) scheme to NOMA-SM in overlay CR networks. The performance of the proposed protocol is analyzed by derivation of an upper bound for the SEP of PR, for the case of using BPSK for both PR and SR and selection of two transmit antennas from the transmit antennas at ST. Analytical and simulation results show that the application of EDAS to NOMA-SM in overlay CR networks improved the performance of PR significantly without affecting the performance of SR and provides much more transmit diversity compared to that with COAS [18].

1.3 Outline of the Thesis

This thesis continues as follows.

In chapter 2, we provide a background introduction and literature review of the key technologies that we used in the thesis: cognitive radio and its classified paradigms (interweave, underlay and overlay), non-orthogonal multiple access (in the downlink and uplink), Spatial modulation, and transmit antenna selection schemes in SM (COAS and EDAS).

In chapter 3, we propose a two-way two-phase spectrum sharing protocol for overlay cognitive radio networks using NOMA and PLNC. The system model, its parameters and assumptions are described. Then, the performance of the proposed protocol is provided by analyzing the outage performance of the PUs and SUs. Finally, analytical and simulation results are presented.

In chapter 4, we investigate the combination of NOMA and SM in overlay CR networks. We also investigate the application of COAS scheme at ST in accordance with PR to the CR-NOMA-SM protocol. The system model is presented and the performance of the proposed protocols is analyzed by deriving an upper bound on the SEP for each link. Analytical and simulation results are discussed.

In Chapter 5, we study the combination of EDAS with the CR-NOMA-SM protocol. We evaluate the performance of the proposed scheme by deriving an upper bound of the SEP at PR for the case of selecting two transmit antennas out of the transmit antennas at ST and using BPSK for PR and SR. Analytical and simulation results to compare the performance of the CR-NOMA-SM protocol with EDAS and COAS is presented.

In Chapter 6, we provide the conclusions of the thesis and shed light on areas possible for future research.



2. BACKGROUND AND LITERATURE REVIEW

Higher Spectrum efficiency, system capacity, energy efficiency, and data rates are of the key performance metrics in 5G communication networks. To achieve such goals, advanced modulation and multiple access/spectrum sharing techniques are being explored [5]. In this chapter, we present some of these key technologies that we used in the thesis, in particular: cognitive radio (CR), non-orthogonal multiple access (NOMA), spatial modulation (SM), and transmit antenna selection (TAS) in SM.

2.1 Cognitive Radio Networks

The ever-increasing demand for wireless communication services and applications has resulted in scarcity in the radio spectrum. Despite this congestion and scarcity in the radio spectrum, most of the allocated spectrum is not efficiently utilized because of the conventional fixed spectrum allocation. To resolve this problem, CR was proposed as a promising technology for enhancing the utilization of the radio spectrum by allowing unlicensed secondary users (SUs) to opportunistically use the spectrum assigned to the licensed primary users (PUs) whenever they are inactive or to share it with them when they are active without degrading the performance of the PUs [8–10].

Research on CR has been divided into three main spectrum-sharing paradigms: *interweave*, *underlay*, and *overlay* [15]. These paradigms are unified by the framework of CR as an intelligent wireless communication device that exploits side information about its environment, like knowledge about the activity, channels, codebooks, and/or messages of the primary users, to improve spectrum utilization [9].

2.1.1 Interweave Paradigm

The interweave paradigm, is based on opportunistic spectrum access (OSA) and was the original motivation for CR. It allows SUs to exploit temporary frequency bands refereed as spectrum holes that are not in constant use by the PUs at the right time and the right location [19]. One essential enabling technique for OSA-based CRs is

spectrum sensing, where the SUs attempt either individually or cooperatively to detect active PUs' transmissions over a specific band, and decide to transmit if the sensing results indicate that all PUs are inactive within this band with high probability [20].

To improve the performance of sensing the spectrum, cooperative sensing have been proposed for the interweave model. The main idea of cooperative sensing is to exploit the spatial diversity in the individual sensing observations of the spatially located CR users to enhance the overall sensing performance. By cooperation, CR users can share their sensing information for making a more accurate combined decision with high sensing precision and hence increase the detection probability [21]. Some other researchers investigated the cooperative relaying technique in the interweave model for CR networks [22, 23]. Cooperative relaying is an approach that turns nodes into partners to forward each other's data, to mitigate fading and other channel impairments in wireless networks [24].

2.1.2 Underlay Paradigm

In the underlay paradigm, the SU is allowed to transmit simultaneously with the PU in the same band regardless the PU is active or inactive, with the limitation that the SU knows how to control its transmit power in such a way to limit its interference at the PU's receiver to an acceptable threshold [10]. Various techniques can be used to meet the interference constraint for the PUs, such as using multiple antennas to guide the SUs' signals away from the PUs' receivers, or by using spread spectrum in which a wide bandwidth is used to spread the SU transmitter's signal below the noise floor and then disspread at the intended SU's receiver [15]. The underlay paradigm can be modeled as an interference channel [25] such that the total SUs interference at the PU receiver is within an acceptable limit. A lot of research on cooperative relaying for CR networks has been investigated for the underlay model such as [26–28].

2.1.3 Overlay Paradigm

In the overlay paradigm, the SUs are assumed equipped with advanced signal processing and encoding techniques to maintain or enhance the communication of the PUs while also gaining some bandwidth for their own communication. For instance the SUs may cooperatively relay the PUs's messages in favor of gaining access to

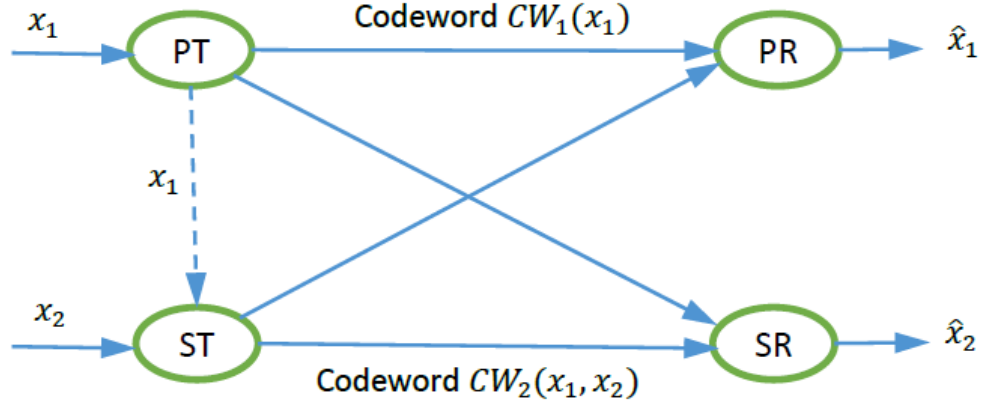


Figure 2.1 : An interference channel with one cognitive transmitter (ST).
 x_1 is known at ST .

the spectrum. The overlay model is based on the idea that the SU's transmitter (the cognitive transmitter) has non-causal knowledge of the message of the PU's transmitter at the start of its transmission, which may be difficult in practice. However, this assumption is reasonable in the case of re-transmissions, i.e., if the initial transmission between the two PUs is not successful and the SU overheard the message in the initial transmission and was able to decode it [15]. For example, assuming that there is a direct cooperation between the PUs and the SUs, when there is no direct link between the two PUs due to multipath fading or out of coverage problems, a SU can cooperatively acts as a relay between them while at the same time transmits its own messages to other SUs. Alternatively, when there is a direct link between the PUs, they benefit from the spatial diversity added by the SU working as a relay.

The overlay paradigm has been mainly investigated in the literature with the assumption that the cognitive transmitter has noncausal knowledge of the PU transmitter's message at the start of its transmission [15], as shown in Figure (2.1). Since the knowledge of the primary transmitter's message at the start of transmission at the cognitive transmitter is difficult in practice, the overlay model has been studied from an information theoretic perspective [29–31]. Cooperative relaying for the overlay model has been considered in many research papers [32–36], which corresponds how the cognitive transmitter obtains the primary transmitter's message; i.e., by relaying. Throughout this thesis, we consider the overlay CR paradigm using cooperative relaying.

2.2 Non-Orthogonal Multiple Access (NOMA)

In orthogonal multiple access (OMA) schemes the radio resources (time/frequency/code) are divided into orthogonal channels to avoid co-channel interference and simplify the detection process at the receiver. However, OMA does not utilize the spectrum efficiently because of the exclusive channel use. To enhance the spectrum efficiency, NOMA is proposed as a multiple access technique that allows multiple users to be multiplexed on the same radio resource [6].

There are two main NOMA schemes: Power-domain NOMA [37] and code-domain NOMA (as sparse code multiple access (SCMA) [38] and pattern division multiple access (PDMA) [39]). In this thesis, we are dealing with the power-domain NOMA and we refer to it simply by NOMA. The basic idea of NOMA is to exploit the power domain, i.e., multiple users are allowed to transmit at the same time span and at the same frequency band but with different levels of power.

To illustrate how NOMA works, we take the two-user downlink NOMA as an example [40]. The downlink NOMA channel is considered as a broadcast channel (BC) [41], as illustrated in Figure (2.2), the network consists of a base station (BS), a far-end user U_1 (with lower channel gain) and a near-end user U_2 (with higher channel gain). Let us assume that the wireless channels experience Rayleigh fading with fading coefficients h_i which are modeled as zero-mean, independent, circularly symmetric complex Gaussian random variables with variances σ_i^2 , i.e., $h_i \sim \mathbb{CN}(0, \sigma_i^2)$, $\forall i \in \{1, 2\}$ and $|h_2|^2 > |h_1|^2$. The BS needs to transmit simultaneously two messages x_1 and x_2 for U_1 and U_2 , respectively, subject to a total transmit power constraint P_t . To accomplish this, the BS uses superposition coding to assign higher power portion of its transmit power $P_1 = \alpha P_t$ for the message x_1 and lower power portion $P_2 = (1 - \alpha) P_t$ for the message x_2 , where $\alpha (0 \leq \alpha \leq 1)$ is the power splitting factor.

The received signal at user U_i is:

$$y_i = h_i(\sqrt{P_1}x_1 + \sqrt{P_2}x_2) + n_i \quad (2.1)$$

where n_i is the additive white Gaussian noise which is modeled as zero mean independent, circularly symmetric, complex Gaussian random variables and variance σ_n^2 at each user, i.e., $n_i \sim \mathbb{CN}(0, \sigma_n^2)$.

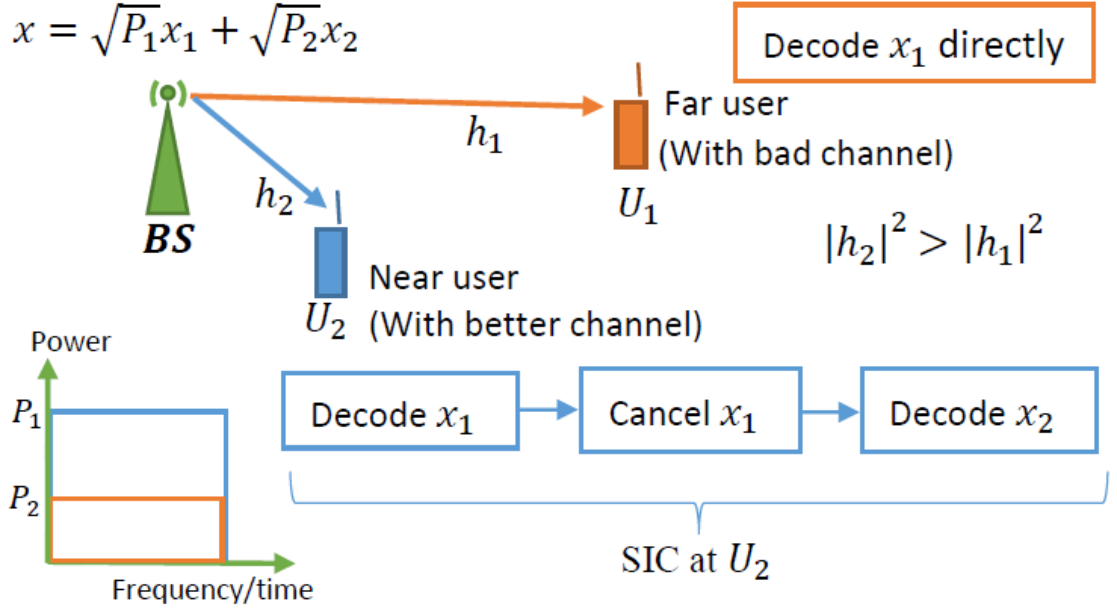


Figure 2.2 : Illustration of two-user downlink NOMA.

At U_1 , the receiver decodes the signal x_1 directly considering the signal x_2 as interference. While at U_2 , successive interference cancellation (SIC) is used, where U_2 first decodes the strong signal x_1 and then cancels it from the received signal and finally decodes its intended signal x_2 . Hence, The achievable rate pair for U_1 and U_2 can be given as:

$$R_1 = \log_2 \left(1 + \frac{P_1 |h_1|^2}{P_2 |h_1|^2 + \sigma_n^2} \right) \quad (2.2)$$

$$R_2 = \log_2 \left(1 + \frac{P_2 |h_2|^2}{\sigma_n^2} \right) \quad (2.3)$$

For illustrating the advantage of NOMA over OMA we take the case of using frequency-division multiplexing (FDM) as an example. With FDM, the BS broadcasts to U_1 and U_2 with powers P_1 and P_2 using non-intersecting frequency bands with bandwidths $(W_1 = \beta W)$ and $(W_2 = (1 - \beta)W)$, respectively, where W is the total bandwidth and $\beta (0 \leq \beta \leq 1)$ is the bandwidth splitting factor. Using the formula of the capacity of a single user band limited channel, the achievable rate pair using FDM for unit bandwidth can be written as:

$$R_1 = \beta \log_2 \left(1 + \frac{P_1 |h_1|^2}{\sigma_n^2 \beta} \right) \quad (2.4)$$

$$R_2 = (1 - \beta) \log_2 \left(1 + \frac{P_2 |h_2|^2}{\sigma_n^2 (1 - \beta)} \right) \quad (2.5)$$

As we vary α and β in equations (2.2) to (2.5) we trace out the curves of the achievable rate regions for NOMA and FDM as shown in Figure (2.3). Similar curves can be

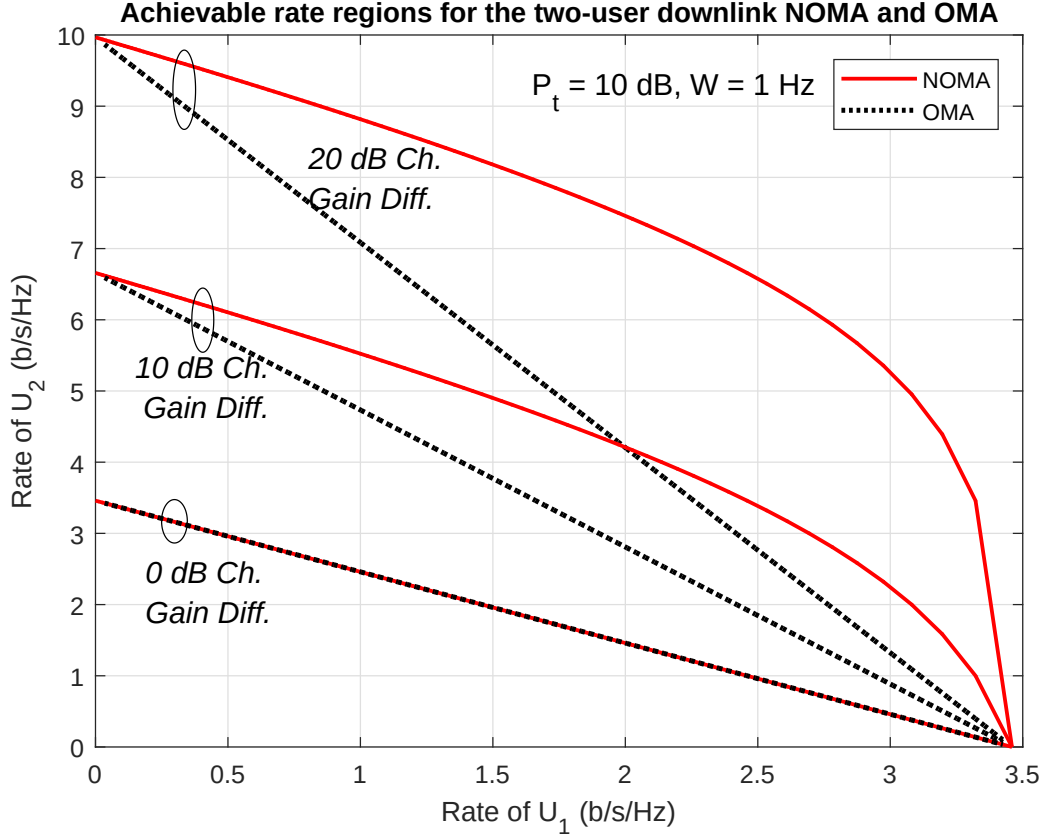


Figure 2.3 : Comparison of achievable rate regions for NOMA and OMA.

obtained for time-division multiplexing (TDM). We can observe that the achievable rate region for NOMA outperforms that for OMA for a given difference in the users' channels gains. It is also clear that the larger the difference between channels gains the larger the difference in the capacity region between NOMA and OMA. In order to maximize the system throughput, user-pairing schemes can be used in NOMA; i.e., by pairing users with the largest difference of channel gain with each other [42, 43]. Therefore, NOMA achieves higher spectral efficiency over OMA schemes for users with different channel gains, that makes NOMA a promising multiplexing technique for future wireless networks [44].

With the advantage of the message of the user with lower channel conditions being decoded by the user with better channel conditions, cooperative NOMA is proposed in [45]. In cooperative NOMA a second phase of transmission is needed. Referring to Figure (2.2), U_2 after performing SIC, it relays the detected message x_1 to U_1 . Therefore, U_1 obtains two copies of x_1 which enhances its performance but on the expense of an extra time slot.

The uplink NOMA operation is somewhat different from that of the downlink NOMA. For example in the two-user uplink NOMA, the two users transmit simultaneously independent messages to the BS. SIC is used at the BS, where it first decodes the signal of the user with the highest channel gain (which is likely to be the strongest) and then subtracts it from the received signal. From the resulting signal it decodes the signal of the user with the lower channel gain [46]. The uplink NOMA channel is considered as a multiple access channel (MAC) with strong interference [47].

For further improvements in the spectral efficiency of NOMA, recent studies have investigated the application of NOMA with multiple antenna systems. For example in [48–50], the authors studied the performance of NOMA for downlink MIMO systems. In [51], the researchers investigated NOMA with SM in a downlink multiuser transmission. In [52], the authors investigated the combination of NOMA and SM in the uplink side. In [53], the authors studied NOMA and SM for vehicle-to-vehicle (V2V) communications. The application of NOMA in CR networks has also attracted many researchers to investigate problems related with outage probability, capacity analysis and power allocation schemes to further improve the system performance [54–58].

Due to the advantages of NOMA mentioned above, NOMA is considered as a promising multiple access technique for 5G networks and it is expected to play an important role in these networks.

2.3 Spatial Modulation (SM)

Along the past decade, SM has attracted a lot of research attention due to its spectral efficiency and energy efficiency. SM was first introduced in [11] as a spatial multiplexing technique that effectively remove inter-channel interference (ICI) and inter-antenna synchronization in MIMO systems since it allows only one transmitting antenna to be active at any transmission period. SM increases the spectral efficiency by utilizing the active antenna index for conveying information besides the usage of conventional APM techniques.

let us consider an SM system with N_t transmitting antennas and N_r receiving antennas as shown in Figure (2.4). At the transmitter, the message to be conveyed is divided

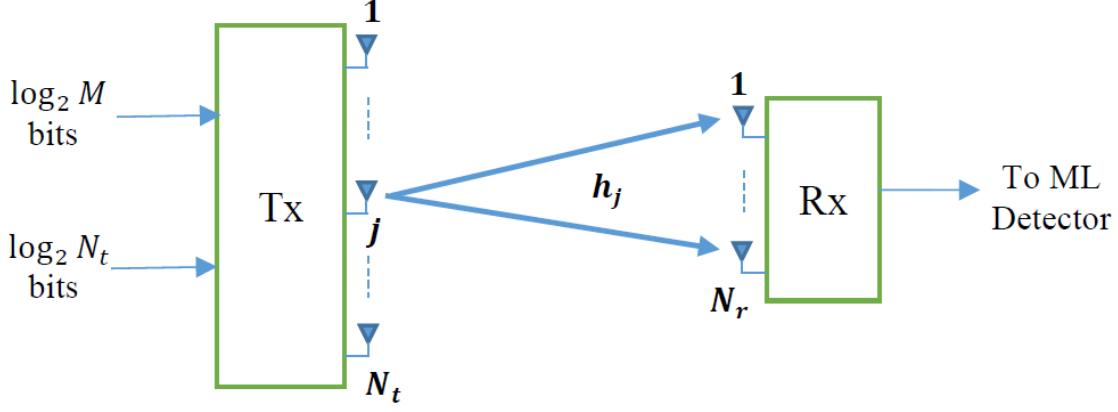


Figure 2.4 : Open Loop SM system.

into two groups of bits. The first group of bits ($\log_2 M$ bits) select the q^{th} symbol (x_q) from a conventional APM technique where M is the constellation size with unit-power signals, i.e., $E\{x_q^* x_q\} = 1$. The second group of bits ($\log_2 N_t$ bits) select the j^{th} transmitting antenna out of the N_t transmitting antennas to transmit the selected symbol x_q . Therefore, on each transmission period the number of bits that can be transmitted is: $\log_2 M + \log_2 N_t$.

