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Collaborative Modulation Multiple Access for Single Hop and Multihop Networks

By
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A Thesis Submitted for the Degree of Doctor of Philosophy

School of Engineering and Informatics

University of Sussex

January 2012

Declaration

I hereby declare that this thesis has not been submitted, either in the same or different form, to this or any other University for a degree and the work produced here is my own except stated otherwise.

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Thesis Submitted in Fulfilment of the Requirements for the Degree of
Doctor of Philosophy

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By: Marwan Aldroubi

Summary

While the bandwidth available for wireless networks is limited, the world has seen an unprecedented growth in the number of mobile subscribers and an ever increasing demand for high data rates. Therefore efficient utilisation of bandwidth to maximise link spectral efficiency and number of users that can be served simultaneously are primary goals in the design of wireless systems. To achieve these goals, in this thesis, a new non-orthogonal uplink multiple access scheme which combines the functionalities of adaptive modulation and multiple access called collaborative modulation multiple access (CMMA) is proposed. CMMA enables multiple users to access the network simultaneously and share the same bandwidth even when only a single receive antenna is available and in the presence of high channel correlation.

Instead of competing for resources, users in CMMA share resources collaboratively by employing unique modulation sets (UMS) that differ in phase, power, and/or mapping structure. These UMS are designed to insure that the received signal formed from the superposition of all users' signals belongs to a composite QAM constellation (CC) with a rate equal to the sum rate of all users. The CC and its constituent UMSs are designed centrally at the BS to remove ambiguity, maximize the minimum Euclidian distance (d_{min}) of the CC and insure a minimum BER performance is maintained. Users collaboratively precode their transmitted signal by performing truncated channel inversion and phase rotation using channel state information (CSI) obtained from a periodic common pilot to insure that their combined signal at the BS belongs to the CC known at the BS which in turn performs a simple joint maximum likelihood detection without the need for CSI. The coherent addition of users' power enables CMMA to achieve high link spectral efficiency at any time without extra power or bandwidth but on the expense of graceful degradation in BER performance.

To improve the BER performance of CMMA while preserving its precoding and detection structure and without the need for pilot-aided channel estimation, a new selective diversity combining scheme

called SC-CMMA is proposed. SC-CMMA optimises the overall group performance providing fairness and diversity gain for various users with different transmit powers and channel conditions by selecting a single antenna out of a group of L available antennas that minimises the total transmit power required for precoding at any one time.

A detailed study of capacity and BER performance of CMMA and SC-CMMA is carried out under different level of channel correlations which shows that both offer high capacity gain and resilience to channel correlation. SC-CMMA capacity even increase with high channel correlation between users' channels.

CMMA provides a practical solution for implementing the multiple access adder channel (MAAC) in fading environments hence a hybrid approach combining both collaborative coding and modulation referred to as H-CMMA is investigated. H-CMMA divides users into a number of subgroups where users within a subgroup are assigned the same modulation set and different multiple access codes. H-CMMA adjusts the $d_{min}$of the received CC by varying the number of subgroups which in turn varies the number of unique constellation points for the same number of users and average total power. Therefore H-CMMA can accommodate many users with different rates while flexibly managing the complexity, rate and BER performance depending on the SNR.

Next a new scheme combining CMMA with opportunistic scheduling using only partial CSI at the receiver called CMMA-OS is proposed to combine both the power gain of CMMA and the multiuser diversity gain that arises from users' channel independence. To avoid the complexity and excessive feedback associated with the dynamic update of the CC, the BS takes into account the independence of users' channels in the design of the CC and its constituent UMSs but both remain unchanged thereafter. However UMS are no longer associated with users, instead channel gain's probability density function is divided into regions with identical probability and each UMS is associated with a specific region. This will simplify scheduling as users can initially chose their UMS based on their CSI and the BS will only need to resolve any collision when the channels of two or more users are located at the same region .

Finally a high rate cooperative communication scheme, called cooperative modulation (CM) is proposed for cooperative multiuser systems. CM combines the reliability of the cooperative diversity with the high spectral efficiency and multiple access capabilities of CMMA. CM maintains low feedback and high spectral efficiency by restricting relaying to a single route with the best overall channel. Two possible variations of CM are proposed depending on whether CSI available only at the users or just at the BS and the selected relay. The first is referred to Precode, Amplify, and Forward (PAF) while the second one is called Decode, Remap, and Forward (DMF). A new route selection algorithm for DMF based on maximising d_{min} of random CC is also proposed using a novel fast low-complexity multi-stage sphere based algorithm to calculate the d_{min} at the relay of random CC that is used for both relay selection and detection.

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List of Abbreviations

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
AWGN	Additive White Gaussian Noise
BC	Broadcast Channel
BD	Block Diagonalization
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CBS	Correlation Based Selection
CCMA	Collaborative Coding Multiple Access
CC	Composite QAM Constellation
CDMA	Code Division Multiple Access
CEO	Cross Entropy Optimization
CMMA	Collaborative Modulation Multiple Access
CRFC	Correlated Rayleigh Fading Channel
CSI	Channel State Information
CSIR	Channel State Information at the Receiver
CSIT	Channel State Information at the Transmitter
DFT	Discrete Fourier Transform
DL	Downlink
d_{min}	Minimum Euclidean Distance
DoF	Degree of Freedom
DPC	Dirty Paper Coding
DSA	Decremental Selection Algorithm
DS-SS	Direct Sequence Spread Spectrum
EGC	Equal Gain Combining
EPA	Equal Power Allocation
FDMA	Frequency Division Multiple Access
GA	Genetic Algorithm
GPRS	General Packet Radio Service
GSC	Generalized Selection Combining

GSD	Generalized Sphere Decoding
GSIC	Group Successive Interference Cancellation
GSM	Global System for Mobile Communications
HPG	High Power Group
HPG-MUD	High Power Group Multiuser Detection
HPG-PDBS	High Power Group Phase Difference Based Selection
i.i.d	independently identically distributed
IMT	International Mobile Telecommunication
ISA	Incremental Selection Algorithm
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LDPC	Low Density Parity Check Codes
LOS	Line-of-Sight
LS	Least Squares
LTE	Long Term Evolution
MAAC	Multiple Access Adder Channel
MAC	Multiple Access Channel
MAI	Multiple Access Interference
MAS	Multiple Access Scheme
MBER	Minimum Bit Error Rate
MC-CDMA	Multicarrier Code Division Multiple Access
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum Likelihood
MMSE	Minimum Mean Squares Error
MRC	Maximum Ratio Combining
MSE	Mean Squares Error
MUD	Multiuser Diversity
MUI	Multiple User Interference
MUMA	Multiuser Multiantenna
MU-MIMO	Multiuser Multiple-Input Multiple-Output
NBS	Norm Based Selection
NLOS	No Line-of-Sight
OCDMA	Orthogonal Code Division Multiple Access

OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OS	Opportunistic Scheduling
PAM	Pulse Amplitude Modulation
PDF	Probably Density Function
PIC	Parallel Interference Cancellation
PN	Pseudo-Noise
PN-CDMA	Pseudo-Noise Code Division Multiple Access
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAS	Receive Antenna Selection
RF	Radio Frequency
RSMA	Rate Splitting Multiple Access
SC	Selection Combining
SPC	Superposition Coding
SCBS	Spatial Correlation Based Selection
SD	Sphere Decoding
SDMA	Space Division Multiple Access
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference-plus-Noise-Ratio
SIR	Signal-to-Interference-Ratio
SISO	Single-Input Single-Output
SM	Spatial Multiplexing
SNR	Signal-to-Noise-Ratio
SO	Successive Optimization
SSD	Slab Sphere Decoding
STBC	Space-Time Block Code
STC	Space-Time Coding
STTC	Space-Time Trellis Code
SU-MIMO	Single User Multiple-Input Multiple-Output