At the receiver, the received signal vector can be written as:

$$\mathbf{y} = \sqrt{P_t} \mathbf{h}_j x_q + \mathbf{n} \quad (2.6)$$

where $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$, P_t is the transmit power, $\mathbf{h}_j$ is the j^{th} column of the channel matrix $\mathbf{H}$ between the N_t transmitting antennas and the N_r receiving antennas, and $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the noise vector with entries modeled as complex Gaussian random variables with distribution $\mathbb{CN}(0, \sigma_n^2)$. The entries of $\mathbf{H}$ are independent and identically distributed (i.i.d) circularly symmetric complex Gaussian random variables with distribution $\mathbb{CN}(0, 1)$.

The optimal maximum likelihood (ML) detector [59] can be used to jointly estimate the active transmitting antenna index and the transmitted APM symbol as:

$$[\hat{j}, \hat{q}] = \min_{j', q'} \|\mathbf{y} - \sqrt{P_t} \mathbf{h}_{j'} x_{q'}\|^2 \quad (2.7)$$

Inspired by SM, some variants of SM schemes have been investigated such as: spatial shift keying (SSK) [60], generalized spatial modulation (GSM) [61], and quadrature spatial modulation (QSM) [62].

SSK reduces the complexity of SM by utilizing the spatial domain only, allowing for $\log_2 N_t$ bits to be transmitted on each transmission period.

GSM increases the spectral efficiency of SM in a trade-off with increased receiver complexity, by allowing more than one transmitting antenna to be active at a time to transmit the same symbol. Therefore the number of bits that can be transmitted on each transmission period is: $\log_2 M + \left\lfloor \log_2 \binom{N_t}{N_a} \right\rfloor$, where N_a is the number of active antennas, and $\lfloor z \rfloor$ is the floor of the real number z .

In QSM, orthogonal real and imaginary parts of the selected symbol are transmitted over one or two transmitting antennas. The message to be transmitted is divided into 3 groups of bits. The first group of bits ($\log_2 M$ bits) selects a symbol from the APM constellation. The second group of bits ($\log_2 N_t$ bits) selects the first antenna to transmit the real part of the selected symbol while the third group of bits ($\log_2 N_t$ bits) selects the second antenna to transmit the imaginary part of the selected symbol. Therefore the number of bits that can be transmitted on each transmission period is: $\log_2 M + 2 \log_2 N_t$. QSM achieves spectral efficiency improvement at the expense of synchronizing the transmitting antennas.

In this thesis we consider the basic SM system to be integrated with NOMA in the overlay CR networks.

2.4 Transmit Antenna Selection in SM

For further improvement in the performance of SM, several researchers have investigated closed-loop SM designs to lower the receiver computational complexity and to improve the system error performance. In these closed-loop SM systems as depicted in Figure 2.5, the receiver uses the estimated CSI to select a subset (S_I) from the $N_s = \binom{N_t}{N_{t1}}$ possible enumerations of transmit antenna subsets, where $I = 1, 2, \dots, N_s$. Each subset (S_I) has N_{t1} transmitting antennas out of the N_t transmitting antennas, i.e., has N_{t1} elements. After selecting the suitable subset, the receiver sends its index to the transmitter through the use of feedback control channels to perform the SM technique using that subset. In this case N_t not necessarily be a power of 2 but N_{t1} should be.

In [63], the authors proposed the selection of the subset that minimizes the union bound of the instantaneous bit error rate (BER) of the SM system. In [64], the authors proposed two TAS schemes for use in SM systems: capacity optimized antenna

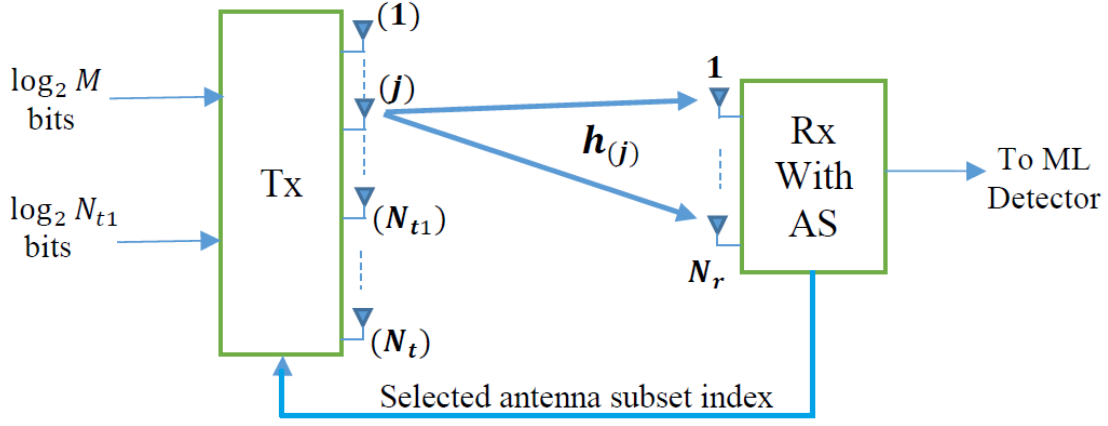


Figure 2.5 : Closed Loop SM system with selection of N_{t1} antennas out of N_t antennas.

selection (COAS) that selects the subset that maximizes the capacity of the SM system, and Euclidean distance optimized antenna selection (EDAS) that selects the subset that maximizes the minimum Euclidean distance in the SM constellation. The authors of [65] further reduced the complexity of the EDAS method in [64] and showed that EDAS outperforms COAS in terms of error performance. In the following subsections we provide a brief review of the COAS and EDAS schemes, which are extensively used in the thesis.

2.4.1 Capacity Optimized Antenna Selection (COAS)

In [64], the authors proposed COAS to maximize the capacity of the SM system. The capacity of an SM system having N_{t1} transmitting antennas can be upper bounded as:

$$C_{SM} \leq \frac{1}{N_{t1}} \sum_{j=1}^{N_{t1}} \log_2 \left(1 + \frac{P_t \|\mathbf{h}_j\|^2}{\sigma_n^2} \right) + \log_2 N_{t1} \quad (2.8)$$

where $\mathbf{h}_j$ is the j^{th} column of the channel matrix $\mathbf{H}_I$ between the N_{t1} transmitting antennas of subset (S_I) and the N_r receiving antennas. Equation (2.8) shows that C_{SM} can be maximized by choosing the N_{t1} transmitting antennas with the largest channel norms. Therefore the receiver uses the estimated CSI to find the indices of the N_{t1} antennas with the strongest channels out of the N_t antennas at the transmitter for every coherence interval and feeds this information back to the transmitter.

The ordering can be given as follows:

$$\underbrace{\|\mathbf{h}_{(1)}\|^2 \geq \|\mathbf{h}_{(2)}\|^2 \geq \dots \geq \|\mathbf{h}_{(N_{t1})}\|^2}_{\text{Largest } N_{t1} \text{ channel norms}} \geq \|\mathbf{h}_{(N_{t1}+1)}\|^2, \dots, \|\mathbf{h}_{(N_t)}\|^2 \quad (2.9)$$

where $\mathbf{h}_{(j)}$ indicates the j^{th} column of $\mathbf{H}$ with the new ordering.

2.4.2 Euclidean distance optimized antenna selection (EDAS)

To select N_{t1} transmitting antennas out of the N_t transmitting antennas, EDAS was proposed [64] as a TAS scheme that selects the I^{th} subset (S_I) that maximizes the minimum-SqED – among all possible $N_s = \binom{N_t}{N_{t1}}$ subsets – as follows:

$$I_{ED} = \max_{\substack{S_I \\ I \in N_s}} \left\{ \min_{\substack{q, q' \in M \\ i, j \in S_I}} \|\mathbf{h}_i x_q - \mathbf{h}_j x_{q'}\|^2 \right\} \quad (2.10)$$

where $\mathbf{h}_i$ and $\mathbf{h}_j$ are the i^{th} and j^{th} columns of $\mathbf{H}_I$. x_q and $x_{q'}$ ($1 \leq q, q' \leq M$) are symbols from the M -QAM constellation set. The exhaustive search of (2.10) requires a very high computational complexity of order $\mathcal{O}(N_s N_{t1}^2 M^2)$ [64]. To reduce the complexity of EDAS, low-complexity schemes were proposed in [64–66]. In [64] the authors proposed a low complexity EDAS (LC-EDAS) that uses QR factorization. LC-EDAS generates an $(N_t \times N_t)$ upper triangular matrix $\mathbf{D}$ whose $(i, j)^{th}$ element D_{ij} is given by:

$$D_{ij} = \begin{cases} \|\mathbf{h}_i\|^2 d_{minQAM}^2, & i = j \\ \min_{q, q' \in M} \|\mathbf{h}_i x_q - \mathbf{h}_j x_{q'}\|^2, & i < j \end{cases} \quad (2.11)$$

where $\mathbf{h}_i$ is the i^{th} column of $\mathbf{H}$ and d_{minQAM}^2 is the minimum-SqED of the QAM constellation. Therefore, the EDAS metric of (2.10) can be replaced by:

$$I_{ED} = \max_{I \in N_s} \left\{ \min_{D_I > 0} D_I \right\} \quad (2.12)$$

where $\mathbf{D}_I$ is the $(N_{t1} \times N_{t1})$ upper triangular sub-matrix generated from $\mathbf{D}$ by extracting the rows and columns equal to the elements in the subset S_I . $\left(\min_{D_I > 0} D_I \right)$ is the minimum of nonzero elements of $\mathbf{D}_I$. The complexity of computing D_{ij} for $(i < j)$ is $\mathcal{O}(M^2)$ which can be reduced to $\mathcal{O}(M)$ by using QR decomposition for computing D_{ij} for $(i < j)$ and solving for x_q for known $x_{q'}$ ($1 \leq q' \leq M$) using equations (7-9) in [64]. Using these two steps, the computational complexity of LC-EDAS is reduced to $\mathcal{O}\left(\binom{N_t}{2} M\right)$.

In [65] the authors used the modulus symmetry of the QAM constellation, i.e. by computing for half the constellation signals, they reduced the complexity of EDAS to $\mathcal{O}\left(\binom{N_t}{2} \frac{M}{2}\right)$. In [66], by exploiting the rotational symmetry of the QAM constellation, i.e. by computing for one quarter the constellation signals, the complexity of EDAS

can be further reduced to $\mathcal{O}\left(\binom{N_t}{2}\frac{M}{4}\right)$. We refer to this algorithm as Quadrature LC-EDAS (QLC-EDAS).

It is worth noting that the complexity of EDAS comprises of two components: computational and search complexities [67]. The computational complexity is due to the computations of the Euclidean distances between SM-symbols in the SM constellation, and the search complexity is due to the comparisons between the different enumerations of the possible transmit antenna subsets to select the subset that maximizes the minimum SqED.

The above mentioned low-complexity algorithms has dealt with reducing the computational complexity of EDAS imposed by computing the SqED matrix ($\mathbf{D}$). To reduce the search complexity recent algorithms have been proposed [67–69]. Specifically, in [69] a tree search based antenna selection (TSAS) algorithm is proposed. By iteratively splitting the Euclidean distance matrix ($\mathbf{D}$) into a set of sub-matrices with smaller dimensions the search complexity can be reduced. The complexity of TSAS is exponentially increasing with $(N_t - N_{t1})$.

Figure (2.6) shows the symbol error rate (SER) performance for SM with/without TAS schemes described above. For 4 b/s/Hz we considered $N_t = 4$ for conventional SM and $N_t = 6$ and $N_{t1} = 4$ for TAS schemes, with $N_r = 4$ and using QPSK in all cases. The SER results demonstrate higher performance of SM-EDAS over SM-COAS. The Figure also shows that the low complexity schemes (QLC-EDAS and TSAS) curves have perfect match with the optimal SM-EDAS curve. Therefore, the complexity of EDAS can be further reduced by joining TSAS with QLC-EDAS to provide an optimal solution with reduced complexity, with the limitation that the quantity $(2^{N_t - N_{t1}})$ is small compared with $\binom{N_t}{N_{t1}}$ since the complexity of TSAS is exponentially increasing with $(N_t - N_{t1})$.

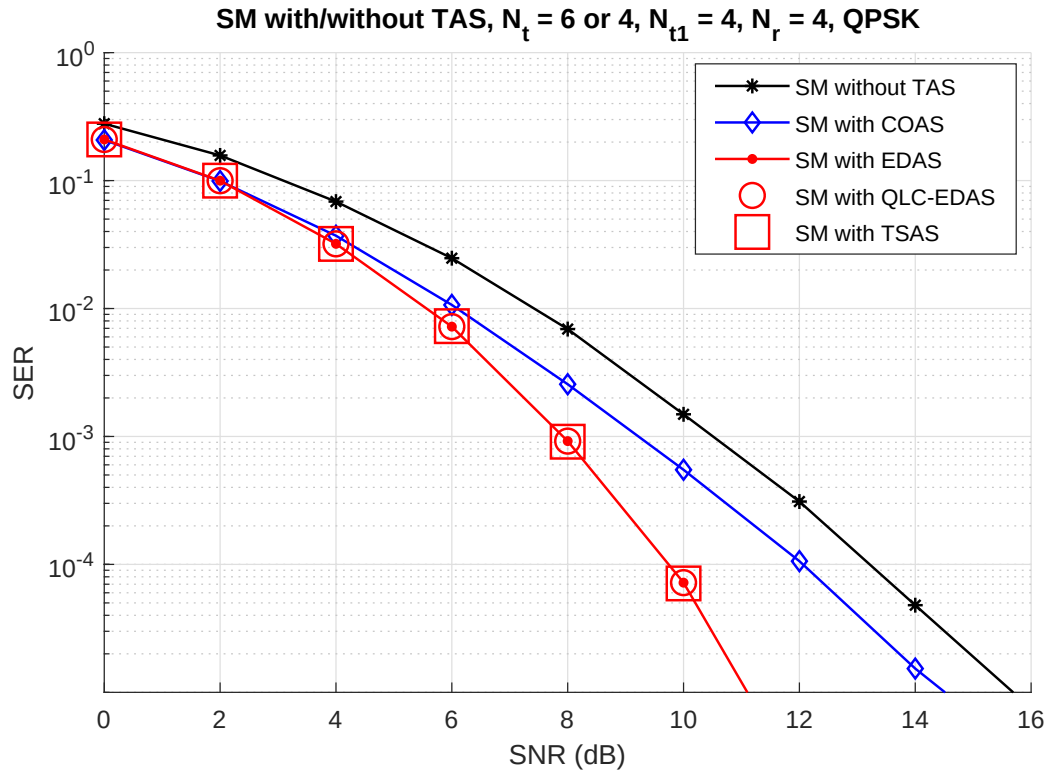


Figure 2.6 : SER performance for conventional SM, SM with COAS, SM with EDAS, SM with QLC-EDAS, and SM with TSAS versus SNR, for $N_t = 4$ or 6 , $N_{t1} = 4$, $N_r = 4$, (4 b/s/Hz).



3. A TWO-WAY TWO-PHASE SPECTRUM SHARING PROTOCOL IN OVERLAY COGNITIVE RADIO NETWORKS

In this chapter we propose a two-way two-phase spectrum sharing protocol for an overlay CR network using NOMA and physical-layer network coding.

3.1 Related Work

The overlay CR model has been discussed in many research papers considering only one-way SUs transmission i.e., the transmission of the relay to the other SU [32–36].

In [32], the authors proposed a one-way two-phase spectrum sharing protocol based on cooperative decode and forward relaying for a secondary system to achieve spectrum access along with a primary system. In the first phase, the primary signal transmitted by the primary transmitter to the primary receiver is overheard and decoded by the secondary transmitter. In the second phase using superposition coding, the detected primary symbol is superimposed by a secondary symbol and then the composite signal is transmitted to both the primary and secondary receivers. Outage probability for the primary and secondary systems have been derived.

In [33], motivated by the work in [32], the authors introduced two-way relaying overlay model in which the communication is performed in three phases. In the first and second phases, the PUs send their messages respectively to the relay (which is a SU), and the relay attempts to decode both signals. In the third phase, the relay broadcasts the physical-layer network coded (PLNC) [70] message of the decoded PUs' signals superimposed by the secondary signal to the PUs and the other SU. The outage probability, a spectrum sharing region and a power allocation scheme has been derived for such system.

In [34–36], motivated by the work in [33], the authors proposed two-phase two-way spectrum sharing overlay techniques. In [34], the relay performs an adaptive relaying technique, where in the first phase if the relay successfully decodes both primary signals, it will use PLNC and superposition coding in the second phase. If the decoding

is not successful, the relay amplifies the received signal, adds the secondary signal to it and then broadcasts the resulting signal. The protocol is analyzed by performing an optimal power allocation at the relay that minimizes the outage probability at the SU subject to outage constraints on the PUs.

In [35], the authors considered using analog network coding (ANC) [71] in the first phase, where the two PUs transmit simultaneously to the relay, and in the second phase the relay amplifies the received signal and then superimposes it by the secondary signal to be broadcast. The outage probability of the primary and secondary networks have been derived, and spectrum sharing regions within which the spectrum sharing protocol can achieve higher (or at least equal) outage performance for the primary users than direct transmission, have been identified.

In [36], three cognitive two-way relaying strategies are considered at the secondary relay: amplify and forward (AF), XOR-based decode and forward (DF-XOR) and superposition based DF (DF-SUP). Outage probabilities of the two primary users under these three strategies are derived for Rayleigh fading channels.

3.2 System Model and Protocol Description

In this chapter we consider an overlay CR network as illustrated in Figure (3.1), consisting of two PUs A and B , and two SUs C and D . C acts as a relay that cooperatively assists the transmissions between the PUs. Throughout this chapter, all nodes are constrained to operate in a half-duplex mode and having single antenna. Independent Rayleigh fading for all transmitter–receiver pairs is assumed. The channel coefficient between nodes i and j are denoted $h_{ij} \forall i, j \in \{A, B, C, D\}$ which is modeled as independent circularly symmetric complex Gaussian random variables with zero mean and variances $d_{ij}^{-\nu}$, i.e., $h_{ij} \sim \mathbb{CN}(0, d_{ij}^{-\nu})$ [33]. d_{ij} is the normalized distance between nodes i and j with respect to the distance between the primary users A and B , i.e., $d_{AB} = 1$. ν denotes the path-loss exponent which ranges from 2 to 5 depending on the type of the environment.

The channel amplitudes $|h_{ij}|$ are positive real random variables and follow a Rayleigh distribution with parameter $d_{ij}^{-\nu}$. We define the random variables $\gamma_{ij} = |h_{ij}|^2$, which are exponentially distributed with parameter d_{ij}^{ν} . Also we assume channel reciprocity, i.e.,

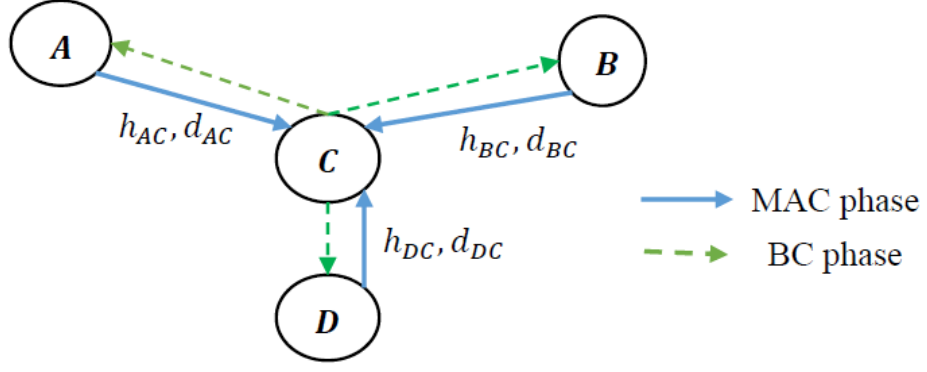


Figure 3.1 : Overlay CR Channel.

$h_{ij} = h_{ji}$. Furthermore, the noise n_i at node $i \in \{A, B, C, D\}$ in any phase of transmission is modeled as independent circularly symmetric complex Gaussian random variables with zero mean and variance σ_n^2 , i.e., $n_i \sim \mathbb{CN}(0, \sigma_n^2)$.

We consider the following scenario: the PU A can be considered as a primary base station (PBS) and B is a an out-of-range or a cell-edge PU – that experiences weak SNRs with the PBS – and they need to communicate with each other. The SU C agrees with some method to work as relay between A and B , in order to gain access to the licensed spectrum. The SU C can be considered as a secondary base station (SBS) that needs to communicate with many SUs. The SU C will select the SU D with the highest channel gain with respect to the channel gains of the PUs A and B , for two-way secondary transmission.

Therefore, the communication process can be done in two phases using NOMA: the uplink NOMA (the Multiple Access Channel (MAC) phase) and the downlink NOMA (the Broadcast Channel (BC) phase).

3.2.1 The uplink NOMA (The MAC phase)

The two PUs A and B and the SU D transmit their signals simultaneously to the relay C . The received signal at C can be written as:

$$y_C = \sqrt{P_p} h_{AC} x_{Ak} + \sqrt{P_p} h_{BC} x_{Bq} + \sqrt{P_D} h_{DC} x_D + n_C \quad (3.1)$$

where x_{Ak} and x_{Bq} are the k^{th} and q^{th} unit power symbols from the M -ary constellation used at A and B respectively. x_D is a unit power symbol from the M -ary constellation used at D . P_p and P_D are the transmit powers of the PUs (A, B) and the SU D , respectively.

The relay C will use successive interference cancellation (SIC) to decode first the desired signal x_D (which is likely to be the strongest) from y_C while considering x_{Ak} and x_{Bq} as interference. Therefore, the signal to interference noise ratio (SINR) at C to decode the message of D is:

$$\begin{aligned}\Gamma_{DC} &= \frac{P_D |h_{DC}|^2}{P_p (|h_{AC}|^2 + |h_{BC}|^2) + \sigma_n^2} \\ &= \frac{\eta_D \gamma_{DC}}{\eta_p (\gamma_{AC} + \gamma_{BC}) + 1}\end{aligned}\quad (3.2)$$

where $\eta_D = \frac{P_D}{\sigma_n^2}$, $\eta_p = \frac{P_p}{\sigma_n^2}$, and $\gamma_{ij} = |h_{ij}|^2$, for $\forall i, j \in \{A, B, C, D\}$.

Thus the maximum average mutual information between D and C is:

$$I_{DC} = \frac{1}{2} \log_2(1 + \Gamma_{DC}) \quad (3.3)$$

where the factor of $(\frac{1}{2})$ accounts for the fact that each transmission from D to C occurs only in the first phase compared to the overall transmission which consists of two phases. If C successfully decodes x_D , it will subtract it from y_C to get:

$$y'_C = y_C - \sqrt{P_D} h_{DC} \hat{x}_D \quad (3.4)$$

where $\hat{x}_D$ is the estimated signal of D at C . Then from y'_C the relay C tries to decode both x_{Ak} and x_{Bq} using optimal detection based on ML principle as follows:

$$[\hat{k}, \hat{q}] = \min_{k, q} |y'_C - \sqrt{P_p} (h_{AC} x_{Ak} + h_{BC} x_{Bq})|^2 \quad (3.5)$$

Then, if C successfully decodes the data of A and B , it computes $p = \hat{k} \oplus \hat{q}$ to obtain the p^{th} symbol (x_p) from the M -ary constellation used at both A and B to be transmitted in the BC phase.

3.2.2 The downlink NOMA (The BC phase)

The relay C needs to transmit the symbol x_p (obtained from the first phase) to both PUs A and B and also it needs to transmit its own message x_{CD} to the SU D . Therefore, the relay C will use superposition coding to assign part of its transmit power P_s to relay the symbol x_p and the remaining part for transmitting its own symbol x_{CD} . Hence, C generates the composite signal $x_c = \sqrt{\alpha P_s} x_p + \sqrt{(1 - \alpha) P_s} x_{CD}$, where $\alpha (0 \leq \alpha \leq 1)$ is the power splitting factor. x_{CD} is a zero mean unit power signal intended for the

SU D . Therefore the corresponding received signal at receiver $j \in \{A, B, D\}$ can be expressed as:

$$\begin{aligned} y_j &= h_{Cj}x_c + n_j \\ &= \sqrt{\alpha P_s}h_{Cj}x_p + \sqrt{(1-\alpha)P_s}h_{Cj}x_{CD} + n_j \end{aligned} \quad (3.6)$$

The PUs A and B decodes directly the symbol x_p from y_A and y_B , respectively, considering the message intended for D as interference. Then, at each user, the detector makes XOR operation between the estimated primary PLNC symbol index $\hat{p}$ and its own symbol index (k, q) to obtain the estimation of the other user's symbol index $(\hat{q}, \hat{k})$.

At the SU D , SIC is used to first decode the symbol x_p from y_D , then subtracts it from y_D , and then from the resulted signal it decodes its desired symbol x_{CD} .

Hence, the maximum average mutual information between the relay C and user $j \in \{A, B, D\}$ to decode the symbol x_p can be written as:

$$I_{Cj} = \frac{1}{2} \log_2 \left(1 + \frac{\alpha \eta_s \gamma_{Cj}}{(1-\alpha) \eta_s \gamma_{Cj} + 1} \right) \quad (3.7)$$

For the SU D , after successfully decoding the symbol x_p , it will subtract it from the received signal y_D to get $y'_D = y_D - \sqrt{\alpha P_s}h_{CD}\hat{x}_p$ from which it will decode x_{CD} . Hence the maximum average mutual information between C and D to decode for x_{CD} conditioned on the correct decoding of the symbol x_p can be given by:

$$I'_{CD} = \frac{1}{2} \log_2 (1 + (1-\alpha) \eta_s \gamma_{CD}) \quad (3.8)$$

3.3 Performance Analysis: Outage Behavior

In this part we analyze the performance of the above described protocol in terms of outage events and outage probabilities. An outage event occurs when the maximum average mutual information (I) for a link is less than the target rate (R) of that link, i.e., when $(I < R)$, and therefore, the outage probability is $Pr(I < R)$ [72]. We assume that the target rates for PUs and SUs are R_{pt} and R_{st} , respectively.

3.3.1 Outage probability of the secondary users

The Outage probability of the relay C to decode the message of the SU D (P_{OUT-C}^D) in the MAC phase can be obtained using (3.2) and (3.3) as follows :

$$\begin{aligned} P_{OUT-C}^D &= Pr(I_{DC} < R_{st}) = Pr(\Gamma_{DC} < R_s) \\ &= 1 - \frac{\eta_D^2 d_{AC}^v d_{BC}^v}{(\eta_p d_{DC}^v R_s + \eta_D d_{AC}^v) ((d_{BC}^v + \eta_p) d_{DC}^v R_s + \eta_D d_{BC}^v)} \end{aligned} \quad (3.9)$$

where $R_s = 2^{2R_{st}} - 1$, and we utilized the CDF of the random variable Γ_{DC} given by (A.4) (see Appendix A. for proof) which can be written as :

$$F_{\Gamma_{DC}}(z) = 1 - \frac{\lambda_v \lambda_w}{(\lambda_u z + \lambda_v)(\lambda_u z + \lambda_w)} \quad (3.10)$$

with $\lambda_u = \frac{d_{DC}^v}{\eta_D}$, $\lambda_v = \frac{d_{AC}^v}{\eta_p}$, $\lambda_w = \frac{d_{BC}^v}{d_{BC}^v + \eta_p}$, and $\lambda_v \neq \lambda_w$.

To calculate the outage probability of the SU D to decode the message of the relay C after SIC in the BC phase (P_{OUT-D}^C), we refer to section 2, where D uses successive decoding in the BC phase to decode the symbol x_p first and then x_{cd} . Hence the outage probability of D can be written as:

$$\begin{aligned} P_{OUT-D}^C &= 1 - Pr(I_{DC} > R_{st}) Pr(I_{AC} > R_{pt}) Pr(I_{BC} > R_{pt}) \\ &\quad \times Pr(I_{CD} > R_{pt}) Pr(I_{CD}' > R_{st}) \end{aligned} \quad (3.11)$$

where,

$$\begin{aligned} Pr(I_{AC} > R_{pt}) &= Pr(\gamma_{AC} > \frac{R_p}{\eta_p}) \\ &= \exp\left(-\frac{R_p d_{AC}^v}{\eta_p}\right) \end{aligned} \quad (3.12)$$

$$\begin{aligned} Pr(I_{BC} > R_{pt}) &= Pr(\gamma_{BC} > \frac{R_p}{\eta_p}) \\ &= \exp\left(-\frac{R_p d_{BC}^v}{\eta_p}\right) \end{aligned} \quad (3.13)$$

$$\begin{aligned} Pr(I_{CD} > R_{pt}) &= Pr\left(\frac{\alpha \eta_s \gamma_{CD}}{(1 - \alpha) \eta_s \gamma_{CD} + 1} > R_p\right) \\ &= \begin{cases} \exp\left(-\frac{d_{CD}^v R_p}{\eta_s (\alpha(1 + R_p) - R_p)}\right) & , \text{if } \frac{R_p}{R_p + 1} < \alpha < 1 \\ 0 & , \text{if } 0 < \alpha \leq \frac{R_p}{R_p + 1} \end{cases} \end{aligned} \quad (3.14)$$

where we utilized (B.4), the CDF of the random variable Γ_{CD} in Appendix B. Using (3.8) we have:

$$Pr(I'_{CD} > R_{st}) = \exp\left(-\frac{d_{CD}^v R_s}{(1-\alpha)\eta_s}\right) \quad (3.15)$$

where $R_p = 2^{2R_{pt}} - 1$, $R_s = 2^{2R_{st}} - 1$. Since γ_{ij} is an exponential random variable with rate parameter d_{ij}^v we have $Pr(\gamma_{ij} > R) = \exp(-d_{ij}^v R)$.

From (3.9), (3.12)-(3.15) into (3.11) we obtain:

$$P_{OUT-D}^C = \begin{cases} 1 - \exp\left(-\frac{d_{CD}^v R_p}{\eta_s(\alpha(1+R_p)-R_p)} - \frac{d_{CD}^v R_s}{(1-\alpha)\eta_s} - \frac{(d_{AC}^v + d_{BC}^v)R_p}{\eta_p}\right) \\ \quad \times \frac{\eta_D^2 d_{AC}^v d_{BC}^v}{(\eta_p d_{DC}^v R_s + \eta_D d_{AC}^v)((d_{BC}^v + \eta_p)d_{DC}^v R_s + \eta_D d_{BC}^v)} & , if \frac{R_p}{R_p+1} < \alpha < 1 \\ 1 & , if 0 < \alpha \leq \frac{R_p}{R_p+1} \end{cases} \quad (3.16)$$

3.3.2 Outage probability of the primary users

The outage probability of A to decode the message of B (P_{OUT-A}^B) – through the cooperation with C – can be computed as follows:

$$P_{OUT-A}^B = 1 - Pr(I_{DC} > R_{st}) Pr(I_{AC} > R_{pt}) \\ \times Pr(I_{BC} > R_{pt}) Pr(I_{CA} > R_{pt}) \quad (3.17)$$

where,

$$Pr(I_{CA} > R_{pt}) = Pr\left(\frac{\alpha \eta_s \gamma_{CA}}{(1-\alpha)\eta_s \gamma_{CA} + 1} > R_p\right) \\ = \begin{cases} \exp\left(-\frac{d_{CA}^v R_p}{\eta_s(\alpha(1+R_p)-R_p)}\right) & , if \frac{R_p}{R_p+1} < \alpha < 1 \\ 0 & , if 0 < \alpha \leq \frac{R_p}{R_p+1} \end{cases} \quad (3.18)$$

where we utilized (A.4), the CDF of the random variable Γ_{CA} in Appendix B.

Substituting equations (3.9), (3.12), (3.13) and (3.18) into (3.17), we obtain:

$$P_{OUT-A}^B = 1 - \frac{\eta_D^2 d_{AC}^v d_{BC}^v}{(\eta_p d_{DC}^v R_s + \eta_D d_{AC}^v)((d_{BC}^v + \eta_p)d_{DC}^v R_s + \eta_D d_{BC}^v)} \\ \times \exp\left(-\frac{(d_{AC}^v + d_{BC}^v)R_p}{\eta_p}\right) \exp\left(-\frac{d_{CA}^v R_p}{\eta_s(\alpha(1+R_p)-R_p)}\right) \\ for \frac{R_p}{R_p+1} < \alpha < 1, \text{ and } 1 \text{ elsewhere.} \quad (3.19)$$

In a similar way, we can obtain the outage probability of B to decode the message of A (P_{OUT-B}^A) as:

$$P_{OUT-B}^A = 1 - \frac{\eta_D^2 d_{AC}^v d_{BC}^v}{(\eta_p d_{DC}^v R_s + \eta_D d_{AC}^v) ((d_{BC}^v + \eta_p) d_{DC}^v R_s + \eta_D d_{BC}^v)} \times \exp\left(-\frac{(d_{AC}^v + d_{BC}^v) R_p}{\eta_p}\right) \exp\left(-\frac{d_{CB}^v R_p}{\eta_s (\alpha(1 + R_p) - R_p)}\right) \text{ for } \frac{R_p}{R_p + 1} < \alpha < 1, \text{ and } 1 \text{ elsewhere.} \quad (3.20)$$

3.4 Results and Discussion

To evaluate the performance of the proposed protocol, we have conducted simulations for the outage probability of the PUs and SUs. For comparison purposes, the outage probability of the PU $A(B)$ to decode the message of the PU $B(A)$ without spectrum sharing can be computed as follows:

$$\begin{aligned} P_{outA-direct} &= P_{outB-direct} = Pr(I_{AB} < R_{pt}) \\ &= Pr\left(\frac{1}{2} \log_2(1 + \eta_p \gamma_{AB}) < R_{pt}\right) \\ &= 1 - \exp\left(-\frac{R_p}{\eta_p}\right) \end{aligned} \quad (3.21)$$

We consider the outage performance of the PUs and SUs for the network shown in Figure (3.1) with various parameters for distances, SNRs and target rates. For all simulations and analytical expressions the path loss exponent is taken as $v = 4$. We assume equal channels for the PUs A and B , therefore, we plot only the outage probability of A to decode the message of B .

Figures (3.2) – (3.4) show the outage performance of the proposed protocol when the SU D is nearer to the relay C than the PUs (A and B), for target rates $R_{pt} = R_{st} = 0.5, 1, 2$ bit per channel use ($bpcu$) required at the primary and secondary users, respectively. The system parameters are listed in Table (3.1) with $d_{AC} = d_{BC} = 0.5$ fixed for all figures. In all cases we can see that the proposed protocol provides better performance for the PUs compared to the case without spectrum sharing (i.e., direct transmission between A and B). We also observe that the analytical results are in agreement with the simulation results.

The optimum value of the power split factor α (for $\frac{R_p}{R_p + 1} < \alpha < 1$) can be obtained from the curve of the outage probability of the SU D to decode the message of C in the

Table 3.1 : System parameters for Figures (3.2) – (3.6).

Parameter	Fig. (3.2)	Fig. (3.3)	Fig. (3.4)	Fig. (3.5)	Fig. (3.6)
d_{DC}	0.1	0.1	0.1	0.3	0.3
η_p (dB)	15	20	20	15	15
η_s (dB)	15	20	30	15	30
η_D (dB)	15	20	30	15	30
R_{pt} (bpcu)	0.5	1	2	0.5	0.5
R_{st} (bpcu)	0.5	1	2	0.5	0.5

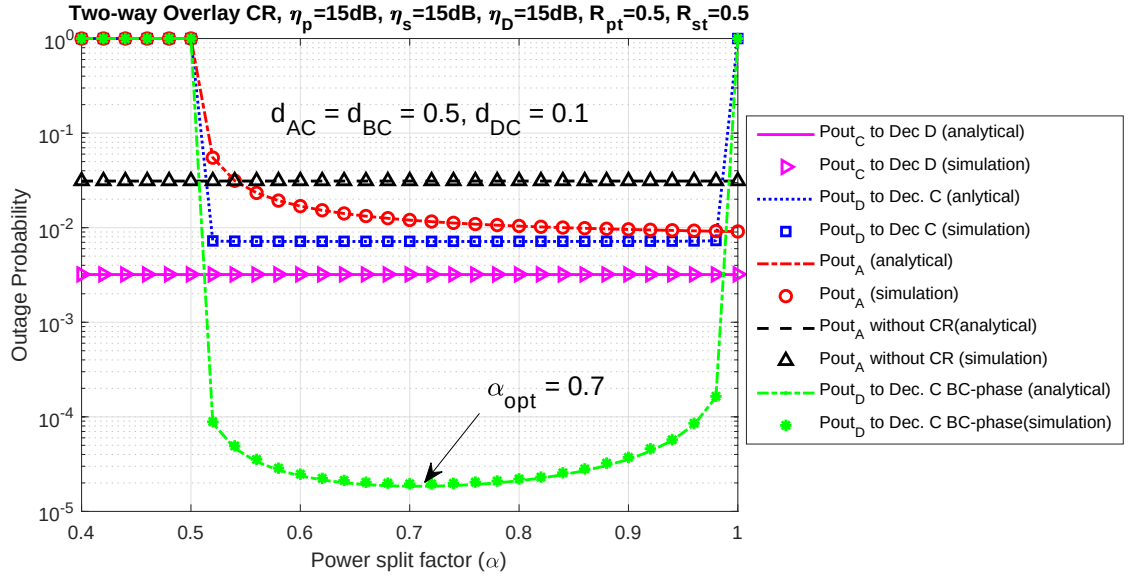


Figure 3.2 : Outage probability vs. power split factor for rates $R_{pt} = R_{st} = 0.5$ b/s/Hz for both PR and SR , respectively.

BC phase only. Conditioned on the successful decoding of the primary and secondary messages at the relay C in the MAC phase, the outage probability of the SU D in the BC phase can be expressed as:

$$\begin{aligned}
 P_{OUT-D}^{BCphase} &= \left[P_{OUT-D}^C \mid \text{Conditioned on correct decoding at } C \text{ in MAC phase} \right] \\
 &= 1 - \Pr(I_{CD} > R_{pt}) \Pr(I'_{CD} > R_{st}) \\
 &= \begin{cases} 1 - \exp\left(-\frac{d_{CD}^v R_p}{\eta_s(\alpha(1+R_p)-R_p)} - \frac{d_{CD}^v R_s}{(1-\alpha)\eta_s}\right) & , \text{if } \frac{R_p}{R_p+1} < \alpha < 1 \\ 1 & , \text{if } 0 < \alpha \leq \frac{R_p}{R_p+1} \end{cases} \quad (3.22)
 \end{aligned}$$

For Figures (3.2) – (3.4), we can observe that $\alpha_{opt} \approx 0.7, 0.84$ and 0.95 , respectively, where for $\alpha < \alpha_{opt}$ the outage probability of the primary user A goes to 1, and for $\alpha > \alpha_{opt}$ the outage probability of the secondary user D goes to 1. Also, we can see that, as α exceeds the threshold $\frac{R_p}{R_p+1}$, the outage probability of D decreases with

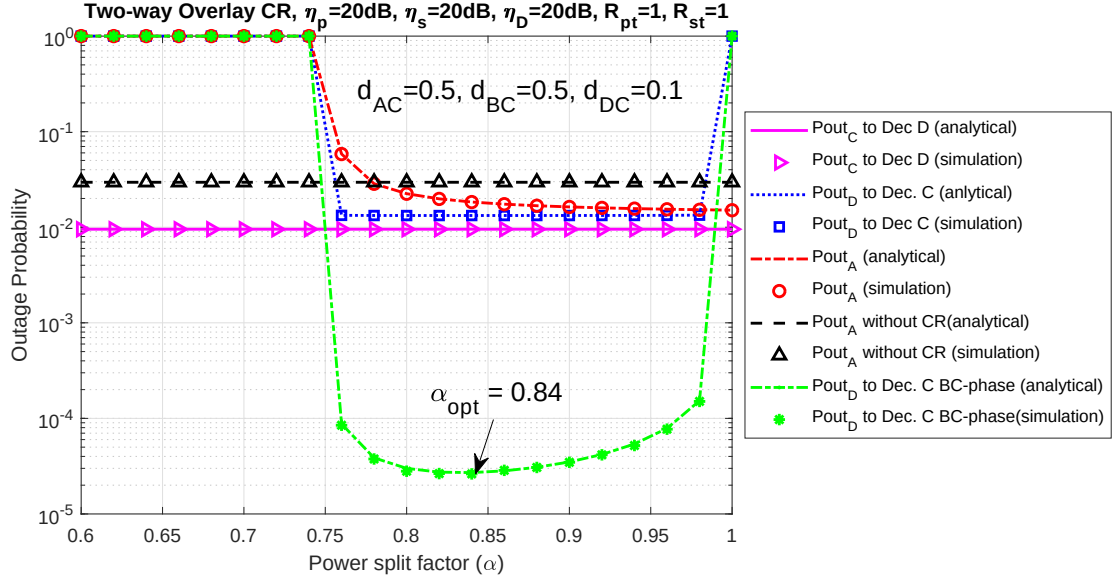


Figure 3.3 : Outage probability vs. power split factor for rates $R_{pt} = R_{st} = 1$ b/s/Hz for both *PR* and *SR*, respectively.

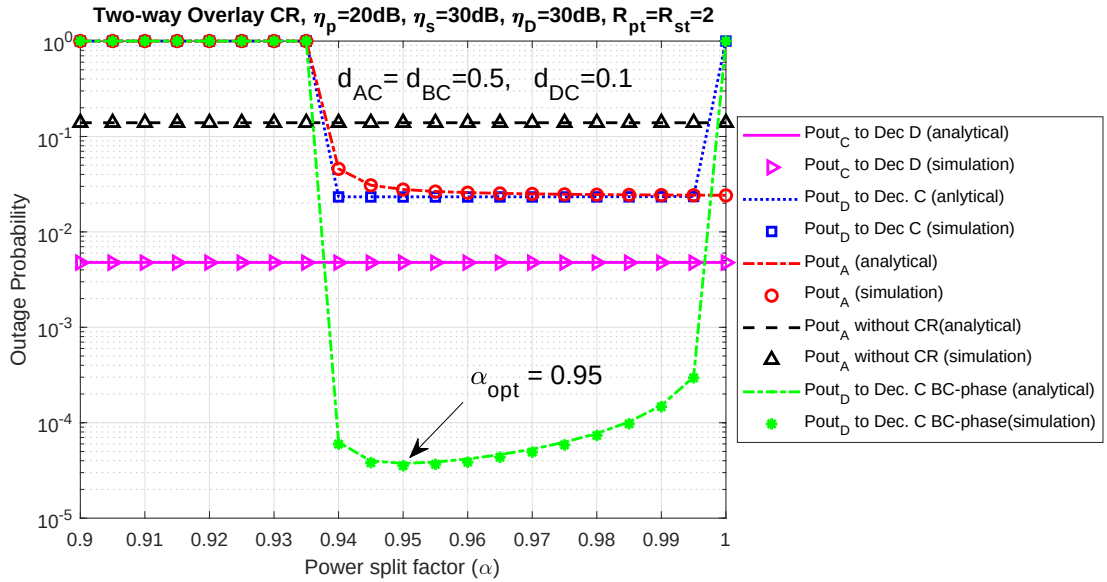


Figure 3.4 : Outage probability vs. power split factor for rates $R_{pt} = R_{st} = 2$ b/s/Hz for both *PR* and *SR*, respectively.