SVD	Singular Value Decomposition
TAS	Transmit Antenna Selection
TDMA	Time Division Multiple Access
THP	Tomlinson-Harashima Precoding
UL	Uplink
UPA	Unequal Power Allocation
V-BLAST	Vertical-Bell Labs Layered Space-Time
VP	Vector Perturbation
WH	Walsh Hadamard
WiMAX	Worldwide Interoperability for Microwave Access
ZF	Zero Forcing
ZFBF	Zero Forcing Beamforming

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1 Introduction

1.1 Motivation

Wireless communication has become an indispensable part of everyday life and a major driver for economic growth and human development in the developed and developing worlds alike. No other technology has managed to find its way to, and change, every aspect of human activity from the way we socialise and entertain ourselves to the way we bank and do business. No wonder then that the number of mobile subscribers has mushroomed from just over 2 billion to 5.3 billion (76% of world inhabitants) in the period between 2005 and 2011 according to the latest survey by the International Telecommunication Union (ITU). Moreover, the emerging trends of embedding high resolution camera (8 megapixels and above), Global Positioning System (GPS) chips, the merger between mobile phones and computers in the form of smart phones and tablet computers, and the emergence of cloud computing has transformed mobile phones (and with it cellular traffic) from voice-telephony devices to portable interactive computers. In turn that has opened the way for many new position-based, data, and multimedia applications such as voice over IP (VoIP), video *and* audio downloads, and upload of user-created content, mapping services, location-based online search, mobile TV, and interactive games developed for mobile phones.

However the fulfilments of the promises of the wireless revolution and the wider deployment, customer acceptance and commercial success of new multimedia services depend on satisfying several requirements. Firstly the number of users that can be accommodated within a cell need to be significantly increased without necessarily increasing the number of base stations (BS). Secondly data and multimedia traffic require a high data rate in order of 100 Mb/s for high mobility users and up to 1 GB/s for low mobility or fixed users as recommended by the ITU for International Mobile Telecommunication IMT-Advanced. An acceptable quality of service (QOS) and high data rate should also be available to users depending on their needs rather than their location within the cell. Thirdly the projected increase in data traffic should not come at the expense of reduced battery life and increased transmission power due to health hazards and the simple fact that the ability of being wireless is ultimately limited by the size and battery-life of the mobile unit. Finally the cost of delivering high quality services and high data rate should be kept affordable.

Fulfilling the above mentioned requirements is particularly challenging in wireless environments due to some intrinsic characteristics of wireless networks. Firstly the broadcast nature of wireless transmission causes inter-and intra-cell interference at both the BS and the mobile users. Secondly the fading nature of wireless channels not only cause attenuation in radio signals which increases with frequency but also causes rapid variations in the signal to noise ratio (SNR) of the received signal. Finally wireless resources (such as bandwidth, time, and power) are limited and can't be increased with demand as is the case with fibre-optic networks. Therefore, maximising bandwidth efficiency, exploiting all available degrees of freedom (time, frequency, code and space), minimising power consumption and adaptation to fading and interference are the main research objectives enabling improved performance and capacity.

To address these challenges, the latest and evolving wireless networking standards such as the Worldwide Interoperability for Microwave Access (WiMAX), Third Generation Partnership Project (3GPP), represented by IEEE 802.16m and Long Term Evolution advanced (LTE)-Advanced and the ITU's IMT-Advanced, all envisage the concurrent deployment of a number of compatible technologies in the physical and multiple access layers [1].

One of these key technologies is multi-carrier multiple access schemes (MAS) which are based on orthogonal frequency division multiplexing such as OFDMA and multi-carrier CDMA. These schemes enable efficient and high bandwidth efficiency as well as robust performance against fading by converting the cell bandwidth into many parallel orthogonal, yet overlapping and flat fading sub channels.

Another technology that is envisioned to be used concurrently with OFDMA is multiple-input multiple output communication (MIMO) which exploits the rich scattering environment and the availability of multiple antennas at the receiver to allow many users to access the network, simultaneously achieving linear increase in system capacity without consuming extra bandwidth or power. In addition to its capacity gain, MIMO can provide spatial diversity to improve the bit error rate (BER) performance and reduce users' transmit power. However MIMO is limited by the number of receive antennas, the amount of feedback required for scheduling and precoding, and by channel correlations due to insufficient antenna separation at the terminals and/or poor scattering environment. As a result, the sum rate capacity and bit error rate (BER) performance are significantly degraded. Moreover the cost of employing multiple Radio Frequency RF chains remains high.

Although MIMO and OFDMA have the potential to greatly improve cell capacity and link spectral efficiency, they are constrained by the finite nature of wireless resources, channel fading and correlation, size of handheld devices, battery life and computational complexity. This will put a huge burden on the infrastructure-based nature of cellular networks where users communicate directly with the BS hence requiring a substantial increase in cell density which is expensive and not practical. However the high density of mobiles users in urban areas and their multiple air-interfaces capabilities (WLAN, Bluetooth, and 4G) will see the emergence of new hybrid architecture combining both ad-hoc and infrastructure-based networks also known as cooperative communication or multihop cellular networks [2]. These schemes allow users to utilise each other's independent channels to shorten the range of communication links, decrease path loss, increase diversity gain, mitigate shadowing effect, and decrease inter and intra cell interference.

1.2 Research Aims and Objectives

- To design low-feedback high-capacity non-orthogonal multiple access schemes based on signal set expansion.
- To design low-complexity low-overhead spatial diversity schemes for non-orthogonal multiuser MAS based on superposition coding.
- Design high-rate cooperative diversity schemes that allow users to utilise high order of cooperative diversity without comprising their transmission rate suing adaptive modulation and relaying.

1.3 Contributions of the thesis

A number of contributions have been made in this work; below is a summary of main findings and contributions:

1) A novel high-capacity multiple access scheme called CMMA is proposed. CMMA utilises well-established physical-layer concepts of collaborative multi-user transmission over Multiple Access Adder Channel (MAAC), superposition coding, and adaptive modulation in an innovative manner to enable multiple users transmitting over fading channels to share the same bandwidth simultaneously and combine their power collaboratively to achieve high link spectral efficiency.

- CMMA is resilient to channel correlation, so it can be applied to retain spatial multiplexing, improve BER performance and maximise the channel and user capacity for multi-user MIMO in the presence of high channel correlation.
- CMMA can serve multiple users even with a single receive antenna, therefore it can provide a practical solution to retain spatial multiplexing and high spectral efficiency in many applications where employing multiple antennas is impractical due to size constraints such as wireless sensor networks.