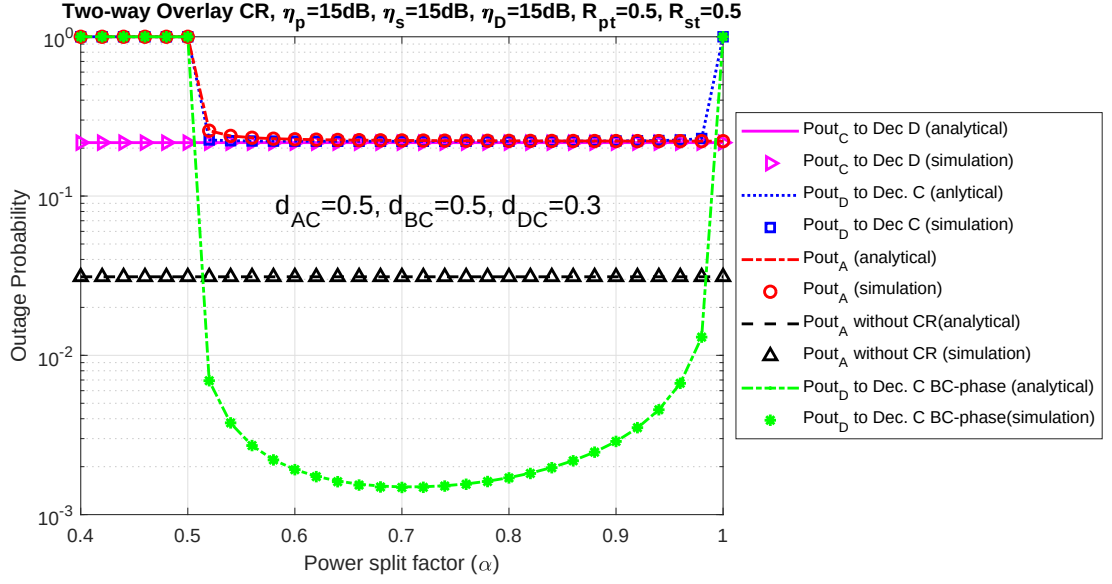


Figure 3.5 : Outage probability vs. power split factor when the distance between the SUs increases from 0.1 to 0.3.

increasing α until ($\alpha = \alpha_{opt}$) and then increases to 1. This is due to the fact that D uses successive decoding in the second phase. As α increases above the threshold $\frac{R_p}{R_p+1}$ and below α_{opt} , the allocated power for the XORed primary symbol increases and the allocated power for the secondary message decreases but still good enough for the detection of the secondary message x_{CD} at D . When α exceeds α_{opt} , the allocated power for the secondary signal decreases until D becomes unable to decode x_{CD} , thus the outage probability increases to 1. Also, we can observe that the overall outage probability of the SU D given by (3.11) appears to remain constant as $\frac{R_p}{R_p+1} < \alpha < 1$, since the value of the probabilities $Pr(I_{CD} > R_{pt})$ and $Pr(I'_{CD} > R_{st})$ goes to 1 as d_{DC}^v goes to zero in (3.11), therefore the dependence on α becomes unnoticeable.

Figure (3.5) shows that as the distance between C and D increases from $d_{DC} = 0.1$ to 0.3 (with same other parameters as for Figure (3.2)), the performance gets worse since C is unable to decode the SU's and PU's messages and hence the outage probability increases for all users. In this case the secondary users (C and D) are required to increase their transmit power (as shown in Figure (3.6)) to provide a strong interference channel letting C and D able to use SIC in the MAC and BC phases, respectively.

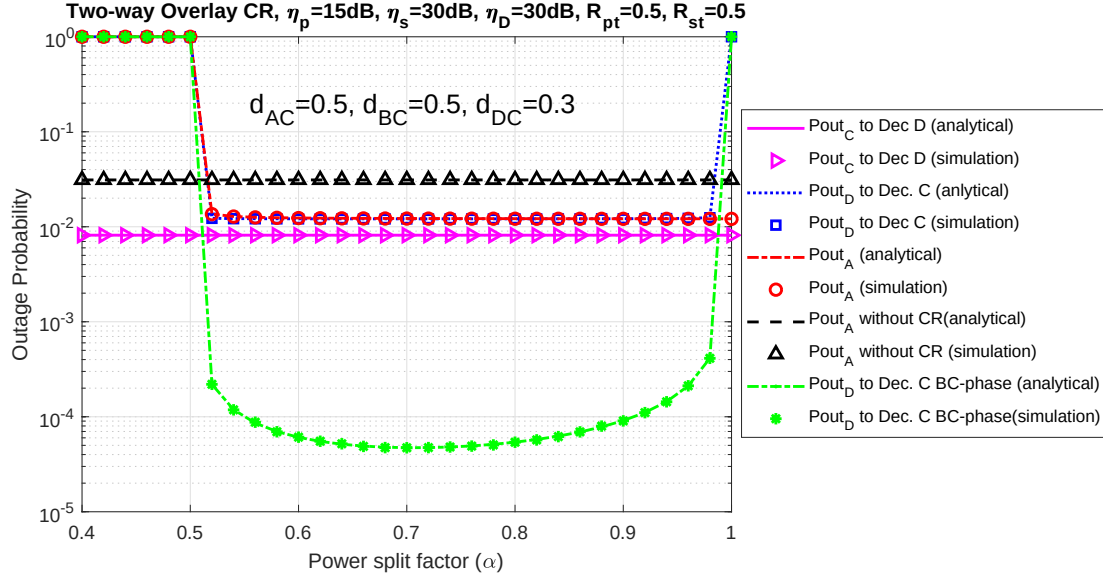


Figure 3.6 : Outage probability vs. power split factor, when the distance between the SUs increases from 0.1 to 0.3 and increasing the SUs' transmit powers.

3.5 Summary

In this chapter, we proposed a two-way spectrum sharing protocol for the overlay cognitive two-way two-phase channel which allows for two-way SUs communication while assisting the communication between the PUs. Closed form expressions for the outage probabilities for both the PUs and SUs has been derived. Analytical and simulation results show that the proposed protocol offers efficient spectrum utilization (and hence higher system capacity) over the three-phase and two-phase spectrum sharing protocols in literature with one-way SUs transmission.

4. NON-ORTHOGONAL MULTIPLE ACCESS PROTOCOL FOR OVERLAY COGNITIVE RADIO NETWORKS USING SPATIAL MODULATION AND ANTENNA SELECTION

In this chapter we propose a spectrum sharing protocol for overlay cognitive radio (CR) networks using non-orthogonal multiple access (NOMA), spatial modulation (SM) and capacity optimized antenna selection (COAS). The performance of the proposed protocol is investigated by derivations of upper bounds on the average symbol error probabilities at the primary and secondary receivers and by Monte Carlo simulations.

4.1 Related Work

The application of SM in overlay CR networks has been recently investigated. In [73], the authors considered using SM at the secondary transmitter (ST) to relay the primary transmitter's (PT's) APM symbol using decode-and-forward (DF) technique while the symbol intended for the secondary receiver (SR) is used to select the transmitting antenna index. The performance of the protocol is evaluated by computing upper bounds on the bit error probabilities (BEP) for single antenna primary and secondary receivers. The authors of [73] extended their work in [74] for different relaying strategies: fixed and incremental amplify and forward, and selective decode and forward, with upper bounds on the BEP have been derived. In [75], the authors considered the same idea of [73] but using amplify and forward (AF) and multiple antenna primary and secondary receivers. The performance is evaluated by deriving upper bounds for the average symbol error rates (SER) at the primary and secondary receivers.

On the other hand, the application of NOMA in CR networks has recently attracted many researchers to investigate problems related with outage probability, capacity analysis, and power allocation schemes to further improve the system performance in terms of sum rate, spectral efficiency, and energy efficiency [54–58]. In [54] the impact of user pairing on the performance of CR-inspired NOMA (CR-NOMA), is characterized. The concept of CR-NOMA is to serve the SU on the condition that the

PU's QoS is guaranteed. An exact expression for the outage probability achieved by CR-NOMA is derived. In [55] the authors applied NOMA to large-scale underlay CR networks and the system performance is evaluated by deriving closed-form expressions of the outage probability using stochastic geometry technique. In [56] the authors studied the power allocation problem for NOMA-based CR networks and proposed a low complexity algorithm that guarantees the QoS requirements for both the PUs and SUs. In [57], the researchers proposed an algorithm to maximize the energy efficiency of a generalized CR inspired NOMA system, subject to both the transmit power constraint and the QoS guarantees for all PUs. In [58], the authors applied NOMA to overlay CR networks with multiple SUs, and proposed two SUs scheduling schemes based on reliability and fairness, respectively, to optimize the system outage performance. Closed form expressions of outage probabilities has been derived.

The integration of NOMA and SM has been considered recently, for example in [51], the researchers investigated NOMA with SM in a downlink multiuser transmission and the performance has been compared with orthogonal multiple access-based SM (OMA-SM) and transmit antenna grouping based SM (TAG-SM) schemes. In [52] the authors proposed a hybrid detection scheme to combine SM and NOMA in the uplink side.

Motivated by the advantages of NOMA, SM and overlay CR, in this chapter, we propose a spectrum sharing protocol for overlay CR networks using NOMA and SM. The combination of NOMA, SM and CR will allow more users to transit simultaneously, that results in higher spectral efficiency, massive connectivity and higher data rates. The proposed protocol allows a ST to relay a PT's message to a PR and at the same time superimposes his message to an SR. With NOMA, superposition coding is used at ST and SIC is used at the receivers. SR uses SIC to detect the signal intended for PR and then cancels it to detect its own signal while PR uses direct decoding to detect its own signal considering the intended signal for SR as an interference. This decreases the detection complexity considerably compared to the case without NOMA in which the detectors are required to jointly detect both SM symbols at each receiver.

Since the CR principle requires higher priority for the PUs, we study the application of COAS at ST in accordance with PR to the proposed CR-NOMA-SM protocol, to provide higher QoS transmission for PR.

The performance of the proposed protocol is investigated through derivations of upper bounds for the average symbol error probabilities (SEP) at PR and SR for CR-NOMA-SM protocol and through Monte Carlo simulations.

This chapter is organized as follows. Section (4.2) presents the system model and the proposed overlay CR-NOMA-SM protocol description with and without COAS. The performance analysis of the primary and secondary users is presented in section (4.3). The analytical and simulation results are discussed in section (4.4). Finally section (4.5) provides a summary for the chapter.

4.2 System Model

In this chapter, we consider an overlay cognitive radio network as shown in Figure (4.1). The primary network consists of a PT with N_p transmit antennas, and a PR with N_{r1} receive antennas. The secondary network consists of a ST with N_t transmit antennas and N_r receive antennas and a SR with N_{r2} receive antennas. ST acts as a relay that cooperatively assists the communication between PT and PR while gaining access to the spectrum to convey its own information to SR. Figure (4.2), shows a possible scenario for the overlay CR network that we investigate through this chapter and chapter 5, in which PT represents a primary base station (PBS) and ST represents a secondary base station (SBS) that serves multiple SRs. Out-of-range PRs use NOMA-SM and cooperation with ST to communicate with PT, while in-range PRs use direct transmission to communicate with PT directly. To achieve the most benefits of NOMA, ST is assumed to perform user pairing by selecting the SR with the highest channel gain – among all other SRs represented by dots in Figure (4.1) – with respect to the channel gain of the intended PR. ST uses decode and forward algorithm to relay the message of PT to PR. It is assumed that no direct link exists between PT and PR, like the case of a cell-edge user that experiences very low SNRs. Throughout this chapter all nodes are constrained to operate in a half-duplex mode. We assume independent Rayleigh fading for all transmitter–receiver pairs. The channel matrices for the PT-ST, ST-PR, and ST-SR links are $\mathbf{B}$, $\mathbf{H}$ and $\mathbf{G}$ with entries distributed as $b_{ij} \sim \mathbb{CN}(0,1)$,

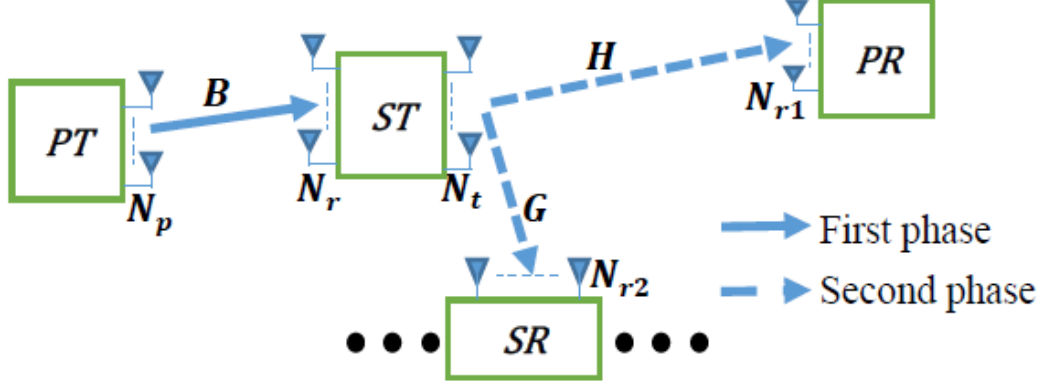


Figure 4.1 : System model of the overlay CR network.

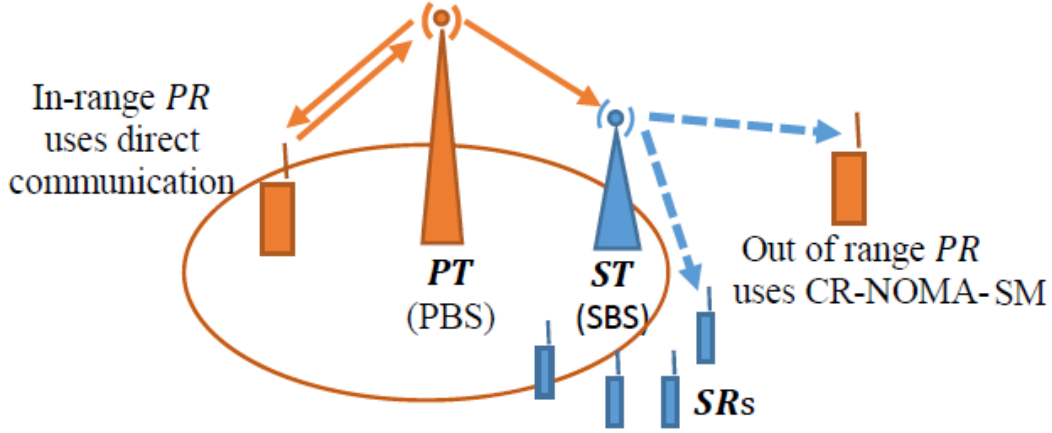


Figure 4.2 : A possible scenario for the proposed network.

$h_{ij} \sim \mathcal{CN}(0, \sigma_h^2)$, $g_{ij} \sim \mathcal{CN}(0, \sigma_g^2)$, respectively. The noise at any node is modeled as $\mathcal{CN}(0, \sigma_n^2)$. P_p and P_s are the transmit powers of PT and ST, respectively. It is assumed that perfect channel state information (CSI) is available at all receivers.

4.3 CR-NOMA-SM without AS

As shown in Figure (4.1), the communication process can be done in two phases.

4.3.1 The first phase

In the first phase, PT transmits its message to ST using SM. The message is divided into two group of bits: $(\log_2 M)$ bits select the q^{th} symbol (x_q) from the M -ary constellation set, and $(\log_2 N_p)$ bits select the i^{th} transmit antenna out of the N_p transmit antennas to transmit the selected symbol x_q . The signal vector received at ST can be written as:

$$\mathbf{y}_{ST} = \sqrt{P_p} \mathbf{b}_i x_q + \mathbf{n}_{ST} \quad (4.1)$$

where $\mathbf{b}_i$ (the i^{th} column of $\mathbf{B}$) represents the channel vector between the active antenna at PT and the receiving antennas at ST. $\mathbf{n}_{ST}$ is the noise vector at ST. For equally likely symbols, the optimal ML detector is given by:

$$[\hat{i}, \hat{q}] = \min_{i', q'} \|\mathbf{y}_{ST} - \sqrt{P_p} \mathbf{b}_{i'} x_{q'}\|^2 \quad (4.2)$$

where $1 \leq i' \leq N_p$, and $1 \leq q' \leq M$.

4.3.2 The second phase

In the second phase, based on successful decoding of the message of PT, ST generates two messages using NOMA-SM that are transmitted simultaneously to both PR and SR as follows. ST assigns N_{t1} transmit antennas for SM for PR, and N_{t2} transmit antennas for SM for SR (where $N_{t1} + N_{t2} \leq N_t$). The splitting of the transmitting antennas depends on the required rates at both PR and SR. For example, consider the case where the required rates at both PR and SR are 4 and 3 bpcu (bits per channel use), respectively, and $N_t = 6$. One possible scenario at ST is to assign $N_{t1} = 4$ with QPSK to provide 2 bit of information through the active antenna index and 2 bits of information through the APM technique. The remaining 2 antennas and using QPSK can be assigned to SR to provide the required 3 bits of information.

Using NOMA, ST splits its transmit power P_s between the two users according to their channel gain strengths. Then ST transmits simultaneously the detected primary message from first phase with power portion P_{s1} for PR (using SM with the N_{t1} antennas group), and a new message with power portion P_{s2} for SR (using SM with the N_{t2} antennas group), where $P_{s1} + P_{s2} = P_s$.

Therefore the signal vector received at PR can be expressed as:

$$\mathbf{y}_{PR} = \sqrt{P_{s1}} \mathbf{h}_j x_p + \sqrt{P_{s2}} \mathbf{h}_k x_s + \mathbf{n}_{PR} \quad (4.3)$$

where $j(1 \leq j \leq N_{t1})$ and $k(N_{t1} + 1 \leq k \leq N_{t1} + N_{t2})$ represent the indices of the activated antennas at ST. $\mathbf{h}_j$ and $\mathbf{h}_k$ are the j^{th} and k^{th} columns of $\mathbf{H}$, respectively, representing the channel vectors between the activated antennas (at ST) and PR. x_p and x_s are the p^{th} ($1 \leq p \leq M_1$) and s^{th} ($1 \leq s \leq M_2$) APM symbols intended for PR and SR, respectively. M_1 and M_2 are the APM constellation sizes that are used for PR and SR, respectively. PR decodes its intended message directly considering the

message intended for SR as an interference. The optimal detector at PR based on the ML principle is:

$$[\hat{j}, \hat{p}] = \min_{j', p'} \left\| \mathbf{y}_{PR} - \sqrt{P_{s1}} \mathbf{h}_{j' p'} \right\|^2 \quad (4.4)$$

where $1 \leq j' \leq N_{t1}$, and $1 \leq p' \leq M_1$.

The signal vector received at SR is expressed as:

$$\mathbf{y}_{SR} = \sqrt{P_{s1}} \mathbf{g}_j x_p + \sqrt{P_{s2}} \mathbf{g}_k x_s + \mathbf{n}_{SR} \quad (4.5)$$

where $\mathbf{g}_j$ and $\mathbf{g}_k$ are the j^{th} and k^{th} columns of $\mathbf{G}$, respectively, representing the channel vectors between the activated antennas and SR. $\mathbf{n}_{SR}$ is the noise vector at SR. SR uses SIC to decode the message intended for PR and then cancels it from the received signal $\mathbf{y}_{SR}$ to obtain:

$$\mathbf{y}'_{SR} = \mathbf{y}_{SR} - \sqrt{P_{s1}} \mathbf{g}_{\hat{j}} x_{\hat{p}} \quad (4.6)$$

where $\hat{j}$ and $\hat{p}$ are the estimated antenna index and the estimated APM symbol index of the message intended for PR at SR. From $\mathbf{y}'_{SR}$ SR decodes its own message using ML detector as:

$$[\hat{k}, \hat{s}] = \min_{k', s'} \left\| \mathbf{y}'_{SR} - \sqrt{P_{s2}} \mathbf{g}_{k' s'} \right\|^2 \quad (4.7)$$

where $N_{t1} + 1 \leq k' \leq N_{t1} + N_{t2}$, and $1 \leq s' \leq M_2$.

4.4 CR-NOMA-SM with COAS

To enhance the QoS for PR we propose the usage of COAS [64] with the proposed protocol, where PR computes the indices corresponding to the N_{t1} largest channel norms out of the N_t transmit antennas of ST for every coherence interval and feeds it back to ST. Then, it is the responsibility of ST to transmit the new ordering information of the antennas to SR, where this can be done during the first phase through the use of feedback control channels. The ordering can be given as follows:

$$\underbrace{\|\mathbf{h}_{(1)}\|^2 \geq \|\mathbf{h}_{(2)}\|^2 \geq \dots \geq \|\mathbf{h}_{(N_{t1})}\|^2}_{\text{Largest } N_{t1} \text{ channel norms}} \geq \underbrace{\|\mathbf{h}_{(N_{t1}+1)}\|^2, \dots, \|\mathbf{h}_{(N_t)}\|^2}_{\text{Ordering is arbitrary}}$$

where $\mathbf{h}_{(j)}$ indicates the j^{th} column of $\mathbf{H}$ with the new ordering. With COAS, the N_{t1} antennas with the largest channel gains with respect to PR will be used for SM toward PR and the next N_{t2} antennas will be used for SM toward SR. Therefore using the antennas with high channel gains (with respect to PR) for SM toward PR and

the antennas with low channel gains (from the perspective of PR) for SM toward SR will result in reducing the secondary symbol interference at PR, thus, enhancing its performance. At SR this antenna re-indexing is random with respect to the channel matrix $\mathbf{G}$, which will result in no change in the performance of SR on the average. After performing COAS, the proposed protocol uses NOMA-SM as described in the CR-NOMA-SM without AS mode.

4.5 Performance Analysis

In this section, the performance of the proposed protocol is investigated by deriving an upper bound for the average symbol error probability (SEP) of each link for the CR-NOMA-SM without AS protocol, which also can be considered as an upper bound for the CR-NOMA-SM with COAS protocol.

4.5.1 The SEP of the PT-ST link

Since the PT-ST link uses SM, the upper bound for the average SEP can be derived from (4.2) as in [59] using the well-known union bounding technique [76] as follows:

$$\overline{SEP}_{PT \rightarrow ST} \leq \frac{1}{MN_p} \sum_{i=1}^{N_p} \sum_{q=1}^M \sum_{i' \neq i}^{N_p} \sum_{q'=1}^M \omega^{N_r} \sum_{\ell=0}^{N_r-1} \binom{N_r-1+\ell}{\ell} (1-\omega)^\ell \quad (4.8)$$

$i'q' \neq iq$

where $\omega = \frac{1}{2} \left(1 - \sqrt{\frac{\sigma_q^2}{1+\sigma_q^2}} \right)$, and $\sigma_q^2 = \frac{P_p(|x_q|^2 + |x_{q'}|^2)}{4\sigma_n^2}$.

4.5.2 The SEP of the ST-PR link

An upper bound for the average SEP of the ST-PR link can be derived using the union bounding technique as follows:

$$\overline{SEP}_{ST \rightarrow PR} \leq \frac{1}{M_1 N_{t1}} \sum_{j=1}^{N_{t1}} \sum_{p=1}^{M_1} \sum_{j' \neq j}^{N_{t1}} \sum_{p'=1}^{M_1} \overline{PEP}_{ST \rightarrow PR} \quad (4.9)$$

$j'p' \neq jp$

where $(1 \leq j, j' \leq N_{t1})$, $(1 \leq p, p' \leq M_1)$, and $\overline{PEP}_{ST \rightarrow PR}$ is the average pairwise error probability (PEP) at PR of deciding that the symbol $x_{p'}$ is transmitted from the j'^{th} transmit antenna, given that the symbol x_p was transmitted from the j^{th} transmit antenna of ST.

The instantaneous PEP at PR ($PEP_{ST \rightarrow PR}^{(i)}$) conditioned on $\mathbf{H}$ can be computed by rewriting (4.3) as follows:

$$\mathbf{y}_{PR} = \sqrt{P_{s1}} \mathbf{h}_j x_p + \tilde{\mathbf{n}} \quad (4.10)$$

where $\tilde{\mathbf{n}} = \sqrt{P_{s2}} \mathbf{h}_k x_s + \mathbf{n}_{PR}$, is the interference plus noise vector – with each component is a complex Gaussian random variable with variance $(P_{s2} \sigma_h^2 + \sigma_n^2)$.

By using (4.4), $PEP_{ST \rightarrow PR}^{(i)}$ can be written as:

$$\begin{aligned} PEP_{ST \rightarrow PR}^{(i)} &= Pr(d_{jp} > d_{jp'} | \mathbf{H}) \\ &= Pr(\tilde{N} > P_{s1} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2 | \mathbf{H}) \\ &= Q\left(\sqrt{\frac{P_{s1} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}}\right) = Q(\sqrt{\gamma}) \end{aligned} \quad (4.11)$$

where $d_{jp} = \|\mathbf{y}_{PR} - \sqrt{P_{s1}} \mathbf{h}_j x_p\|^2$, $\tilde{N} = 2 \Re\{\tilde{\mathbf{n}}^H \sqrt{P_{s1}} (\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'})\}$ is a real Gaussian random variable with zero mean and variance $(2(P_{s2} \sigma_h^2 + \sigma_n^2) P_{s1} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2)$, and

$$\gamma = \frac{P_{s1} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)} = \frac{P_{s1} \sum_{i=1}^{N_{r1}} |h_{ij} x_p - h_{ij'} x_{p'}|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)} \quad (4.12)$$

To obtain the average pairwise error probability ($\overline{PEP}_{ST \rightarrow PR}$) we take the average of ($PEP_{ST \rightarrow PR}^{(i)}$) over the PDF of the random variable γ . The PDF of the random variable γ is difficult to be obtained for the general case when x_p is drawn from complex constellation since the real and imaginary parts of the complex random variable $(h_{ij} x_p - h_{ij'} x_{p'})$ in (4.12) are not independent. Following the procedure in [59], for independence to be satisfied, we consider the case when x_p is drawn from real constellation. Hence (4.12) reduces to $\gamma = \sum_{\ell=1}^{2N_{r1}} v_\ell^2$, where v_ℓ is a zero mean Gaussian random variable with variance $\sigma_v^2 = \frac{P_{s1} \sigma_h^2 (|x_p|^2 + |x_{p'}|^2)}{4(P_{s2} \sigma_h^2 + \sigma_n^2)}$. Therefore, the random variable γ is a chi-square random variable with $2N_{r1}$ degrees of freedom. Then the average PEP can be obtained as in [59, 76]:

$$\begin{aligned} \overline{PEP}_{ST \rightarrow PR} &= \int_0^\infty PEP_{ST \rightarrow PR}^{(i)} f_\gamma(r) dr \\ &= \lambda^{N_{r1}} \sum_{\ell=0}^{N_{r1}-1} \binom{N_{r1}-1+\ell}{\ell} (1-\lambda)^\ell \end{aligned} \quad (4.13)$$

where $\lambda = \frac{1}{2} \left(1 - \sqrt{\frac{\sigma_v^2}{1+\sigma_v^2}}\right)$.

By plugging (4.13) in (4.9), we obtain the upper bound for the average SEP of the ST-PR link.

4.5.3 The SEP of the ST-SR link

As we mentioned in section (4-3), SR uses SIC to first decode the primary message and then cancels it to decode its own intended message. Therefore, the average SEP of the ST-SR link can be upper bounded by the summation of the average SEP of decoding the primary SM symbol at SR ($\overline{SEP}_{ST \rightarrow SR}^{(p)}$) and the average SEP of decoding the secondary SM symbol conditioned on correct decoding of the primary SM symbol at SR ($\overline{SEP}_{ST \rightarrow SR}^{(s)}$) as follows:

$$\overline{SEP}_{ST \rightarrow SR} \leq \underbrace{Pr\{\hat{j}, \hat{p} \neq [j, p]\}}_{(\overline{SEP}_{ST \rightarrow SR}^{(p)})} + \underbrace{Pr\{\hat{k}, \hat{s} \neq [k, s] \mid [\hat{j}, \hat{p}] = [j, p]\}}_{(\overline{SEP}_{ST \rightarrow SR}^{(s)})} \quad (4.14)$$

Following a similar procedure that is used at PR, we can derive the average PEP in each stage for SIC at SR ($\overline{PEP}_{ST \rightarrow SR}^{(p)}$ and $\overline{PEP}_{ST \rightarrow SR}^{(s)}$), and hence the upper bounds for the average SEP in each stage ($\overline{SEP}_{ST \rightarrow SR}^{(p)}$ and $\overline{SEP}_{ST \rightarrow SR}^{(s)}$), respectively, as follows.

$$\overline{PEP}_{ST \rightarrow SR}^{(p)} = \theta^{N_{r1}} \sum_{\ell=0}^{N_{r1}-1} \binom{N_{r1}-1+\ell}{\ell} (1-\theta)^\ell \quad (4.15)$$

$$\text{where } \theta = \frac{1}{2} \left(1 - \sqrt{\frac{\sigma_w^2}{1+\sigma_w^2}} \right), \sigma_w^2 = \frac{P_{s1} \sigma_g^2 (|x_p|^2 + |x_{p'}|^2)}{4(P_{s2} \sigma_g^2 + \sigma_n^2)}.$$

Then,

$$\overline{SEP}_{ST \rightarrow SR}^{(p)} \leq \frac{1}{M_1 N_{t1}} \sum_{j=1}^{N_{t1}} \sum_{p=1}^{M_1} \sum_{j'=1}^{N_{t1}} \sum_{p'=1}^{M_1} \overline{PEP}_{ST \rightarrow SR}^{(p)} \quad (4.16)$$

$j'p' \neq jp$

and,

$$\overline{PEP}_{ST \rightarrow SR}^{(s)} = \kappa^{N_{r2}} \sum_{\ell=0}^{N_{r2}-1} \binom{N_{r2}-1+\ell}{\ell} (1-\kappa)^\ell \quad (4.17)$$

$$\text{where } \kappa = \frac{1}{2} \left(1 - \sqrt{\frac{\sigma_z^2}{1+\sigma_z^2}} \right), \sigma_z^2 = \frac{P_{s2} \sigma_g^2 (|x_s|^2 + |x_{s'}|^2)}{4\sigma_n^2}.$$

Then,

$$\overline{SEP}_{ST \rightarrow SR}^{(s)} \leq \frac{1}{M_2 N_{t2}} \sum_{k=N_{t1}+1}^{N_{t1}+N_{t2}} \sum_{s=1}^{M_2} \sum_{k'=N_{t1}+1}^{N_{t1}+N_{t2}} \sum_{s'=1}^{M_2} \overline{PEP}_{ST \rightarrow SR}^{(s)} \quad (4.18)$$

$ktst \neq ks$

By plugging (4.16) and (4.18) into (4.14) we obtain the overall upper bound for the average SEP of the ST-SR link.

Table 4.1 : System parameters for Figures (4.3) – (4.8).

Parameter	Fig. (4.3)	Fig. (4.4)	Fig. (4.5)	Fig. (4.6)	Fig. (4.7)	Fig. (4.8)
N_t	4	4	8	4	8	16
N_{t1}	2	2	4	2	4	8
N_{t2}	2	2	4	2	4	8
N_{r1}	2	2	4	2	2	2
N_{r2}	2	2	4	2	2	2
APM	BPSK	BPSK	QPSK	BPSK	QPSK	QPSK
σ_h^2	1	1	1	1	1	1
σ_g^2	1	4	4	4	4	4
σ_n^2	1	1	1	1	1	1
P_s (dB)	variable	variable	variable	20	variable	variable
P_{s1} (dB)	variable	variable	variable	αP_s	αP_s	αP_s
P_{s2} (dB)	15	10	7 & 10	$(1 - \alpha)P_s$	$(1 - \alpha)P_s$	$(1 - \alpha)P_s$
R_{PR} (bpcu)	2	2	4	2	4	5
R_{SR} (bpcu)	2	2	4	2	4	5

4.6 Results and Discussion

In this section, we evaluate the performance of the proposed protocol at the primary and secondary receivers via analytical and Monte Carlo simulations for the CR NOMA-SM protocol with and without COAS for different values of system parameters.

Figure (4.3) shows the analytical and simulation SEP performance for equal channel gains PR and SR for the CR NOMA-SM protocol with/without COAS for system parameters as shown in Table (4.1). We can see that the analytical results agree with the simulation results. Also, we can see that, to achieve average SEP of 10^{-3} at PR, by using COAS, the performance of PR is improved by around 5 dB compared to the case of without AS. On the other hand, we observe that the performance of SR does not change in both cases as expected. Also the SEP of SR appears to be constant at high SNRs of the primary symbol, since P_{s2} is fixed and SIC is almost perfect at high SNRs of the primary symbol.

In Figure (4.4), we study the performance of the protocol at PR and SR for distinctive channel strengths. We repeat the simulation with the same parameters as in Figure (4.3), except $\sigma_g^2 = 4$ and $P_{s2} = 10$ dB as shown in Table (4.1). Since the channel for SR is better than that for PR, ST assigns less power for the SR's symbol than that for the previous case of equal channel gains. Figure (4.4) shows that at $P_{s1} = 26$ dB and

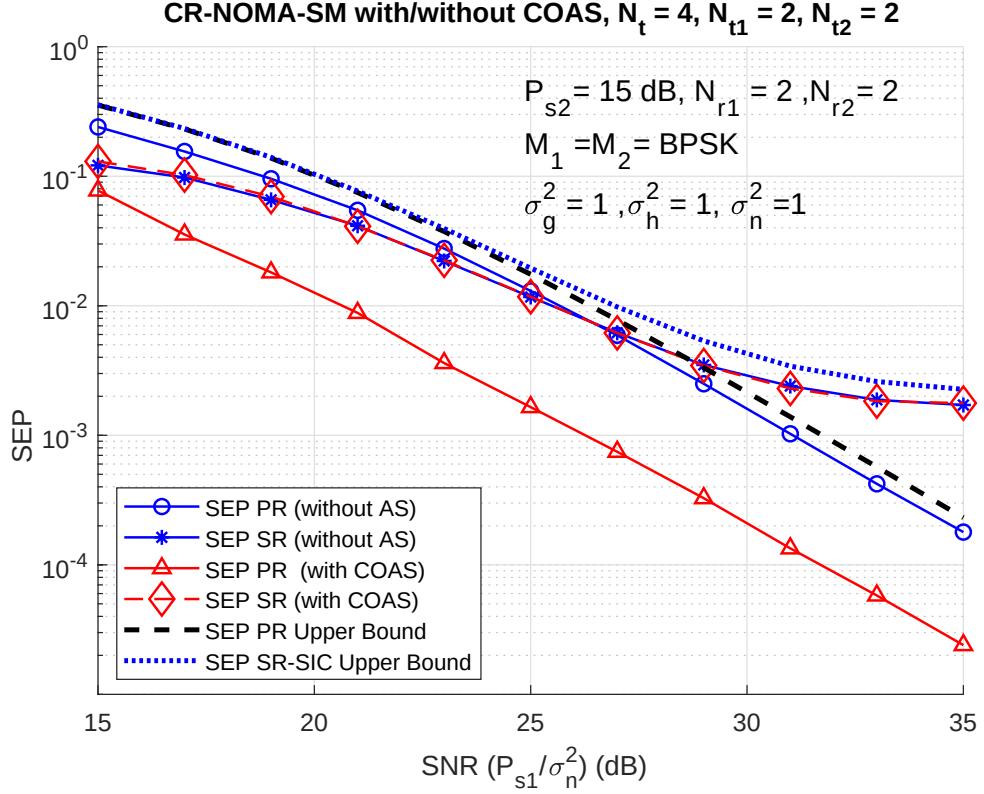


Figure 4.3 : The performance of the proposed protocol at PR and SR with equal channel variances.

$P_{s2} = 10$ dB, the SEP of PR without COAS is approximately 10^{-3} and with COAS it is approximately 2×10^{-4} , and the SEP for SR with/without COAS is approximately 2×10^{-3} . While these values were obtained in Figure (4.3), at $P_{s1} = 31$ dB and $P_{s2} = 15$ dB, i.e. by pairing the users with distinctive channel strengths such that $\sigma_g^2 = 4$ and $\sigma_h^2 = 1$, provides around 5 dB gain in the power assigned for both PR and SR symbols.

Figure (4.5) shows the performance of the proposed protocol with increased transmit antennas at ST, increased receiving antennas at PR and SR, using QPSK and at different values of P_{s2} (7 dB and 10 dB). The system parameters are as shown in Table (4.1). We can observe that the protocol performs well with increased numbers of transmit and receive antennas and using QPSK. We can observe that for PR the results with $P_{s2} = 7$ dB is better than the case with $P_{s2} = 10$ dB since less power for the SR symbol results in less interference at PR and hence the performance will be improved in both cases with and without COAS. On the other hand, for SR, we can observe that at low SNRs for the primary symbol, the results with $P_{s2} = 7$ dB is better than that with $P_{s2} = 10$ dB, since for SIC at SR the interference of the SR symbol is influential and therefore low values of P_{s2} is preferred. While at higher SNRs for the primary symbol,

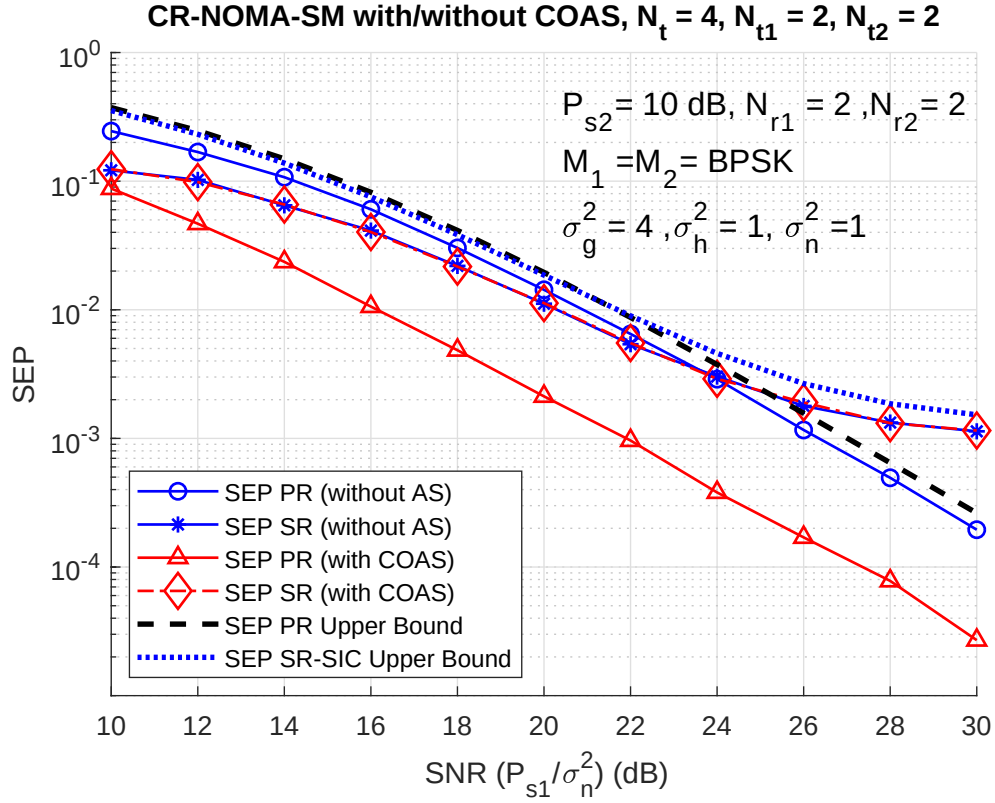


Figure 4.4 : The performance of the proposed protocol at PR and SR with distinctive channel variances.

the performance of SR at $P_{s2} = 10 \text{ dB}$ is better than at $P_{s2} = 7 \text{ dB}$ since for SIC at SR the interference of the SR symbol is somehow negligible and thus SR can decode the primary SM symbol with very low error probability and then decode its own symbol with better error performance at higher values of P_{s2} .

To study the performance of power allocation, Figure (4.6) shows the SEP for both PR and SR versus the power split factor α , where $P_{s1} = \alpha P_s$, $P_{s2} = (1 - \alpha)P_s$ and $0 \leq \alpha \leq 1$, for $P_s = 20 \text{ dB}$. Other parameters are as shown in Table (4.1). We can see that for $P_s = 20 \text{ dB}$, the best value for α is 0.95. With this value of α , we have the SEP of SR is the same with and without AS, and the SEP performance of PR enhanced from 5.5×10^{-3} (without AS) to 9×10^{-4} (with COAS). As the transmit power P_s of ST increases to 25 dB, we find that the optimum value of α also increases to 0.97. The SEP of SR is the same with and without COAS, and the SEP performance of PR enhanced from 2×10^{-3} (without AS) to 3×10^{-4} (with COAS). We can also observe that most of the transmit power is assigned to the primary symbol while less power is assigned to the secondary symbol since the channel of SR is better than that of PR.