- CMMA offers a new model to exploit superposition coding (SPC). Instead of viewing superimposed users as interference to each other. CMMA view them as partners who collaborate to form a composite QAM constellation with maximum possible rate and minimum Euclidian distance. This new approach departs from user-specific power control and successive interference cancellation receivers to a new approach that optimises power, phase, and/or constellation mapping across users by common feedback and collaborative precoding. CMMA offers higher capacity and can accommodate more users (even with equal power) than that of conventional implementations of SPC.
- CMMA allows reliable multiple access with very little overhead and minimum feedback, since users perform precoding independently of each other without access to each other's data or CSI using a simple common feedback from the BS. Also detection at the BS doesn't require CSI.
- CMMA presents a practical low-overheard technique for the coherent combining of multiple signals over fading channels thus implementing the MAAC in realistic wireless environments. In addition, CMMA attains multiple access through modulation instead of multiple access codes. This is significant since these codes achieve multiple access on the expense of a significant reduction in rate per user while our scheme preserves the rate per user and is shown to achieve a much higher capacity compared with collaborative coding multiple access.

2) A new diversity selection combining algorithm for CMMA called SC-CMMA is proposed to benefit from spatial diversity without incurring the substantial increase in both complexity and overheads which result from the feedback of CSI from users back to the BS.

- SC-CMMA maintains the simple feedback, precoding, and detection structure of CMMA.

- Unlike conventional selection combining which was designed for single-input-multiple-output communication, SC-CMMA optimise the group performance by selecting a single antenna which minimises the total transmit power required for precoding at any one time.
- The BS uses the output of the ML detector at the selected antenna as a training sequence to estimate the CSI at the remaining antenna and update the selection process.
- The diversity gain achieved by SC-CMMA increases with transmit correlation between users' channels, thus SC-CMMA offers a low overhead alternative to other uplink multi-user MIMO in the presence of high transmit correlation.

3) A new scheme called CMMA-OS combining opportunistic scheduling using only partial CSI at the BS with dynamic allocation of unique modulation sets according to users' channel conditions is proposed.

- With feedback and complexity equal to that of multi-user diversity (MUD), CMMA-OS can retain not only the diversity gain associated with MUD but also the power gain offered by CMMA.
- CMMA-OS allows all users to transmit at once, so it doesn't suffer the same delay and fairness setbacks of MUD, which makes it suitable for delay-sensitive applications.
- A new selection-combining scheme that maximises the aggregate channel gain across all users is proposed for CMMA-OS. It exploits receive spatial diversity assuming multiple antennas at the receiver but only a single RF chain as a trade-off between performance and complexity. The BS scans all available antennas sending a common pilot from each, which users utilise to extract CSI and simultaneously transmit one symbol back to the BS all using the same power and phase. The BS then uses a simple envelope detector and selects the branch with the highest signal plus noise.

4) A new hybrid approach combining both collaborative coding and modulation referred to as H-CMMA has been investigated to improve the BER performance and reduce the

complexity of CMMA. H-CMMA can adjust the minimum distance of the received composite constellation by varying the number of unique constellation points for the same number of users and average total power to accommodate large number of users with different rates while flexibly managing the complexity and BER performance of the combined simultaneous transmissions depending on the SNR.

5) This thesis also investigates how opportunistic scheduling and collaborative modulation can be employed in relay networks like cooperative and multihop cellular communication to achieve high spectral efficiency, mitigate the half-duplex constraint, and maintain reliable communication through cooperative diversity. A number of schemes have been proposed to fulfil these goals:

- First we propose a new two user's low-overhead channel-aware cooperative diversity scheme that uses scheduling and adaptive modulation to take advantage of the spatial diversity achieved through cooperation while maintaining the same bandwidth compared with non-cooperative schemes. It restricts relaying to the user with the stronger channel and adjusts the size of the QAM constellation used according to whether cooperation occurs or not. It was shown that while having double the spectral efficiency of conventional adaptive decoded and forward, this scheme can still deliver a significant improvement in BER performance with modest reduction in diversity gain.
- A high spectral efficiency communication scheme, called cooperative modulation (CM) is proposed for cooperative multiuser systems. CM combines both the reliability and QOS resulting from the cooperative diversity with order equal to the number of users with the high spectral efficiency and multiple access capabilities of CMMA. CM maintains low feedback and high spectral efficiency by restricting relaying to a single route with the best overall channel. The number of consecutive transmissions required to deliver data from users to the BS is always equal to two, therefore the cost of the half duplex constraint doesn't increase with the number of users. Two possible variations of

CM are proposed depending on whether CSI is available only at the users or just at the BS and the selected relay. The first is referred to Precode, Amplify, and Forward (PAF) while the second one is called Decode, Remap, and Forward (DMF).

- A new route selection algorithm for DMF based on maximising the Euclidian minimum distance of the resulting random composite constellation at relay is proposed. It was shown that it offers significant improvement in BER performance compared with conventional selection methods based on just measuring SNR.
- Finally a fast low complexity multi-stage sphere based algorithm to calculate the minimum distance of random composite constellation is proposed. It exploits several common geometric properties of the composite constellation to greatly reduce the number of calculations needed to obtain the minimum distance which simplify both selection and detection at the relays.

1.4 Outline of the Thesis

This thesis is organised as follows. In chapter two, technical background and literature review of the related work to this thesis are provided. The fading channel principles including parameters, classifications and estimation techniques are studied. Next the principles and features of the most important wireless multiple access techniques are presented. An overview of MIMO communication system is carried out before ending this chapter with a review of MIMO communication.

In Chapter 3, CMMA multiple access scheme is proposed, first related work and motivation is presented before introducing the principles and operation of CMMA. Next a detailed description of CMMA system model is given including signal model, collaborative precoding, joint ML detection, feedback, and synchronisation acquisition. This is followed by the design and properties of composite constellations. Then a new selection combining scheme for CMMA referred to as SC-CMMA is presented including selection criteria and maintenance using blind channel estimation. Finally an analysis of BER and outage probability combined with simulation results and comparisons are presented to evaluate its performance.

In chapter 4, a thorough study of CMMA and SC-CMMA capacity is carried out to find closed form expressions for spectral efficiency as a function of average received SNR. Next we will compare the performance of CMMA with that of Multiuser Diversity. Finally this thesis will study the effect of channel correlation on the performance of CMMA.

Chapter 5 presents two novel schemes to improve the capacity and BER performance of CMMA. The first, referred to as CMMA-OS, increases the capacity of CMMA using opportunistic scheduling, while the second scheme referred to a H-CMMA, combines both collaborative coding and modulation to improve the BER performance and reduce the complexity of joint ML detection. Detailed description of related work and system model for these schemes are presented. In addition, the performance of both schemes was validated through simulations and relevant comparisons. Furthermore the capacity of CMMA-OS was analysed and new selection combining and opportunistic scheduling schemes for CMMA-OS are proposed.

Chapter 6 investigates several schemes employing opportunistic scheduling and collaborative modulation in cooperative communication to achieve high spectral efficiency, mitigate the half-duplex constraint, and maintain reliable communication through cooperative diversity. First an overview of cooperative communication and related work is presented a new full rate low-overhead channel-aware cooperative diversity scheme called COOP-AM is presented for the two user case. Then a high spectral efficiency communication scheme, called cooperative modulation (CM) is proposed for cooperative multiuser systems where all users utilise the same orthogonal resource and the number of consecutive transmissions required to deliver data from users to the BS is always equal to two. Therefore the cost of the half duplex constraint doesn't increase with the number of users. Two possible variations of CM are proposed depending on whether CSI is available only at the users or just at the BS and the selected relay. The first is referred to Precode, Amplify, and Forward (PAF) while the second one is called Decode, Remap, and Forward (DMF). Two relay selection algorithms employing norm-based and minimum distance-based selection are proposed for DMF. A fast low complexity multi-stage sphere-based algorithm to calculate the minimum distance of random composite constellation is proposed to simplify relay selection and detection for DMF. The performance of these proposed schemes is validated through appropriate simulations.