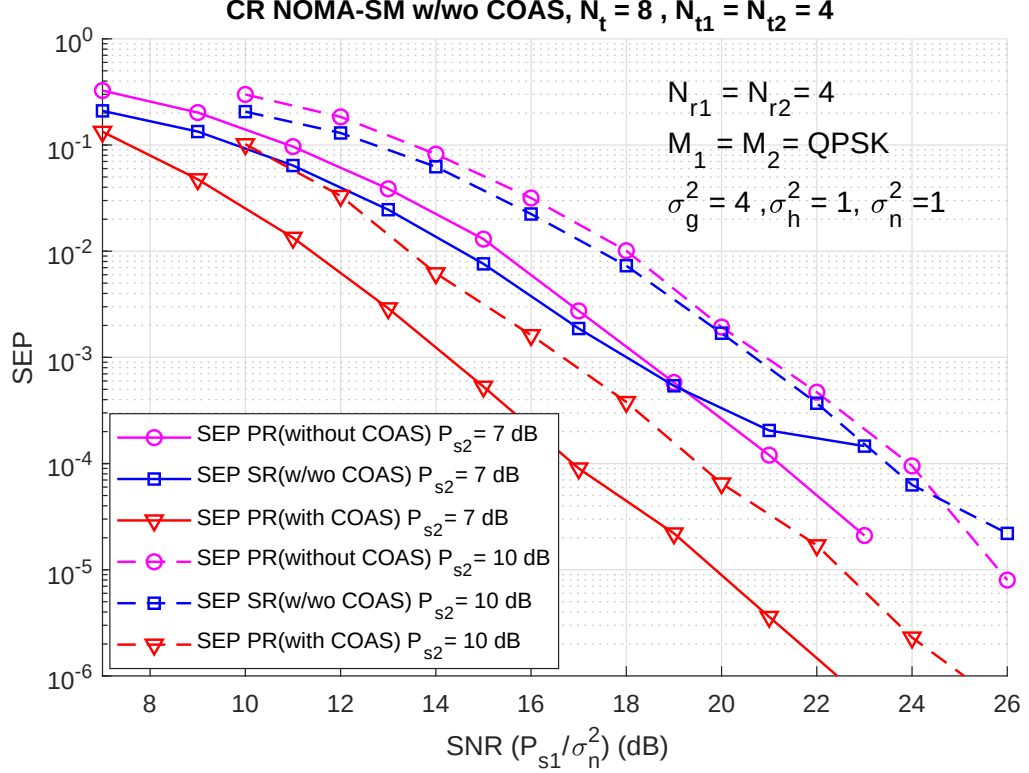


Figure 4.5 : The performance of the proposed protocol at PR and SR with increased transmit antennas at ST and increased receiving antennas at PR and SR, using QPSK and different transmit powers for the secondary SM symbol.

Also, as P_s increases α_{opt} increases and at the same time P_{s2} increases which results in enhanced SEP performance for PR and SR .

Figures (4.7) and (4.8) show the SEP of PR and SR versus P_s , considering fairness between PR and SR by assuming the same receiving SNR of PR and SR after SIC, i.e., $\frac{P_{s1}\sigma_h^2}{P_{s2}\sigma_h^2 + \sigma_n^2} = \frac{P_{s2}\sigma_g^2}{\sigma_n^2}$. By setting $P_{s1} = P_s - P_{s2}$, and solving for P_{s2} we obtain:

$$P_{s2} = \frac{-(\sigma_h^2 + \sigma_g^2)\sigma_n^2}{2\sigma_h^2\sigma_g^2} + \sqrt{\left(\frac{(\sigma_h^2 + \sigma_g^2)\sigma_n^2}{2\sigma_h^2\sigma_g^2}\right)^2 + \frac{P_s\sigma_n^2}{\sigma_g^2}} \quad (4.19)$$

Figures (4.7) and (4.8) show the performance of the proposed protocol for rates 4 and 5 *bpcu* for both PR and SR at $N_t = 8$ and 16, respectively. Other parameters are as shown in Table (4.1). We first observe that the upper bounds apply to QPSK and provides tight bounds. We also observe that with this power allocation scheme, the performance enhances for both PR and SR as P_s increases. Also, the application of COAS results in improving the performance of PR by around 9 dB gain in P_s at SEP of 10^{-3} in both figures without affecting the performance of SR which makes our proposed protocol provides improvements compared to protocols recently proposed.

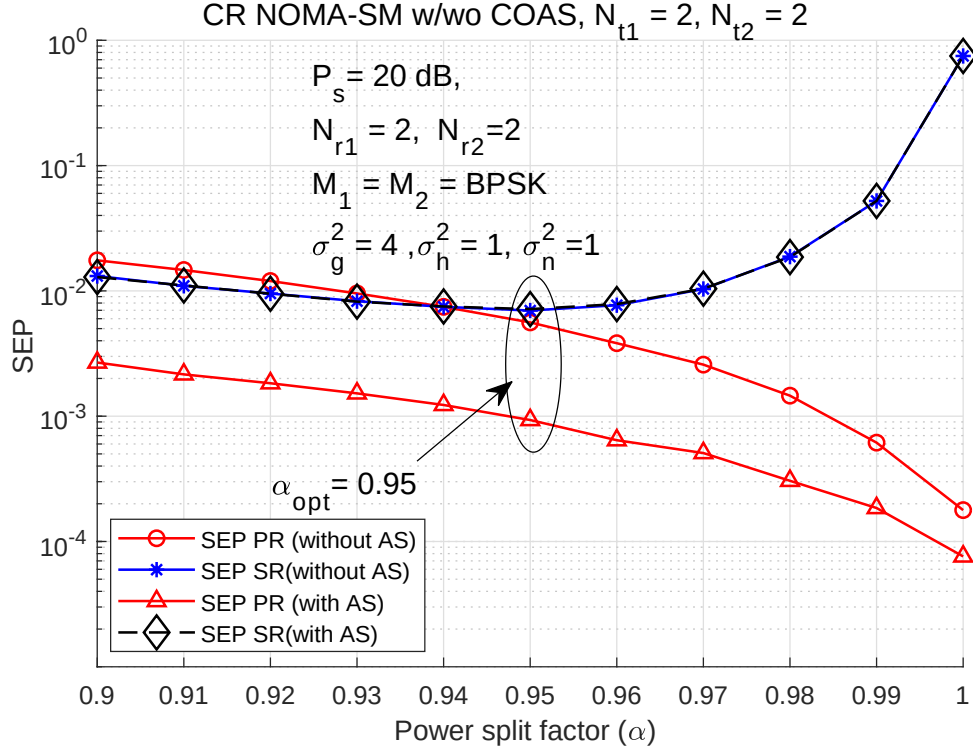


Figure 4.6 : The SEP for PR and SR vs. the power split factor α for $P_s = 20$ dB.

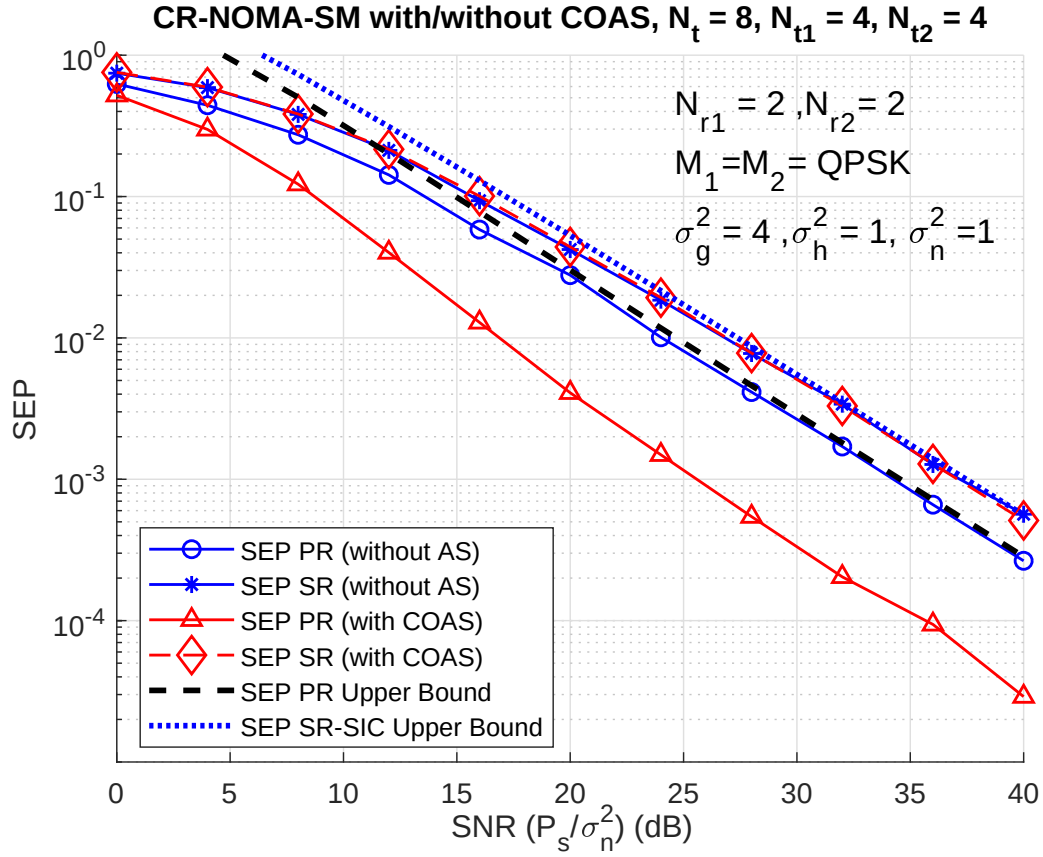


Figure 4.7 : The SEP for PR and SR vs. P_s for 4 bpcu rates for both users.

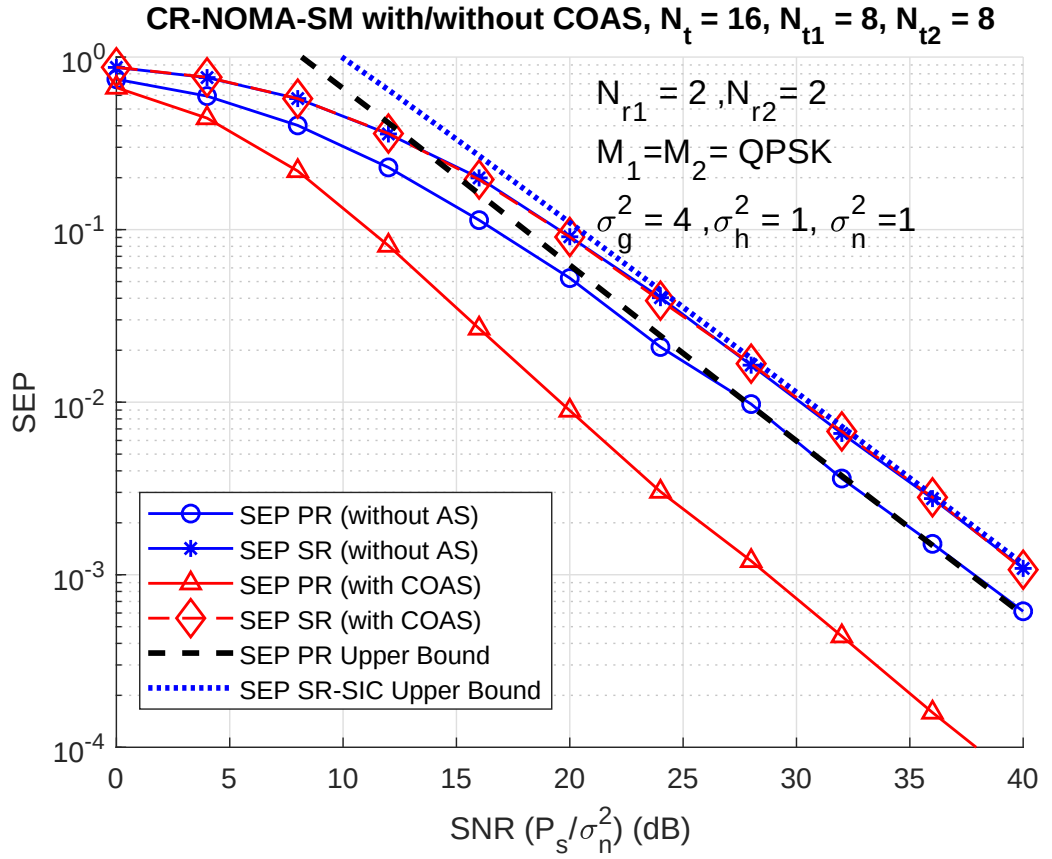


Figure 4.8 : The SEP for PR and SR vs. P_s for 5 bpcu rates for both users.

4.7 Summary

In this chapter, a novel spectrum sharing protocol that uses NOMA, SM and COAS for the overlay cognitive radio network is proposed. The proposed protocol allows ST to transmit simultaneously to both PR and SR using SM, utilizing both the APM technique and the indices of the active antennas of the secondary transmitter. The use of NOMA and SM increases the spectral efficiency of the network. The application of COAS improves further the QoS of PR without affecting the performance of SR, that results in improving the energy efficiency of the system. Upper bounds on the average symbol error probabilities at PR and SR have been derived. Analytical and simulation results show that the proposed protocol offers efficient spectrum utilization and therefore higher system capacity over the spectrum sharing protocols that use SM to convey the primary data through the APM technique to PR and the secondary data through the indices of the active antennas to SR. Also the proposed protocol offers

higher performance than NOMA-SM protocol without AS by utilizing COAS at ST in accordance with PR.



5. NOMA-SM IN OVERLAY COGNITIVE RADIO NETWORKS USING EUCLIDEAN DISTANCE OPTIMIZED ANTENNA SELECTION

This chapter builds upon the results of chapter 4 and explores introducing Euclidean distance optimized antenna selection (EDAS) to NOMA-SM in overlay CR networks. The introduction of EDAS to NOMA-SM, in accordance with PR, results in a significant improvement in the performance of PR without deteriorating the performance of SR. The performance of the proposed protocol is analyzed through a derivation of an upper bound of the symbol error probability (SEP) of PR for the case of selecting two transmit antennas out of the transmit antennas of ST and using BPSK for both PR and SR.

5.1 Related Work

To improve the transmission performance of SM, transmit antenna selection (TAS) has been investigated in SM systems as a means of providing transmit diversity gains. In [64], the authors proposed two TAS schemes for SM systems: Capacity Optimized AS (COAS) that selects the subset that maximizes the capacity of the SM system, and Euclidean distance optimized AS (EDAS) that selects the subset that maximizes the minimum squared Euclidean distance (SqED) in the SM constellation. In [65], the authors showed that EDAS outperforms COAS with increased complexity. The complexity of EDAS comprises of two components: computational and search complexities [67]. The computational complexity is due to the computations of the Euclidean distances between SM-symbols in the SM constellation, and the search complexity is due to the comparisons between the different enumerations of the possible transmit antenna subsets to select the subset that maximizes the minimum SqED.

Several research work have been devoted to reduce the computational complexity of EDAS [64–66]. In [64], the authors proposed a low complexity EDAS (LC-EDAS) that uses QR factorization. In [65], the authors utilized the modulus symmetry of the QAM

constellation to reduce the complexity of EDAS. In [66], by exploiting the rotational symmetry of the QAM constellation, the complexity of EDAS is shown to be further reduced.

On the other hand, Recent studies have considered reducing the search complexity of EDAS as in [67–69]. The authors in [67, 68] proposed sub-optimal algorithms that reduces the search complexity, while approaching the optimal performance of the exhaustive search for EDAS. While in [69], The authors proposed a tree search based antenna selection (TSAS) algorithm that iteratively splits the Euclidean distance matrix into a set of sub-matrices with smaller dimensions. TSAS algorithm is optimal, but with an exponentially increasing complexity.

The combination of TAS schemes and space shift keying (SSK) has been considered in [77]. The authors proposed a cooperative SSK scheme that applies an EDAS-based TAS scheme at the source. The authors proposed the selection between disjoint subsets in the expense of the error performance. A closed form expression for the symbol error rate (SER) of the proposed SSK system for the case of selection of two transmit antennas was derived.

Building upon the results of chapter 4 and motivated by the advantages of EDAS, in this chapter, we study the combination of EDAS with NOMA-SM in overlay CR networks. Joining NOMA and SM altogether increases the system capacity and the data rates of the users by exploiting the power and spatial domains. Employing EDAS with NOMA-SM at ST in accordance with PR will enhance the performance of PR; since it selects the antenna subset that maximizes the minimum SqED for the SM constellation resulting in decreasing the SEP of PR significantly. In addition, the performance of SR will not be affected since the re-ordering of the antennas at ST remains random with respect to SR. The performance of the proposed protocol is analyzed by derivation of an upper bound for the SEP of PR for the case of using BPSK for both PR and SR and selection of two transmit antennas out of the transmit antennas at ST. Also, we compare the performance of the proposed protocol with that of COAS and with that of without-AS through Monte Carlo simulations.

5.2 System Model

In this chapter we consider the system model presented in chapter 4 (see Figures (4.1) and (4.2)), in which an overlay CR network consists of a PT with N_p transmit antennas, a PR with N_{r1} receive antennas, an ST with N_t transmit antennas and N_r receive antennas, and an SR with N_{r2} receive antennas. ST is assumed to perform user pairing by selecting the SR with the highest channel gain with respect to the channel gain of the intended PR. ST uses decode and forward algorithm to cooperatively relay the message of PT to PR and at the same time transmitting its own message to SR. It is assumed that no direct link exists between PT and PR. Independent Rayleigh fading is assumed for all transmitter–receiver pairs. The channel matrices for the PT-ST, ST-PR, and ST-SR links are $\mathbf{B}$, $\mathbf{H}$ and $\mathbf{G}$ with entries $b_{ij} \sim \mathcal{CN}(0, 1)$, $h_{ij} \sim \mathcal{CN}(0, \sigma_h^2)$, $g_{ij} \sim \mathcal{CN}(0, \sigma_g^2)$, respectively. The noise at any node is modeled as $\mathcal{CN}(0, \sigma_n^2)$. The transmit powers of PT and ST are P_p and P_s , respectively. Perfect channel state information (CSI) is assumed to be known by all receivers.

5.3 CR-NOMA-SM with EDAS

In this section, we propose the combination of EDAS and NOMA-SM in overlay CR networks. The proposed protocol lets PR to use EDAS to find the optimum N_{t1} transmit antennas out of the N_t transmit antennas at ST that maximizes the minimum SqED in the SM constellation, and then feeds back these information to ST through the use of feedback control channels. After obtaining the optimum N_{t1} transmit antennas, the proposed protocol with EDAS uses NOMA-SM as described in the CR-NOMA-SM without-AS mode in chapter-4 section-(4.4).

We consider the closed loop SM link (ST-PR) that has N_t transmit antennas and N_{r1} receive antennas and uses M_1 -QAM signal constellation. As we have shown in chapter-2 section-(2.4), to select N_{t1} antennas out of N_t antennas, EDAS selects the I^{th} subset (S_I) that maximizes the minimum-SqED among all possible $N_s = \binom{N_t}{N_{t1}}$ subsets. Therefore the EDAS design metric is:

$$I_{ED} = \max_{\substack{S_I \\ I \in N_s}} \left\{ \min_{\substack{p, p' \in M_1 \\ i, j \in S_I}} \|\mathbf{h}_i x_p - \mathbf{h}_j x_{p'}\|^2 \right\} \quad (5.1)$$

where $\mathbf{h}_i$ and $\mathbf{h}_j$ are the i^{th} and j^{th} columns of $\mathbf{H}_I$ (the channel matrix between the N_{t1} antennas in S_I and the N_{r1} receiving antennas of PR). x_p and $x_{p'}$ ($1 \leq p, p' \leq M_1$) are symbols from the M_1 -QAM constellation set used for PR.

However, the complexity of the exhaustive search of (5.1) is very high, it can be reduced greatly by using low complexity algorithms as we mentioned in chapter-2 section (2.4.2), like merging QLC-EDAS (to reduce the computational complexity) and TSAS (to reduce the search complexity).

5.4 Performance Analysis

In this section, the performance of the proposed protocol CR-NOMA-SM with EDAS is investigated by deriving an upper bound for the average SEP of the ST-PR link. To simplify the analysis, we consider the case of BPSK and $N_{t1} = 2$, i.e., the selection of two transmit antennas out of the N_t transmit antennas at ST.

By recalling equation (4.11) in chapter-4, the instantaneous pairwise error probability at PR ($PEP_{PR}^{(i)}$) is given by:

$$\begin{aligned} PEP_{PR}^{(i)} &= Q \left(\sqrt{\frac{P_{s1} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}} \right) \\ &= Q(\sqrt{\gamma}) \end{aligned} \quad (5.2)$$

where $\gamma = \frac{P_{s1} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)} = \frac{P_{s1} \sum_{i=1}^{N_r} |h_{ij} x_p - h_{ij'} x_{p'}|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$, for the case when x_p is drawn from BPSK constellation, γ reduces to $\sum_{\ell=1}^{2N_{r1}} v_\ell^2$, where v_ℓ is a zero mean Gaussian random variable with variance $\sigma_v^2 = \frac{P_{s1} \sigma_h^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$. Therefore γ is a chi-square random variable with $2N_{r1}$ degrees of freedom.

When applying EDAS to the CR-NOMA-SM protocol, we select the subset with the maximum minimum-SqED (d_{minMax}^2) that satisfies (5.1), which is defined as:

$$d_{minMax}^2 = \max_{\substack{S_I \\ I \in N_s}} \left\{ \min_{\substack{p, p' \in M_1 \\ j, j' \in S_I}} \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2 \right\} \quad (5.3)$$

Since the Q -Function is a decreasing function, therefore when using EDAS, $(PEP_{PR}^{(i)})$ can be upper bounded by substituting $\|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2$ in (5.2) with d_{minMax}^2 (since $\forall \{j, j', p, p'\}: (d_{minMax}^2) \leq \|\mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'}\|^2$ in the selected subset). Therefore

$(PEP_{PR}^{(i)})$ given by (5.2) can be rewritten as:

$$PEP_{PR}^{(i)} \leq Q \left(\sqrt{\frac{P_{s1} d_{minMax}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}} \right) \quad (5.4)$$

We define:

$$PEP_{PR}^{(i)EDAS} = Q \left(\sqrt{\frac{P_{s1} d_{minMax}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}} \right) = Q(\sqrt{\gamma_{Max}}) \quad (5.5)$$

as the instantaneous PEP at PR after using EDAS and $\gamma_{Max} = \frac{P_{s1} d_{minMax}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$.

Therefore the upper bound of the instantaneous SEP at PR after using EDAS can be rewritten as:

$$\begin{aligned} SEP_{PR}^{(i)} &\leq \frac{1}{M_1 N_{t1}} \sum_{j=1}^{N_{t1}} \sum_{p=1}^{M_1} \sum_{j'=1}^{N_{t1}} \sum_{p'=1}^{M_1} PEP_{PR}^{(i)EDAS} \\ &\quad j'p' \neq jp \\ &= (M_1 N_{t1} - 1) PEP_{PR}^{(i)EDAS} \end{aligned} \quad (5.6)$$

By averaging (5.6) we obtain the upper bound of the average SEP of the ST-PR link using CR-NOMA-SM with EDAS protocol as:

$$\overline{SEP}_{PR} \leq (M_1 N_{t1} - 1) \overline{PEP}_{PR}^{EDAS} \quad (5.7)$$

where $\overline{PEP}_{PR}^{EDAS}$ is the average PEP at PR using EDAS.

To find the expression of $\overline{PEP}_{PR}^{EDAS}$, we average $PEP_{PR}^{(i)EDAS}$ over the PDF of the random variable γ_{Max} . The PDF of the random variable γ_{Max} ($f_{\gamma_{Max}}(\tau)$) can be obtained using order statistics [78] (see Appendix C. for proof) as:

$$\begin{aligned} f_{\gamma_{Max}}(\tau) &= \frac{2N_s}{\Gamma(N_{r1})} \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \\ &\quad \times \sum_{i_1=0}^{N_{r1}-1} \dots \sum_{i_{2z+1}=0}^{N_{r1}-1} \frac{\tau^{\xi-1} e^{-\frac{\tau(2z+2)}{2\sigma_v^2}}}{(\prod_{t=1}^{2z+1} i_t!) (2\sigma_v^2)^\xi} \end{aligned} \quad (5.8)$$

where $\xi = (\sum_{t=1}^{2z+1} i_t) + N_{r1}$, $\sigma_v^2 = \frac{P_{s1} \sigma_h^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$, and $\Gamma(a)$ is the Gamma function defined by $\Gamma(a) = \int_0^\infty x^{a-1} e^{-x} dx$.

Then $\overline{PEP}_{PR}^{EDAS}$ can be obtained as follows:

$$\begin{aligned} \overline{PEP}_{PR}^{EDAS} &= \int_0^\infty PEP_{PR}^{(i)EDAS} f_{\gamma_{Max}}(\tau) d\tau \\ &= \int_0^\infty Q(\sqrt{\tau}) f_{\gamma_{Max}}(\tau) d\tau \end{aligned} \quad (5.9)$$

By substituting (5.8) into (5.9), we obtain

$$\begin{aligned} \overline{PEP}_{PR}^{EDAS} &= \frac{2N_s}{\Gamma(N_{r1})} \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \\ &\quad \times \sum_{i_1=0}^{N_{r1}-1} \dots \sum_{i_{2z+1}=0}^{N_{r1}-1} \frac{\int_0^\infty Q(\sqrt{\tau}) \tau^{\xi-1} e^{-\frac{\tau(2z+2)}{2\sigma_v^2}} d\tau}{(\prod_{t=1}^{2z+1} i_t!) (2\sigma_v^2)^\xi} \end{aligned} \quad (5.10)$$

By using ([79], eq. (3.63)), we have

$$\begin{aligned} \int_0^\infty Q\left(\frac{x}{\delta}\right) x^{2\xi-1} e^{-\frac{x^2}{2}} dx &= \frac{(\xi-1)!}{2} \left(1 - (\delta^2 + 1)^{-0.5}\right)^\xi \\ &\quad \times \sum_{m=0}^{\xi-1} (2)^{-m} \binom{\xi-1+m}{m} (1 + (\delta^2 + 1)^{-0.5})^m \end{aligned} \quad (5.11)$$

By doing transformation for the variables in the integral part in (5.10): let $\tau = \frac{x^2}{\delta^2}$, $d\tau = 2 \frac{x}{\delta^2} dx$, and $\frac{2(z+1)}{\sigma_v^2} = \delta^2$, and using (5.11), we obtain

$$\begin{aligned} \int_0^\infty Q(\sqrt{\tau}) \tau^{\xi-1} e^{-\frac{\tau(2z+2)}{2\sigma_v^2}} d\tau &= \frac{2}{\delta^{2\xi}} \int_0^\infty Q\left(\frac{x}{\delta}\right) x^{2\xi-1} e^{-\frac{x^2}{2}} dx \\ &= \frac{(\xi-1)!}{\delta^{2\xi}} \left(1 - (\delta^2 + 1)^{-0.5}\right)^\xi \\ &\quad \times \sum_{m=0}^{\xi-1} (2)^{-m} \binom{\xi-1+m}{m} (1 + (\delta^2 + 1)^{-0.5})^m \end{aligned} \quad (5.12)$$

By substituting (5.12) into (5.10) we obtain the expression of $\overline{PEP}_{PR}^{EDAS}$ as:

$$\begin{aligned} \overline{PEP}_{PR}^{EDAS} &= \frac{2N_s}{\Gamma(N_{r1})} \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \\ &\quad \times \sum_{i_1=0}^{N_{r1}-1} \dots \sum_{i_{2z+1}=0}^{N_{r1}-1} \frac{(\xi-1)!}{\prod_{t=1}^{2z+1} i_t!} \left[\frac{1 - (\delta^2 + 1)^{-0.5}}{4(z+1)} \right]^\xi \\ &\quad \times \sum_{m=0}^{\xi-1} (2)^{-m} \binom{\xi-1+m}{m} (1 + (\delta^2 + 1)^{-0.5})^m \end{aligned} \quad (5.13)$$

By substituting (5.13) into (5.6) we obtain the union bound for the average SEP of the ST-PR link using the CR-NOMA-SM protocol with EDAS.

For the case when the receiving antennas at PR is 2, i.e., $N_{r1} = 2$, (5.13) can be reduced to:

$$\begin{aligned} \overline{PEP}_{PR}^{EDAS} &= \frac{2N_s}{\Gamma(N_{r1})} \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \\ &\quad \times \sum_{T=0}^{2z+1} \binom{z+1}{T} (\xi-1)! \left[\frac{1 - (\delta^2 + 1)^{-0.5}}{4(z+1)} \right]^\xi \\ &\quad \times \sum_{m=0}^{\xi-1} (2)^{-m} \binom{\xi-1+m}{m} (1 + (\delta^2 + 1)^{-0.5})^m \end{aligned} \quad (5.14)$$

where $T = (\sum_{t=1}^{2z+1} i_t)$, and we use the fact that: $\prod_{t=1}^{2z+1} i_t! = 1 \forall i_t = \{0, 1\}$, and $\sum_{i_1=0}^{N_{r1}-1} \dots \sum_{i_{2z+1}=0}^{N_{r1}-1} f(T) = \sum_{T=0}^{2z+1} \binom{z+1}{T} f(T)$.

5.5 Results and Discussion

In this section, we evaluate the performances for the CR-NOMA-SM protocol with and without EDAS at PR and SR analytically and via Monte Carlo simulations. All simulations for EDAS are carried out using QLC-EDAS (which is optimal with low complexity). The power allocation used in the simulations considers fairness between PR and SR by assuming the same receiving SNR of PR and SR after SIC, i.e., $\frac{P_{s1}\sigma_h^2}{P_{s2}\sigma_h^2 + \sigma_n^2} = \frac{P_{s2}\sigma_g^2}{\sigma_n^2}$. By setting $P_{s1} = P_s - P_{s2}$, and solving for P_{s2} we get:

$$P_{s2} = \frac{-(\sigma_h^2 + \sigma_g^2)\sigma_n^2}{2\sigma_h^2\sigma_g^2} + \sqrt{\left(\frac{(\sigma_h^2 + \sigma_g^2)\sigma_n^2}{2\sigma_h^2\sigma_g^2}\right)^2 + \frac{P_s\sigma_n^2}{\sigma_g^2}}.$$

5.5.1 Effect of user pairing

Figure (5.1) shows the effect of user pairing on the SEP performance of the proposed protocol for channel gain differences (0, 6 and 10 dB). Other system parameters are shown in Table (5.1). We can observe that as the difference in SR and PR channel gains increases the SEP for PR and SR improves both with and without EDAS. We can also observe that the analytical results of the upper bound for the SEP at PR using CR-NOMA-SM with EDAS are in agreement with the simulations results.

We also observe that the SEP performance of SR does not change with EDAS than the case without-AS. Therefore, in this figure and the following figures, we plot only one curve for the SEP of SR (with/without AS), since all curves for the proposed protocol with and without-AS coincide with each others.

Table 5.1 : System parameters for Figures (5.1) – (5.4).

Parameter	Fig. (5.1)	Fig. (5.2)	Fig. (5.3)	Fig. (5.4)
N_t	4	{4, 6, 8}	8	8
N_{t1}	2	2	4	4
N_{t2}	2	2	4	4
N_{r1}	2	2	2	4
N_{r2}	2	2	2	4
APM	BPSK	BPSK	16-QAM	64-QAM
σ_h^2	1	1	1	1
σ_g^2	{1, 4, 10}	4	4	4
σ_n^2	1	1	1	1
P_s (dB)	variable	variable	variable	variable
P_{s1} (dB)	αP_s	αP_s	αP_s	αP_s
P_{s2} (dB)	$(1 - \alpha)P_s$	$(1 - \alpha)P_s$	$(1 - \alpha)P_s$	$(1 - \alpha)P_s$
R_{PR} (bpcu)	2	2	6	8
R_{SR} (bpcu)	2	2	6	8

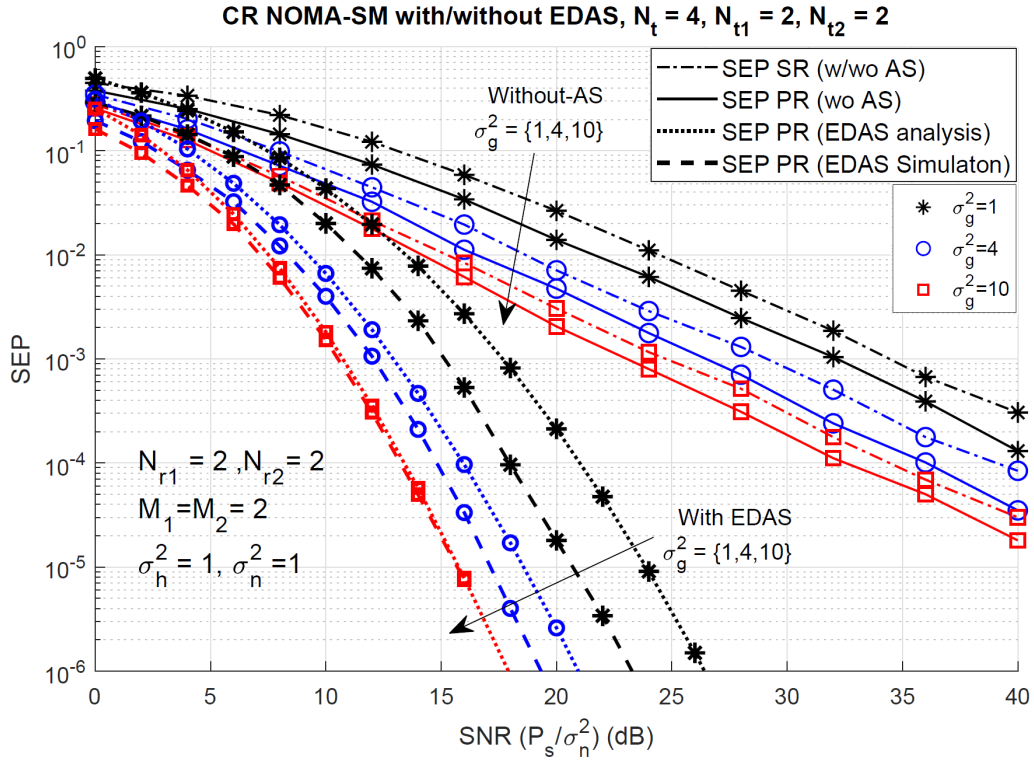


Figure 5.1 : Effect of user pairing for channel gain differences 0, 6 and 10 dB using CR-NOMA-SM with and without EDAS at $N_t = 4, N_{t1} = 2$, and using BPSK for both users.

5.5.2 Effect of fixing N_{t1} with increasing N_t

Figure (5.2) shows the SEP performance of the proposed protocol for both PR and SR, at $N_t \in \{4, 6, 8\}$, while fixing $N_{t1} = 2$, for the case of channel gain difference is 6 dB ($\sigma_g^2 = 4$ and $\sigma_h^2 = 1$). Other parameters are shown in Table (5.1). The Figure shows that the analytical and simulation results of the SEP at PR using CR-NOMA-SM with EDAS are in agreement with each other. Figure (5.2) also shows that introducing EDAS to the CR-NOMA-SM protocol improved the performance of PR with increasing diversity. For example, to achieve a SEP of 10^{-4} for PR, CR-NOMA-SM with EDAS provides $\{21, 23.5$ and 25 dB $\}$ gain in P_s over the protocol without-AS for $N_t \in \{4, 6, 8\}$, respectively. We can also observe that as N_t increases (with N_{t1} fixed) the performance of PR using the CR-NOMA-SM with EDAS protocol improves further, i.e. the proposed protocol preserves the transmit diversity gain of EDAS.

Figure (5.2) also shows the SEP performance of PR for the CR-NOMA-SM with COAS where we can observe that as N_t increases (with N_{t1} fixed) the performance of the CR-NOMA-SM with COAS is almost the same. This indicates that increasing N_t with fixed N_{t1} does not affect the performance of COAS (i.e. does not provide transmit diversity gain), and this is reasonable – where COAS selects the N_{t1} antennas with the largest channel gains – since for a given channel distribution, selecting 2 maximums out of 4 or 6 or 8 from the same distribution on the long run will be the same on average, as shown in Figure (5.2). Furthermore, one can notice that EDAS provides much more diversity compared to COAS considering the slopes of the corresponding curves. By comparing the performance of the proposed protocol using EDAS and COAS we can see that CR-NOMA-SM with EDAS outperforms that with COAS, for example, to achieve a SEP of 10^{-4} for PR, CR-NOMA-SM with EDAS provides $\{13, 15.5$ and 18 dB $\}$ gain in P_s over that with COAS for $N_t \in \{4, 6, 8\}$, respectively.

5.5.3 Effect of using higher order modulation

Figure (5.3) and (5.4) show the SEP performance of the proposed protocol for rates 6 and 8 bpcu for both PR and SR, using 16-QAM and 64-QAM for both users, respectively, at $N_t = 8$ and $N_{t1} = N_{t2} = 4$. Other parameters are shown in Table (5.1). From both Figures, we observe that CR-NOMA-SM with COAS performs better

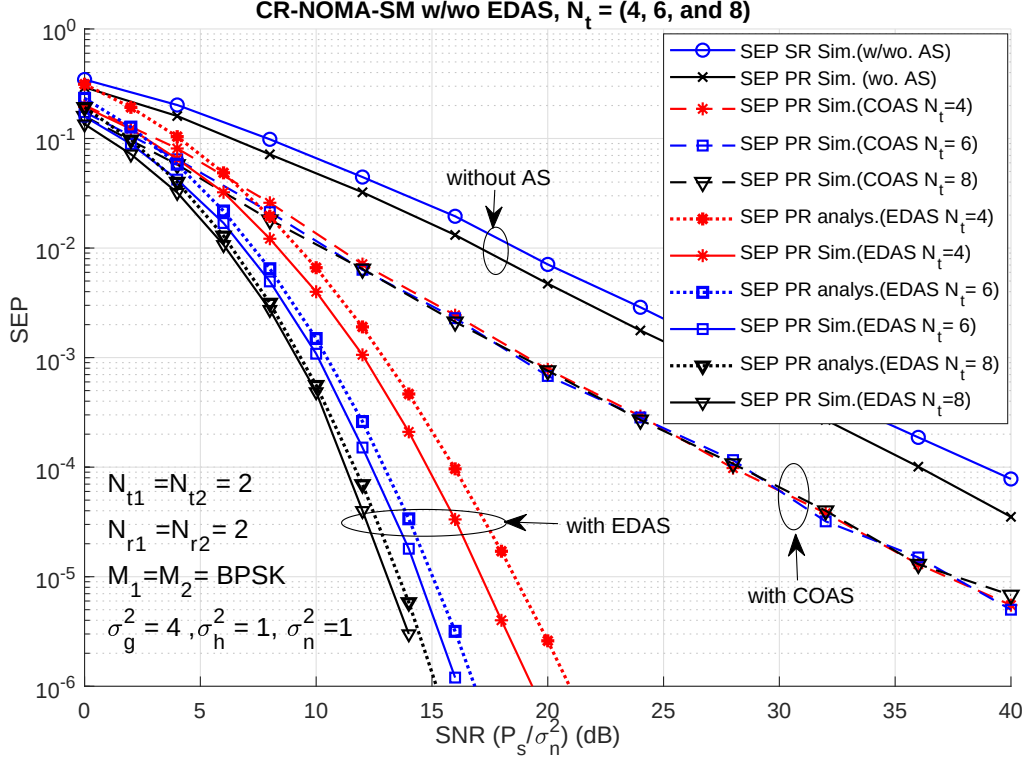


Figure 5.2 : The SEP for PR and SR versus P_s using CR-NOMA-SM with and without EDAS, $N_t \in \{4, 6, 8\}$, with fixed $N_{t1} = 2$, and using BPSK for both users.

than that with EDAS until a certain SNR value, which we refer as the crossing point. Beyond the crossing point, the performance of EDAS outperforms that with COAS with higher diversity. It can be observed that as the data rate increases the crossing point value increases. In Figure (5.3) the crossing point appears at SNR of 24 dB while in Figure (5.4) occurs at SNR of 38 dB.

5.6 Summary

In this chapter, we proposed a spectrum sharing protocol that combines NOMA, SM and EDAS for overlay CR networks. The use of NOMA and SM in CR increases the spectral efficiency of the network while preserving the desirable properties of SM, allowing higher numbers of users to be multiplexed simultaneously on the same frequency band, with higher levels of data rates. Introducing EDAS to CR-NOMA-SM has been shown to improve the performance of the protocol for PR significantly without deteriorating the performance of SR. This may results in greater savings in the transmit power which improves the system energy efficiency. It has also been shown that the performance of the protocol with EDAS outperforms that with

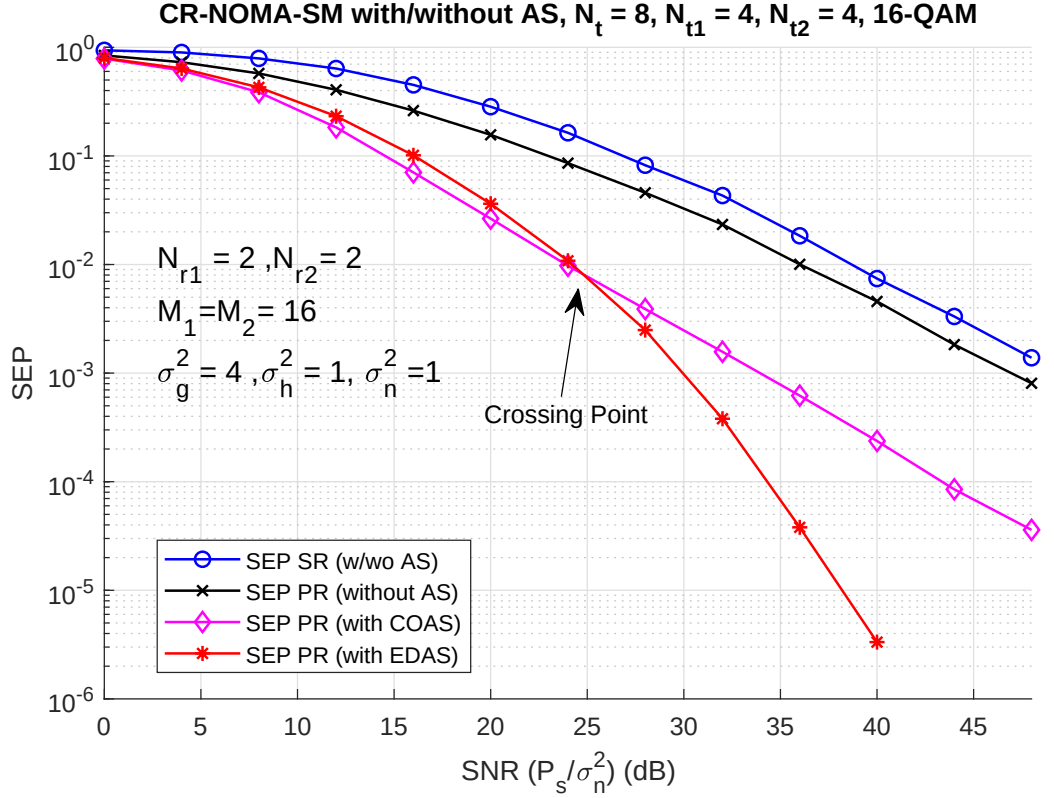


Figure 5.3 : The SEP performance of PR and SR for data rate 6 bpcu using CR-NOMA-SM with and without EDAS at $N_t = 8, N_{r1} = N_{r2} = 4$, $N_{r1} = N_{r2} = 2$, and 16-QAM for both users.