Finally, chapter 7 concludes the thesis, with a summary of main findings and contributions and some discussion on future work.

2 Overview of Multiuser Cellular Communications

2.1 Introduction

In this chapter, technical background and literature review of the related areas to the work in this thesis are provided. Fading channel model was first explained, followed by an overview of channel estimation methods and finally an overview of most common used wireless multiple access schemes was provided before ending this chapter with a review of MIMO communication.

2.2 Multipath Fading channels

One of the most important characteristics of wireless networks is the broadcast and multipath fading nature of the wireless channel. The wireless environment in which the signal propagates is usually rich in scatterers such as building, cars, trees, ground terrain, or the atmosphere (atmospheric ducting and ionospheric reflection) in outdoor scenarios, or walls, furniture, and people in indoor scenario [4][3] [3].

This causes the radio signal to reflect of, refract through, or diffuse around these scattering obstacles, which not only dissipate signal power causing path or propagation loss, but also these obstacles act as secondary sources causing the originally transmitted signal from the source to arrive at the receiver from different paths, each one of these paths has a different length (usually larger in distance than the direct line of sight (LOS)) and thus will arrive at the received antennas at different times, from different directions, and with different power and phase. Depending on the relative phase between signals from different paths, they might add up constructively (thus increasing the combined signal power) or add destructively, (thereby decreasing the combined signal power).

The signal to noise ratio (*SNR*) and the phase of the received signal will fluctuate over both time and frequency domain due to the relative movement of not only the communication terminals but also the scatterers (cars on a highway). Furthermore the *SNR* of the combined received signal will vary considerably over space even within short distances on the scale of half wavelength due the high frequencies used in wireless communication. This random fluctuation in the received signal power in time, frequency, and space domains is referred to as ***multipath fading***. An example of multipath fading channel is shown in Fig 2.1.

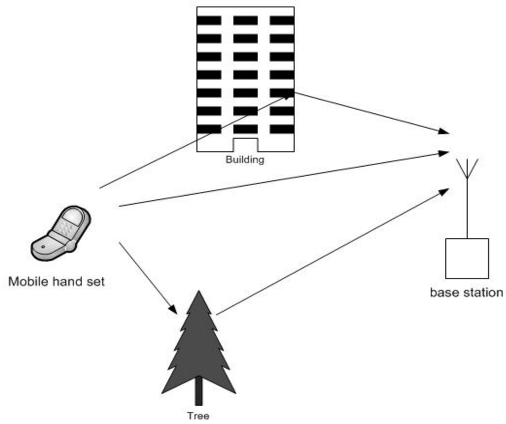


Figure 2- 1: An example of multi-path fading channel

In addition to fading, another important effect caused by the multipath phenomena is ***dispersion*** which refers to expansion in time of the duration of a single transmitted symbol which may in worst case scenario lead to it overlapping with successive symbols causing inter-symbol interference (ISI). Dispersion can also be due to the band pass filter nature of the wireless channel, if the bandwidth of the transmitted signal exceeds that of the channel, the channel becomes frequency selective where different frequency components of transmitted signal fade independently distorting the shape of the transmitted pulse and causing it to expand and collide with successive symbols.

2.2.1 Characteristics of Fading Channel

Fortunately, although the multipath phenomena are highly complex, random and often non-linear, practical measurements of the multipath fading channel show that fading channels can be fairly accurately modelled as a linear time-variant filter and a number of statistical models has been proposed and widely used to study the effects of the wireless channel.

Variations in the *SNR* of the received signal caused by fading can be classified into two main categories: ***large-scale fading*** and ***small scale fading***. [3][4]

large scale fading represents the average signal power attenuation or path loss due to motion over large areas. It is the result of shadowing, where a large obstruction such as a hill or large building obscures the main signal path between the transmitter and the receiver. Statistically, large scale fading is described by average path-loss and log-normally variation about the mean.

While ***small scale fading*** causes severe variation in received signal power and phase over small distances in the order of half wavelength. In urban environment the mobile user is surrounded by many scatters and located much lower than the BS therefore usually no dominant direct line of sight (LOS) exists and fading is usually caused by many reflective paths. Small scale fading in the absence of dominant LOS path is usually modelled using Rayleigh probability distribution and often referred to as ***multipath Rayleigh fading.***

The time and frequency response of a multipath fading channel can be defined by several important parameters:

Coherence bandwidth: denoted by f_c, is the maximum frequency separation within which all frequencies experience coherent or identical fading over time. Any two frequencies separated by more than f_c experience independent fading. This frequency selectively of wireless channel is caused by the time delay between reflected paths. Therefore the coherent bandwidth is calculated by measuring the delay spread T_m which is defined as maximum delay between the first and last received paths of significant power. The relation between multi-path delay spread of a channel and the coherence bandwidth is approximately given by

$$f_c \approx \frac{1}{T_m} \tag{2-1}$$

Coherence time t_c: is defined as the duration over which the channel impulse response remains unchanged. Therefore, if a symbol duration is smaller than t_c, the channel can be considered as time invariant throughout the detection of a symbol.

Doppler shift: refers to the maximum shift of the received carrier frequency due to the relative motion between the transmitter and the receiver. The Doppler power spectral density (f) of the mobile channel is often expressed as

$$s(f) = \frac{1}{\pi f_d \sqrt{1 - \left(\frac{f}{f_d}\right)^2}} \tag{2-2}$$

where f is the carrier frequency and $\pm f_d$ is the maximum range of frequency Doppler shifts which is given

$$f_d = \frac{V}{\lambda} \tag{2-3}$$

where V is the relative velocity of transmitter and receiver; and λ is the signal wavelength. The Doppler phenomenon causes the channel to be time variant. Therefore the coherence time is often measured by calculating the maximum Doppler shift where the relationship between the two is given by

$$t_c \approx \frac{1}{f_d} \tag{2-1}$$

Transmitted signals over fading channels can undergo different fading profiles depending on the relationship between signal parameters (like symbol duration and bandwidth) and channel parameters (coherent time and bandwidth). If the coherence bandwidth is greater than the signal bandwidth, the transmitted signal is said to undergo ***flat fading***. Otherwise, the transmitted signal undergoes ***frequency-selective fading***. Frequency selective fading causes the received signal impulse to expand in time and collide with adjacent symbols which result in inter-symbol interference (ISI).

On the other hand, the relationship between the Doppler shift and signal bandwidth determines where fading can be classified as ***fast*** or ***slow***. If the Doppler shift of the channel is much less than the signal bandwidth, the signal is said to undergo slow fading and hence fading remains unchanged for a block of consecutive symbols.

2.2.2 Channel Estimation Techniques

Channel estimation performs an indispensable part in communication system. In fact most detection, precoding, scheduling, diversity combining schemes can't be implemented without accurate channel estimation. There are several techniques used in wireless networking for channel estimation depending on what type of CSI are required (full, statistical, or partial) and the overhead or cost associated with estimation. However most channel estimation scheme fall into four main categories

- ***Pilot-based estimation:*** [5]pilots also known as training sequences are a block of data transmitted which is known at the receiver and is used to determine the unknown parameters. This category of estimation techniques provide an acceptable performance and hence are used in many practical systems. However, the training sequences are often long and introduce large overhead resulting in reduced bandwidth efficiency. In the literature many research work has been conducted to find optimum training sequences [6]. A well-known example of training based estimation technique is least squares (LS) estimation [7].
- ***Blind channel estimation***: In these techniques the estimator relies on the statistical knowledge of the fading channel or data. Blind estimation requires complex processes that often have slow convergence time and the performance results are not as good as

training-based techniques (J. J. Werner, 1999). Most popular examples of the blind techniques are minimum mean squared error (MMSE) [7].

- ***Semi-blind techniques***: In this category of techniques the high bandwidth redundancy of training-based estimations and low performance of blind methods are compensated by combining small training sequences and statistical knowledge of the required parameters in order to improve the performance of the estimator [8][9][10].
- ***Superimposing –based estimation***: There is a wide range of channel estimation methods which embed the training sequence to the data and namely are known as pilot hiding[11], implicit[12], and superimposed [13][14] training techniques. In superimposing the training sequence is arithmetically added to the information data. In this way, no bandwidth is lost for training sequence. To make use of the training sequence, knowledge of statistical characteristics of the sequence is vital. Since the training sequence is periodic, the received data will exhibit periodically time-varying mean that is used for channel estimation.

2.3 Wireless Multiple Access Schemes

Multiple access schemes (MAS) perform a fundamental function in wireless networks, allowing users to share resources fairly while maximizing network throughput. The most common multiple access model is that where many users transmit to a common receiver (such as BS in wireless cellular networks). In the following sections, the main characteristics of some important multiple access techniques are briefly reviewed.

2.3.1 Frequency Division Multiple Access (FDMA)

FDMA[3][4][17][18] was the first MAS used for cellular networks due to its ease of implementation in analogous continuous communications. FDMA divides the available cell bandwidth W into N frequency channels thus it can serve up to N users simultaneously where each one of these *N* users are allocated a unique frequency band for its exclusive use as shown in Figure 2- 2. If one of these frequency channels is not used, it become a wasted resource that can't be used to increase the capacity or rate of other active users, making FDMA is inflexible MAS when it comes to serving users with different rate requirement , on the other hand however FDMA does not require synchronization or timing control, which makes it simple to implement, Moreover FDMA channels usually have narrow bandwidth (30 KHz in APMS) and therefore they are usually implemented in narrowband systems where no or little equalization is required. Even though each user transmit in a dedicated portion of the system bandwidth , guard bands -where no transmission is allowed- are observed between channels to minimize inter-channel interference caused by the nonlinear effects of power amplifiers operating near saturation which spread the signal bandwidth and generate inter-modulation frequencies. Therefore not all of the available bandwidth can be used for data transmission.

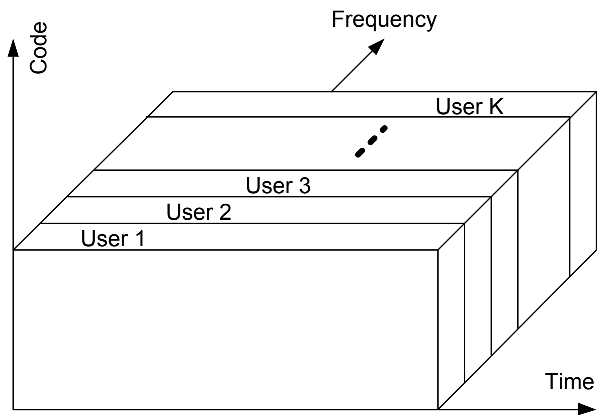


Figure 2- 2 Time ,frequency, and code illustration of FDMA

2.3.2 Time Division Multiple Access (TDMA)

In digital wireless systems, data transmission are often discrete hence there is no need to allocate a dedicated frequency channel to a user for the whole duration of the communication session. Furthermore data rate requirement differs between the downlink and uplink and between users. To address these issues, TDMA is widely used in wireless cellular networks (such as Global System for Mobile Communications (GSM) and General Packet Radio Service (GPRS)) as a complementary multiple access scheme to FDMA [3][4][17][31]as illustrated in Figure 2- 3 , TDMA allows each user to transmit using the entire available bandwidth for a portion of the time. Each frequency channel is divided into a number of periodically recurring time slots and multiple users are allocated a number of time slots which can vary according to their rate requirements. The assignment of time slots to users can either be ***static*** where i^{th} time slot of each frame is assigned to the i^{th} user or ***dynamic*** where the user with the strongest channel at time slot i^{th} is permitted to transmit to make use of multiuser diversity. The number of slots in a frame, how many time slots are assigned to each user, and how this assignment is performed, depends on a number of factors such as permissible delay, available bandwidth, modulation technique etc. Since users are only allowed to transmit during their allocated time slots, accurate time synchronizations and guard periods of no transmission between slots are required to eliminate inter-user interference. Higher transmission rates (larger bandwidth) than FDMA makes TDMA more vulnerable to ISI thus adaptive equalization is needed, however the bursty discrete nature of TDMA can reduce power consumption for mobile phones since users' RF circuitry are only turned on during the users designated time slots .

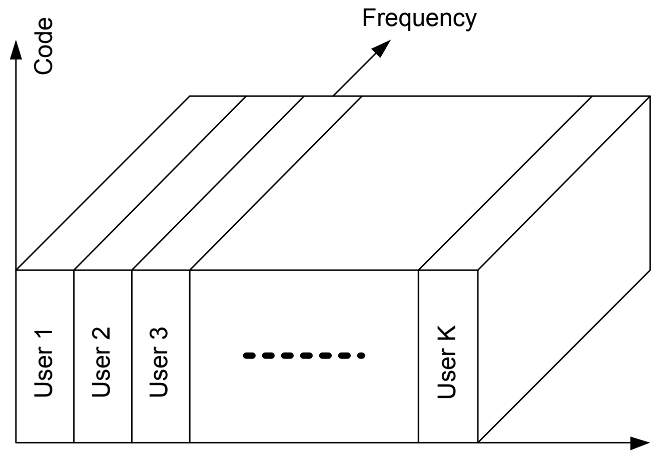


Figure 2- 3 Time, frequency, and code illustration of TDMA

2.3.3 Coding Division Multiple Access (CDMA)

CDMA [3][4][19][20][21][31] allows multiple users to access the network simultaneously and over the same bandwidth by multiplying the data of each user by a unique spreading code with a rate much higher than that of the user's signal which in turn lead to bandwidth expansion or the spreading of the original user' narrowband signal over a much larger bandwidth. The receiver has a priori knowledge of the spreading codes used for transmission and will simply multiply the received signal with the original code to dispread the signal to its original bandwidth and cancel or minimize the interference from other users.

The wideband nature of CDMA makes it highly likely to result in large delay spread and frequency selective fading. This large delay between paths allows the receiver to reliably detect and resolve a number of independent paths which can be coherently combined to provide high path diversity making it highly resilient to multipath fading. Spreading the signal over large bandwidth also results in lower power spectral efficiency making it harder to jam and more resilient to interference.

In a CDMA system, each user is assigned a particular pseudo-random PN-code with noise-like properties which is used to spread its data signal as shown in Figure 2- 4. These PN-codes are generated using shift registers of length i which generate a deterministic and repeated sequences of length $2^{i} - 1$. These PN-sequences should posses a number of important characteristics to have multiple-access capabilities:

A. Different PN-codes should have low or zero cross-correlation to minimize or cancel the interuser interference at the receiver.

B. The relative frequency of 1s and 0s in a PN-sequence should be balanced in order to avoid having a DC-component in the spreaded data signal.