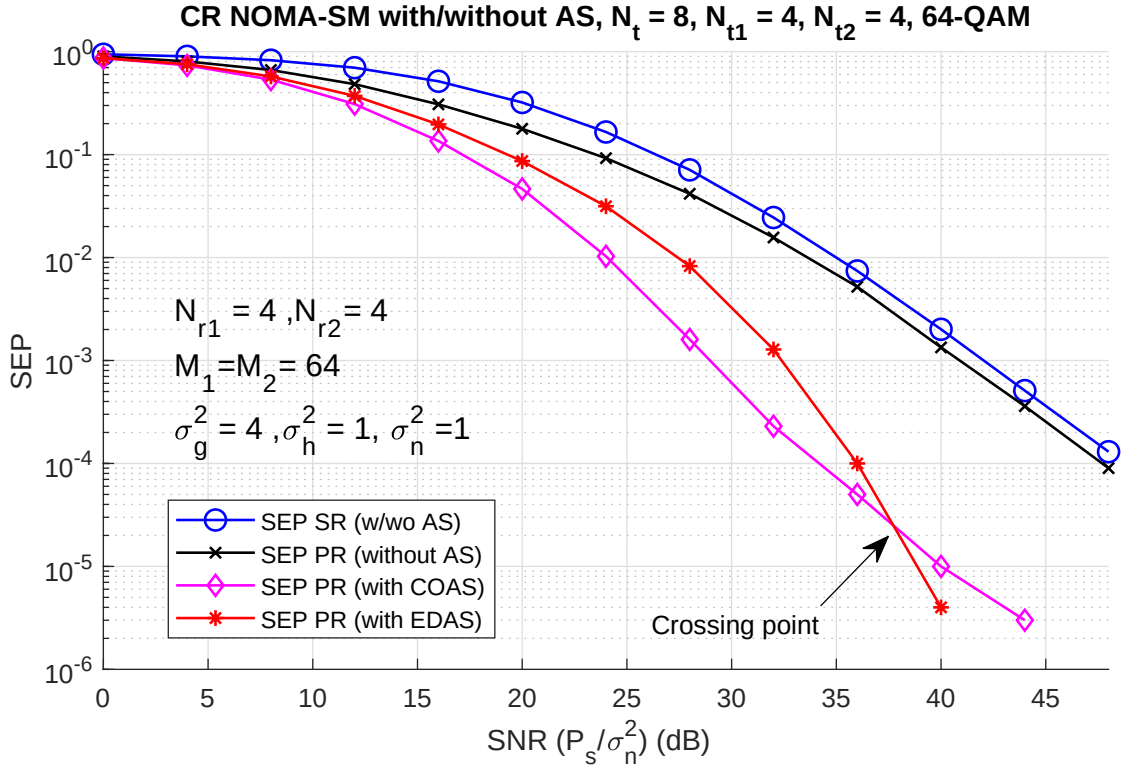


Figure 5.4 : The SEP performance of PR and SR for data rate 8 bpcu using CR-NOMA-SM with and without EDAS at $N_t = 8, N_{r1} = N_{r2} = 4$, $N_{r1} = N_{r2} = 4$, and 64-QAM for both users.

COAS with a trade-off of increased complexity which can be reduced by applying low-complexity algorithms. The system performance is validated by deriving an upper bound expression for the SEP at PR, for the case of selecting two antennas out of the transmit antennas at ST and using BPSK for PR and SR.



6. CONCLUSIONS AND RECOMMENDATIONS

6.1 General Conclusion

To contribute in resolving the problem of the inefficient use of the scarce radio spectrum and increasing the system throughput, in this thesis, we have proposed novel and effective spectrum sharing protocols for the overlay cognitive radio networks using NOMA, SM and transmit antenna selection.

First, in chapter 3, we proposed a two-way two-phase spectrum sharing protocol for overlay cognitive radio networks using NOMA and physical layer network coding. We considered the case of single antenna primary and secondary users, where one of the secondary users acting as a relay to cooperatively assist the transmission between the PUs. By utilizing the difference in channel gains of PUs-Relay and the SU-relay links, two-way transmission between the PUs through the cooperation with the relay and at the same time two-way transmission between the relay and the other SU is achieved in two phases, without degrading the PUs' performance. We assumed that the channel between the relay and the other SU is better than that between the relay and the PUs, where the relay can be considered as a secondary base station that services multiple SUs and selects the SU with the highest channel gain with respect to the PUs links. In the first phase, the PUs and the other SU are allowed to transmit simultaneously. The relay uses SIC to decode first the message of the SU (since it is expected to be strong than the PUs' messages) and then subtracts it from the received signal. Then from the resulted signal, the relay jointly decodes the PUs messages. In the second phase, the relay uses superposition coding to generate a new message composed of the XORed messages of the PUs and a new message for the SU. At the SU SIC is performed to decode first the XORed primary message and then canceling it to decode its intended message. While at each PU, the XORed primary message is decoded directly considering the SU's message as interference. From the detected primary XORed message, each PU can detect its intended message using the XOR operation

with his original transmitted message to the other PU. The performance of the protocol is analyzed by deriving the outage probabilities of the PUs and SUs. Analytical and simulation results show that the proposed protocol offers efficient spectrum utilization and therefore improved system capacity over the three-phase and two-phase spectrum sharing protocols with one-way SUs transmission in the literature.

Second, since NOMA is well matched to the overlay CR paradigm, in chapter 4, we investigated the combination of SM and NOMA in overlay CR networks for multiple antennas primary and secondary users. The proposed protocol allows a secondary transmitter (ST) to cooperatively relay the message of a primary transmitter (PT) to a primary receiver (PR) and at the same time transmits its own message to a secondary receiver (SR). The use of NOMA and SM is shown to increase the spectral efficiency of the primary and secondary receivers. Upper bounds on the average symbol error probabilities at the primary and secondary receivers have been derived. We further investigated the application of COAS to NOMA-SM and it was shown that the performance of the primary receiver is further improved without affecting the performance of the secondary receiver. Analytical and simulation results show that the proposed protocol offers higher spectral efficiency and higher system capacity over other spectrum sharing protocols that use SM to convey the primary data through the APM technique to the primary receiver and the secondary data to the secondary receiver through the indices of the active antennas. Also the proposed protocol with AS offered higher performance over than NOMA-SM protocol without-AS by utilizing a low complexity antenna selection scheme like COAS at the secondary transmitter in accordance with the primary receiver.

Third, we built upon the results of chapter 4, and studied the introduction of EDAS to NOMA-SM in overlay CR networks. The application of EDAS at ST in accordance with PR results in decreasing the SEP of PR significantly, since it selects the antenna subset that maximizes the minimum squared Euclidean distance for the SM constellation at PR. We derived an upper bound for the SEP of PR, for the case of using BPSK for both PR and SR and selection of two transmit antennas from the transmit antennas at ST. It has been shown that NOMA-SM with EDAS in overlay CR networks provides much more transmit diversity compared to that with COAS.

To conclude, the usage of NOMA and SM in overlay cognitive radio networks allows multiple users to be multiplexed on the same radio resources while preserving the desirable properties of SM, which results in boosting the system spectral efficiency, system capacity and data rates. By deploying transmit antenna selection schemes (like EDAS and COAS) to NOMA-SM in overlay CR networks, much savings in the transmit power can be obtained, which results in higher levels of energy efficiency of the system.





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APPENDICES

APPENDIX A. : The CDF of the random variable $\Gamma_{DC} = \frac{\eta_D \gamma_{DC}}{\eta_P(\gamma_{AC} + \gamma_{BC}) + 1}$

APPENDIX B. : The CDF of the random variable $\Gamma_{Cj} = \frac{\alpha \eta_s \gamma_{Cj}}{(1-\alpha)\eta_s \gamma_{Cj} + 1}$

APPENDIX C. : The PDF of the random variable $\gamma_{Max} = \frac{P_{s1} d_{minMax}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$





APPENDIX A.

In this section, we derive the cumulative distribution function (CDF) of the the random variable $\Gamma_{DC} = \frac{\eta_D \gamma_{DC}}{\eta_p (\gamma_{AC} + \gamma_{BC}) + 1}$.

To obtain the CDF of the random variable $\Gamma_{DC} = \frac{\eta_D \gamma_{DC}}{\eta_p (\gamma_{AC} + \gamma_{BC}) + 1}$ where γ_{iC} is an exponential random variable with parameter $d_{iC}^v \forall i \in \{A, B, D\}$:

Let $Z = \frac{U}{Y}$ and $Y = V + W$ where $U = \eta_D \gamma_{DC}$, $V = \eta_p \gamma_{AC}$ and $W = \eta_p \gamma_{BC} + 1$, are exponential random variables with parameters $\lambda_u = \frac{d_{DC}^v}{\eta_D}$, $\lambda_v = \frac{d_{AC}^v}{\eta_p}$, and $\lambda_w = \frac{d_{BC}^v}{d_{BC}^v + \eta_p}$, respectively.

We can find that the probability density function (PDF) of Y is:

$$f_Y(y) = \begin{cases} \frac{\lambda_v \lambda_w}{\lambda_v - \lambda_w} (e^{-\lambda_w y} - e^{-\lambda_v y}) & , \lambda_v \neq \lambda_w \\ \lambda^2 y e^{-\lambda y} & , \lambda_v = \lambda_w = \lambda \end{cases} \quad (\text{A.1})$$

Hence the PDF of the random variable $Z = \frac{U}{Y}$ can be obtained as follows:

$$\begin{aligned} f_Z(z) &= \int f_{Z,Y}(Z|y) f_Y(y) dy \\ &= \int_0^\infty |y| f_U(zy) f_Y(y) dy \end{aligned} \quad (\text{A.2})$$

After some manipulations we obtain:

$$f_Z(z) = \begin{cases} \frac{\lambda_u \lambda_v \lambda_w}{\lambda_v - \lambda_w} \left[\frac{1}{(\lambda_u z + \lambda_w)^2} - \frac{1}{(\lambda_u z + \lambda_v)^2} \right] & , \lambda_v \neq \lambda_w \\ \frac{2\lambda_u \lambda^2}{(\lambda_u z + \lambda)^3} & , \lambda_v = \lambda_w = \lambda \end{cases} \quad (\text{A.3})$$

From which we can obtain the CDF of Z as follows:

$$\begin{aligned} F_Z(z) &= \int_0^z f_Z(t) dt \\ &= \begin{cases} 1 - \frac{\lambda_v \lambda_w}{(\lambda_u z + \lambda_v)(\lambda_u z + \lambda_w)} & , \lambda_v \neq \lambda_w \\ 1 - \frac{\lambda^2}{(\lambda_u z + \lambda)^2} & , \lambda_v = \lambda_w = \lambda \end{cases} \end{aligned} \quad (\text{A.4})$$



APPENDIX B.

In this section, we derive The CDF of the random variable $\Gamma_{Cj} = \frac{\alpha \eta_s \gamma_{Cj}}{(1-\alpha)\eta_s \gamma_{Cj} + 1}$.

$$\begin{aligned}
 Pr(I_{Cj} > R_{pt}) &= Pr \left\{ \frac{1}{2} \log_2 \left(1 + \frac{\alpha \eta_s \gamma_{Cj}}{(1-\alpha)\eta_s \gamma_{Cj} + 1} \right) > R_{pt} \right\} \\
 &= Pr \left\{ \frac{\alpha \eta_s \gamma_{Cj}}{(1-\alpha)\eta_s \gamma_{Cj} + 1} > R_p \right\} \\
 &= Pr \{ \Gamma_{Cj} > R_p \} \\
 &= Pr \left\{ \gamma_{Cj} (\alpha(1+R_p) - R_p) > \frac{R_p}{\eta_s} \right\}
 \end{aligned} \tag{B.1}$$

where $R_p = 2^{2R_{pt}} - 1$.

If $(\alpha(1+R_p) - R_p) > 0$ then

$$\begin{aligned}
 Pr(I_{Cj} > R_p) &= Pr \{ \Gamma_{Cj} > R_p \} = Pr \left\{ \gamma_{Cj} > \frac{R_p}{\eta_s (\alpha(1+R_p) - R_p)} \right\} \\
 &= \exp \left(- \frac{d_{Cj}^v R_p}{\eta_s (\alpha(1+R_p) - R_p)} \right)
 \end{aligned} \tag{B.2}$$

if $(\alpha(1+R_p) - R_p) \leq 0$ then

$$Pr \{ \Gamma_{Cj} > R_p \} = Pr \left\{ 0 \text{ or neagative} > \frac{R_p}{\eta_s} \right\} = 0 \tag{B.3}$$

Hence,

$$Pr \{ \Gamma_{Cj} > R_p \} = \begin{cases} \exp \left(- \frac{d_{Cj}^v R_p}{\eta_s (\alpha(1+R_p) - R_p)} \right) & , \text{if } \frac{R_p}{R_p+1} < \alpha < 1 \\ 0 & , \text{if } 0 < \alpha \leq \frac{R_p}{R_p+1} \end{cases} \tag{B.4}$$



APPENDIX C.

In this section, we derive the probability density function (PDF) of the random variable $\gamma_{Max} = \frac{P_{s1} d_{minMax}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$, for the case of selecting two transmitting antennas ($N_{t1} = 2$) out of the N_t transmitting antennas at ST and using BPSK for both PR and SR, where d_{minMax}^2 is given by:

$$d_{minMax}^2 = \max_{\substack{S_I \\ I \in N_s}} \left\{ \min_{\substack{p, p' \in M_1 \\ j, j' \in S_I}} \left\| \mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'} \right\|^2 \right\} \quad (\text{C.1})$$

and S_I is the I^{th} subset that maximizes the minimum-SqED among all possible $N_s = \binom{N_t}{N_{t1}}$ subsets.

As shown in chapter 5 section (5.4) that the random variable $\gamma = \frac{P_{s1} \left\| \mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'} \right\|^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$ $= \sum_{\ell=1}^{2N_{r1}} v_\ell^2$ – where v_ℓ is a zero mean Gaussian random variable with variance $\sigma_v^2 = \frac{P_{s1} \sigma_h^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$ – is a chi-square random variable with $2N_{r1}$ degrees of freedom.

Therefore the CDF and PDF of γ are given by ([76] – Equation (2.3-24) and Equation (2.3-21)), respectively, as:

$$F_\gamma(\tau) = 1 - e^{-\frac{\tau}{2\sigma_v^2}} \sum_{i=0}^{N_{r1}-1} \frac{\left(\frac{\tau}{2\sigma_v^2}\right)^i}{i!} \triangleq 1 - u \quad (\text{C.2})$$

with $u = e^{-\frac{\tau}{2\sigma_v^2}} \sum_{i=0}^{N_{r1}-1} \frac{\left(\frac{\tau}{2\sigma_v^2}\right)^i}{i!}$, and

$$f_\gamma(\tau) = \frac{\tau^{N_{r1}-1} e^{-\frac{\tau}{2\sigma_v^2}}}{\Gamma(N_{r1}) (2\sigma_v^2)^{N_{r1}}} \quad (\text{C.3})$$

To find the CDF and PDF of the random variable $\gamma_{Max} = \frac{P_{s1} d_{minMax}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$, we first derive the CDF and PDF of the random variable $\gamma_{min} = \frac{P_{s1} d_{min}^2}{2(P_{s2} \sigma_h^2 + \sigma_n^2)}$, where d_{min}^2 is the minimum SqED in the I^{th} subset (S_I) defined by:

$$d_{min}^2 = \min_{\substack{p, p' \in M_1 \\ j, j' \in S_I}} \left\| \mathbf{h}_j x_p - \mathbf{h}_{j'} x_{p'} \right\|^2 \quad (\text{C.4})$$

For $N_{t1} = 2$ and using BPSK, each subset (S_I) has two distinguishable SqEDs and the EDAS algorithm selects the minimum of them. By using order statistics ([78] – Equation (1)) we obtain the CDF and PDF of the random variable γ_{min} as:

$$F_{\gamma_{min}}(\tau) = F_\gamma(\tau) \{2 - F_\gamma(\tau)\} = 1 - u^2 \quad (\text{C.5})$$

and,

$$f_{\gamma_{min}}(\tau) = 2\{1 - F_{\gamma}(\tau)\} f_{\gamma}(\tau) = 2u f_{\gamma}(\tau) \quad (\text{C.6})$$

Then, the EDAS algorithm selects the subset that maximizes the minimum-SqED among all the N_s subsets.

Using equations (C.5) and (C.6) and order statistics ([78] – Equation (1)) we can obtain the CDF and PDF of the random variable γ_{Max} as:

$$F_{\gamma_{Max}}(\tau) = (F_{\gamma_{min}}(\tau))^{N_s} \quad (\text{C.7})$$

and,

$$f_{\gamma_{Max}}(\tau) = N_s (F_{\gamma_{min}}(\tau))^{N_s-1} f_{\gamma_{min}}(\tau) \quad (\text{C.8})$$

By substituting (C.5) and (C.6) in to (C.8), we obtain:

$$f_{\gamma_{Max}}(\tau) = N_s (1 - u^2)^{N_s-1} 2u f_{\gamma}(\tau) \quad (\text{C.9})$$

Using the binomial expansion of $(1 - u^2)^{N_s-1}$, and using (C.2), we have:

$$\begin{aligned} (1 - u^2)^{N_s-1} &= \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z (u^2)^z \\ &= \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \left(e^{-\frac{\tau}{2\sigma_v^2}} \sum_{i=0}^{N_{r1}-1} \frac{\left(\frac{\tau}{2\sigma_v^2}\right)^i}{i!} \right)^{2z} \end{aligned} \quad (\text{C.10})$$

Substituting (C.3) and (C.10) into (C.9), we obtain:

$$\begin{aligned} f_{\gamma_{Max}}(\tau) &= 2N_s \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \left(e^{-\frac{\tau}{2\sigma_v^2}} \sum_{i=0}^{N_{r1}-1} \frac{\left(\frac{\tau}{2\sigma_v^2}\right)^i}{i!} \right)^{2z+1} \\ &\quad \times \frac{\tau^{N_{r1}-1} e^{-\frac{\tau}{2\sigma_v^2}}}{\Gamma(N_{r1}) (2\sigma_v^2)^{N_{r1}}} \end{aligned} \quad (\text{C.11})$$

By using the relation ([80] – Equation (14)), we have :

$$\left(\sum_{i=0}^{N_{r1}-1} \frac{\left(\frac{\tau}{2\sigma_v^2}\right)^i}{i!} \right)^{2z+1} = \sum_{i_1=0}^{N_{r1}-1} \dots \sum_{i_{2z+1}=0}^{N_{r1}-1} \frac{\left(\frac{\tau}{2\sigma_v^2}\right)^{\sum_{t=1}^{2z+1} i_t}}{(\prod_{t=1}^{2z+1} i_t!)} \quad (\text{C.12})$$

By substituting (C.12) into (C.11), we obtain the PDF of the random variable γ_{Max} as:

$$\begin{aligned}
f_{\gamma_{Max}}(\tau) &= \frac{2N_s}{\Gamma(N_{r1})} \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \\
&\times \sum_{i_1=0}^{N_{r1}-1} \cdots \sum_{i_{2z+1}=0}^{N_{r1}-1} \frac{\tau^{\xi-1} e^{-\frac{\tau(2z+2)}{2\sigma_v^2}}}{(\prod_{t=1}^{2z+1} i_t!) (2\sigma_v^2)^\xi}
\end{aligned} \tag{C.13}$$

where $\xi = (\sum_{t=1}^{2z+1} i_t) + N_{r1}$.

For the case when the receiving antennas at PR is 2, i.e., $N_{r1} = 2$, the PDF of the random variable γ_{Max} given by (C.13) can be reduced to:

$$\begin{aligned}
f_{\gamma_{Max}}(\tau) &= \frac{2N_s}{\Gamma(N_{r1})} \sum_{z=0}^{N_s-1} \binom{N_s-1}{z} (-1)^z \\
&\times \sum_{T=0}^{2z+1} \binom{z+1}{T} \frac{\tau^{\xi-1} e^{-\frac{\tau(2z+2)}{2\sigma_v^2}}}{(\prod_{t=1}^{2z+1} i_t!) (2\sigma_v^2)^\xi}
\end{aligned} \tag{C.14}$$

where $T = (\sum_{t=1}^{2z+1} i_t)$, and we use the fact that: $(\prod_{t=1}^{2z+1} i_t!) = 1, \forall i_t = \{0, 1\}$, and

$$\sum_{i_1=0}^{N_{r1}-1} \cdots \sum_{i_{2z+1}=0}^{N_{r1}-1} f(T) = \sum_{T=0}^{2z+1} \binom{z+1}{T} f(T).$$



CURRICULUM VITAE



Name Surname: Said Abdelmoneim Abdelwahab Emam

Place and Date of Birth: Kalyobiya, Egypt 08/11/1978

E-Mail: emams@itu.edu.tr & saidimam@hotmail.com

EDUCATION:

- **B.Sc.:** 2000, Banha University, Faculty of Engineering at shoubra, Electronic and Telecommunications Department.
- **M.Sc.:** 2007, Banha University, Faculty of Engineering at shoubra, Electronic and Telecommunications Department.

PROFESSIONAL EXPERIENCE AND REWARDS:

- **2002 - 2007:** Teaching Assistant, Banha University, Faculty of Engineering at shoubra, Egypt.
- **2007 - 2011:** Telecom Engineer at Saad Group, Alkhobar, Saudi arabia.
- **2012 - present:** Teaching Assistant, Banha University, Faculty of Engineering at shoubra, Egypt.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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