There are a number of spreading codes that are widely used in wireless systems which may differ in correlation, orthogonally and implementation complexity such as: Walsh-Hadamard codes, m-sequences, Gold-codes and Kasami-codes. Walsh sequences are orthogonal while the other sequences have non-zero low cross-correlation values.

Orthogonal Walsh codes have zero cross-correlation properties but are highly sensitive to any offsets between sequences which actually lead to large cross-correlation values and high interference. Therefore their implementation is restricted to the downlink of the wireless networks where perfect synchronization can be achieved since all data streams are transmitted from the BS. For a given bandwidth W the number of unique orthogonal codes that can be generated is limited as well as the number of users that can accommodated.

Non-orthogonal codes therefore are used for the uplink of the wireless channel where synchronization between users is difficult to achieve. There nonzero but low cross correlation means that the contribution from other users can't be completely nulled at the receiver although they will be greatly minimized assuming perfect power control among the received signals from all users. This cohcannel interference from other users will increase linearly with the number of users leading to a degradation in BER performance and thus the rate that can be achieved per user. Therefore although the number of users that can access the network is not limited by the availability of orthogonal resources like TDMA and FDMA which place a hard limit on user capacity, the capacity of CDMA depends on the average bit error rate degradation that can be tolerated which correspond to a threshold for the ratio of the incoming signal power over the interference power and noise (SINR), and thus CDMA is said to be interference-limited.

The capacity of CDMA is highly dependent on an effective power control to manage the cochannel interference between users and maintain an acceptable SINR at the BS. Two main ways of providing power control are used in practice: an open-loop power control where users adapt their power based on the power of the pilot signal received from the base station and closed loop power control which relies on a feedback channel between the BS and users. The choice of power control employed usually depends on whether TDD or FDD is used to separate between the uplink and downlink channels. Usually the feedback is sent every 0.67ms from the BS to users to adapt their power up or down in the range of 0.5-1 dB [22].

Equal power control between users minimise the co-channel interference at the BS however that comes at the expense of low sum rate since the rate per user is limited to that with the weakest channel. Therefore to achieve higher rates, multiuser detection using superposition coding and successive interference cancellation (SIC) receiver can be employed to maximise capacity and enable users with different rates to communicate together.[23]

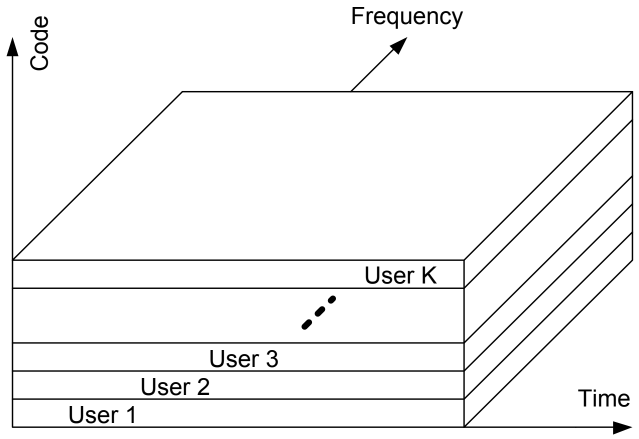


Figure 2- 4: Time, frequency and code illustration of the CDMA

2.3.4 Space Division Multiple Access (SDMA)

SDMA [4][24][25] is a high spectral efficiency and power-efficient MAS that maintains orthogonally between users by exploiting the space degree of freedom allowing multiple users to communicate simultaneously without subdivision in time, frequency, or code. An illustration of SDMA is shown in Figure 2- 5 SDMA employs highly directional antenna arrays consisting of N antenna elements sufficiently spaced out and individually power and phase weighted so that the array response achieves high antenna gain in the desired direction while experiencing low or null array response elsewhere. This high antenna directionality and beam steering focuses power towards desired users while minimising interference from other active users which enables the BS to serve users over longer distances and with better QOS. The number of users that can be served simultaneously depends on the separation between users and number of elements in the antenna array since the number and width of beams is highly dependent on this number. By using N antenna array, SDMA can support simultaneous transmission of up to $N-1$ users in a given system bandwidth W. SDMA therefore can enable frequency reuse even within the same cell which linearly increases the cell capacity however it is likely that a number of users are located within the same beam therefore SDMA is usually used in it conjunction with other MAS such as CDMA, TDMA, and FDMA. Where these MAS are used to service users located within the same beam width while SDMA is used to increase cell range and enable frequency reuse within the cell.

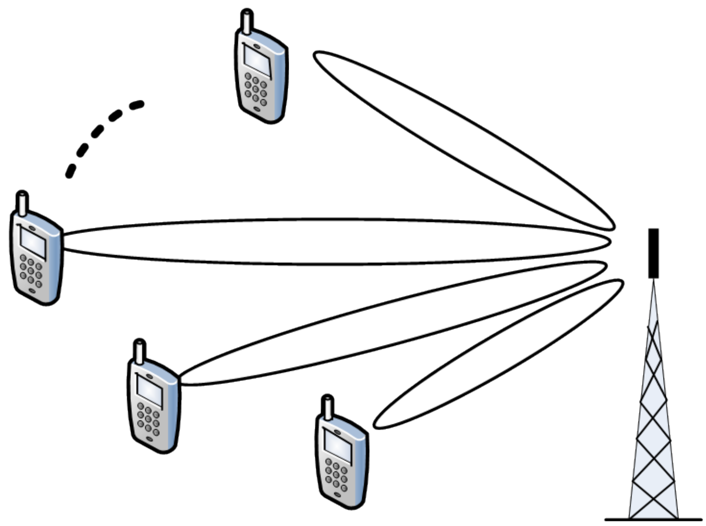


Figure 2- 5: illustration of SDMA

2.3.5 Orthogonal Frequency Division Multiple Access (OFDMA)

Orthogonal frequency division multiplexing (OFDM) is a narrowband orthogonal multi-carrier MAS used for LTE and 4G networks [1] [26][26][27][28][29]. In OFDM, the information to be transmitted is mapped onto several parallel overlapping sub-carriers which are chosen so that they are orthogonal to each other by separating the carriers by n/T_S (where T_S is the symbol time and n is a nonzero integer usually chosen as one). Additionally, a guard interval called cyclic prefix (CP) is added to each symbol to mitigate ICI. The bandwidth of each subcarrier overlaps with neighbouring subcarriers insuring high spectral efficiency. In addition, the bandwidth of each sub-carrier is narrower than the coherence bandwidth of the channel insuring flat fading eliminating the need for complex equalization. In practical implementations, OFDM modulation is performed with an Inverse Fast Fourier Transform (IFFT) while a Fast Fourier Transform (FFT) is used for demodulation.

Orthogonal frequency division multiple access (OFDMA) is basically a FDMA/OFDM hybrid MAS and is currently used in wireless LAN (IEEE 802.11a & 11g), WiMAX (IEEE 802.16), and 3GPP LTE downlink systems. A Block diagram of a N-user BPSK OFDMA is shown in Figure 2- 6.

OFDMA divides the system bandwidth into many sub-channels then allocates a number of dedicated sub-channels to each user allowing up to N simultaneous multiuser transmissions. The number of sub-carriers per user can differ to porivde mulitrate transmission and diffrentianted Qos. Also Sub-carrier allocation to different users can be either ***adaptive*** tor ***fixed***.

Fixed sub-carrier allocation doesn't adapt to users' channel conditions and remain unchanged throughout the communication session which makes it simple to implement without incurring high overheard. The subcarriers allocated to each user in this method can either by adjacent which simplifies frequency and time synchronization on the expense of vulnerability to deep fading [27]or the sub-carriers assigned to each user can be separated by more than the coherent bandwidth of the channel to exploit maximum frequency diversity at the expense of a minimum separation between sub-carriers from different users requiring stringent cross-user synchronization to avoid ICI [28]

Adaptive sub-carrier allocation on the other hand dynamically allocates sub-carriers to users based on their channel condition in order to optimise performance criteria such as minimise the total transmit power ,maximise sum capacity [29].

Despite its many advantages, OFDMA suffers from two main challenges:

***Peak to Average Power Ratio (PAPR)**:* OFDM may exhibit high signal peak with respect to the average signal level due to the superposition of modulated symbols over many sub-carriers. Practical amplifiers in the transmitters have a limited amplitude range, in which they behave linearly. Also the power consumption of a power amplifier depends largely on the peak power than the average power [26]. PAPR can be reduced by: (a) coding over long time intervals which reduces the data throughput. (b) Clipping: The peak signal is clipped before transmission which although is simple to implement, leads to in-band distortion and out-of-band radiation problems. (c) Adding extra sub-carriers with zero power.

Time and Frequency Synchronization: OFDM is very sensitive to lack of time and frequency synchronization which leads to frequency and phase offset causing ICI and ISI [27]. Synchronization is especially critical for the uplink where data streams are transmitted from different users each with its own multipath channel and local oscillator. OFDMA synchronization consists of two stages: estimation and correction. The estimation stage is achieved either using periodic pilots embedded in users' data or by using virtual sub-carriers with no transmission which the BS monitors to insure that they always have zero-power [27]. After estimation stage, the BS feedbacks the time and frequency correction required by users. Time synchronization is usually done by adjusting the length of the cyclic prefix. For frequency synchronization, this is usually done by adjusting their voltage controlled oscillator (VCO).[27]

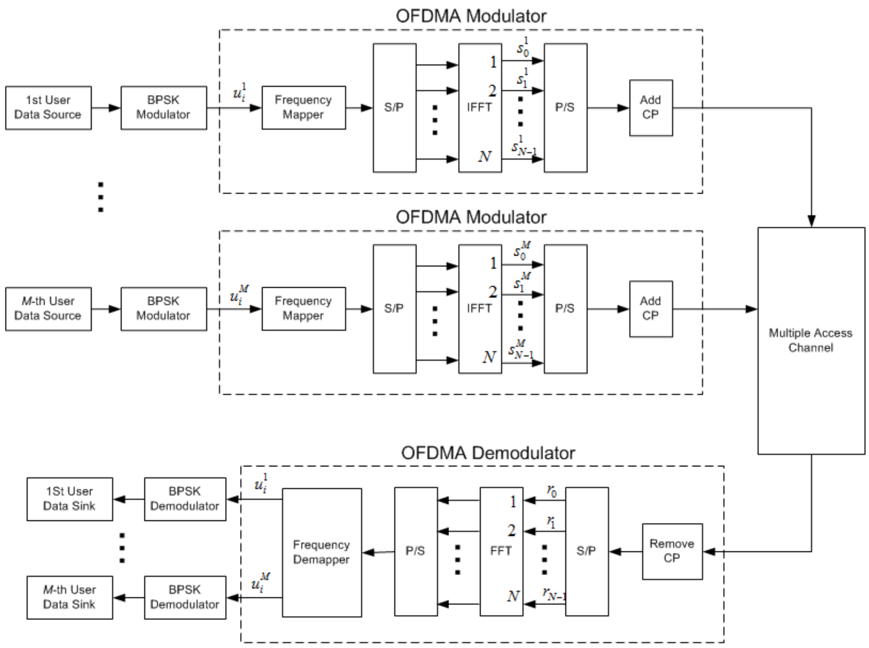


Figure 2- 6: Block diagram of a N-user BPSK OFDMA uplink system.

2.3.6 Multi-Carrier CDMA

Both CDMA and OFDM offer resilience against frequency selective fading in very different ways. CDMA exploits the multipath nature of frequency selective channel by employing Rake receivers which resolve and coherently combine the multipath components achieving path diversity. However at high data rates in the order of 100s Mbits/sec envisioned for 4G, The delay spread becomes excessive leading to severe ISI and code synchronization becomes quite challenging.

OFDM on the other hand transmits data in multiple overlapping narrowband subcarriers converting the frequency selective channel into several parallel flat fading channels. However, as the rate per sub-carrier increase, time and frequency synchronization becomes very difficult leading to frequency offset, and intolerable ICI. Hence combining CDMA with OFDM known as Multi-carrier CDMA [26][30] is beneficial for both systems as it can lower the symbol rate at each sub-carrier so that a longer symbol time is easier to synchronise and maintain frequency orthogonally.

Multi-carrier CDMA retains most advantages of both schemes such as the flat fading and high spectral efficiency properties of OFDM and the soft capacity, multipath diversity and the flexibility to the asynchronous nature of the multimedia traffic properties of CDMA. In addition MC-CDMA also simplifies sub-carrier selection since all the subcarriers are assigned to all users.

Multicarrier CDMA schemes can be classified into two main groups depending on whether spreading is performed in time or frequency domains. The first group referred to as *MC-CDMA* first spreads the serial data stream of each user by using a unique spreading code before modulating each sub-carrier with a single chip hence spreading the chips in the frequency domain. Therefore while in conventional DS-CDMA each user symbol is transmitted in the form of sequential chips, each of which is narrow in time and wide in bandwidth, In MC-CDMA due to the FFT transform, chips are not transmitted sequentially in time but in parallel over many subcarriers therefore chips are longer in time and narrower in bandwidth. The modulation and demodulation of MC-CDMA are performed using simple FFT and IFFT operators. The MC-CDMA not only mitigates the ISI but also achieves high degree of frequency diversity. MC-CDMA is usually used in the downlink therefore orthogonal Walsh-Hadamard codes are used to fully eliminate interference between users.

The second group of multi-carrier CDMA converts the data stream of each user into parallel data streams then spread each sub-stream in the time domain by multiplying it with a spreading code such as Walsh-Hadamard or PN sequences and then modulating them into sub-carriers. In fact each sub-carrier is a DS-CDMA system. Thus, single- and multiuser detection techniques known for DS-CDMA can be applied in each data stream over the sub-carriers. Depending on the frequency separation between sub-carriers this category can be divided into two schemes. If the frequency separation is equal to (1/ data symbol time) then the system is referred to ***Multi-tone CDMA*** (***MT-CDMA***). Otherwise if frequency separation is equal to (1/ chip time) then the scheme is referred to as ***Multicarrier DS-CDMA (MC-DS-CDMA)***. The MT-CDMA uses spreading codes in multiples of the number of subcarriers as compared to MC-DS CDMA. Hence while MC-DS-CDMA maintains them minimum frequency orthogonality between subcarriers while MT-CDMA, frequency separation between subcarriers no longer satisfies the orthogonality condition therefore longer spreading codes with length multiples to that of the number of subcarriers has to be used but that also enables MT-CDMA to accommodate more users than DS-MS-CDMA.

In all three schemes, all the sub-carriers are used by each user and the multiple access functionality is provided by CDMA. Figure 2- 7 demonstrates the time, frequency and code dimensions of MC-CDMA and MC-DS-CDMA techniques.

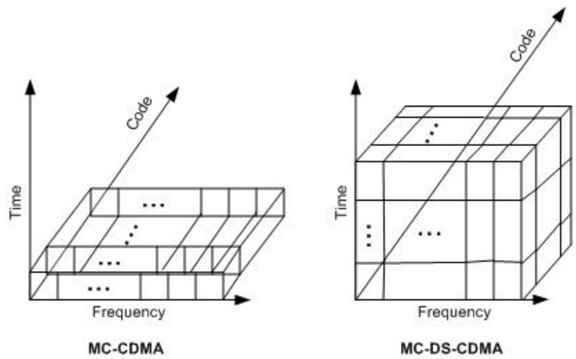


Figure 2- 7 : Time, frequency and code dimensions of MC-CDMA and MC-DS-CDMA.

2.3.7 Collaborative Coding Multiple Access (CCMA)

CCMA [32][33][34][35][36][37][39][40] is narrowband non-orthogonal MAS which allows several users to transmit simultaneously over a common channel without any subdivision in time, frequency, or code. Hence unlike CDMA, CCMA allows multiple access functionally without expanding the bandwidth of the transmitted signal. In CCMA, each user is provided with a unique codebook to insure that the sum transmission of users over a common channel form uniquely decodable codewords that can be jointly decoded at the receiver to unscramble individual users' data. These codebooks are chosen from a family of codes referred to as multiple access coding. The majority of these codes are constructed for the multiple access adder channel model (MAAC). Although these codes are mainly designed to guarantee unique decodablity, they can also have error and detection and correction capabilities. However short block codes with no error correction capability used in synchronous CCMA are shown to achieve better performance and are simpler to implement. A block diagram of M-user CCMA is shown in Figure 2-8 where M users transmit independent data over a common multiple access channel (MAC). Each user i, $1 \leqslant i \leqslant M$ is assigned a set of l_i codewords of length n bits chosen from a unique set of collaborative codes $C_i = \{c_{1i,} c_{2i,} \ldots, c_{l_i i\}}$. The data of each user is first encoded using its unique collaborative codebook then its mapped using a linear digital modulation scheme. The received signal is a composite codeword of length n bits formed from the superposition of consistent users' codewords. At the receiver joint ML joint detection and decoding is performed by calculating the squared Euclidian distance between the received composite codeword and all $\prod_{i=1}^{M} l_i$ allowable codeword combinations and choosing the one with smallest distance which is finally de-mapped to the corresponding data of each user. The total sum rate R_{sum} in bits per channel use for this coding scheme is given by:

$$R_{sum} = \sum_{l=1}^{M} \log_2 \frac{l_l}{n} \tag{2.5}$$

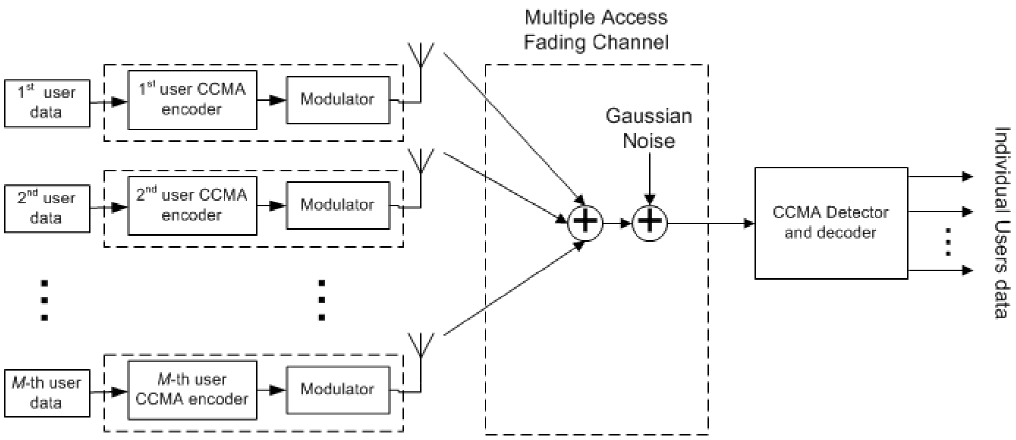


Figure 2- 8: Block diagram of a M-user CCMA system

Collaborative coding with a sum rate higher unity than that which can achieve a higher capacity than orthogonal MAS like TDMA and FDMA has been constructed for CCMA , for example the coding scheme proposed for two users in [32] can achieve a sum rate of 1.29 bits/channel use . Another coding scheme proposed in [33] for three users achieve a sum rate of 1.5 bits/channel use. However despite its high sum rate and non-orthogonal nature, the implementation of CCMA especially in wireless networks suffers from a number of important setbacks:

A. CCMA suffers from degradation in BER performance caused by the increase in the size of the composite symbol constellation formed from the linear addition of independent codewords over the channel.

B. Since coherent combining of signals over a baseband common channel is fairly straight forward, CCMA has been successfully employed in [40] on the downlink of CDMA to extend users capacity by allowing two users to share the same spreading sequence. However on the uplink side, when signals from multiple users are transmitted in fading environments, fading causes independent distortion and delay to users' signals making coherent combining and synchronization extremely challenging. Few works have been done to address this issue such as complex-valued CCMA (CV_CCMA) in [37] which uses joint channel estimation and detection in addition to spatial diversity to implement CCMA in flat fading channels. The minimum length of a codeword in CV_CMMA is *1+M* to guarantee that each codeword is unique and linearly independent however much longer codes are required to achieve a sum rate higher than unity. For example in the 2-user CV_CCMA using BPSK modulation , the length of the codeword needs to be increased to 5 in order to achieve a sum rate of 1.2 bit/channel use.

C. The minimum length of the codeword increases with the number of users leading to only a modest increase in sum rate on the expense of a significant drop in BER performance and an increase in the complexity of joint ML detection. Hence in reality the number of users that can be accommodated by CCMA is restricted to two or three users in most cases.

2.4 Multiple-Input Multiple-Output (MIMO) Communications

MIMO communications refers to a set of wireless communications schemes that exploit the spatial dimension through the use of multiple antennas at both communication ends. Provided that a rich scattering environment and enough separation between antenna-elements exist to allow for independent uncorrelated channels between any two pair of receive-transmit antennas, MIMO attains a linear increase in system capacity in the order of minimum number of received /transmit antennas $N_{min} = min(N_t, N_r)$ without any extra power or bandwidth [3][43][52]. The benefits of MIMO can be realised through spatial multiplexing which allows for the concurrent transmission over the same bandwidth of up to N_{min} independent data streams. MIMO can also be used to attain a reliable communication over fading channel through spatial diversity where a maximum diversity gain with an order of $N_t \times N_r$ can be achieved through space-time coding when a single data stream is transmitted. A combination of both spatial diversity and multiplexing gain can also be realized. MIMO was originally proposed and extensively studied for a single user scenario when a single transmitter/ receiver are both equipped with multiple antennas. However recent research shows that multiple users equipped with a one antenna can form a virtual multi-antenna user, hence extending MIMO to multiuser scenario. In the following sections we will provide an overview of both single user (SU) and multiple users (MU) MIMO and explain various linear and non-linear precoding and detection techniques used in MIMO.

2.4.1 Single-User MIMO (SU-MIMO)

SU-MIMO as the name suggests [3][41][42], involves a point to point transmission where a single transmitter equipped with N_t antennas transmit to a single receiver equipped with N_r antennas as shown in Figure 2- 9. Where the received signal **y** is given by

$$\begin{bmatrix} y_1 \\ \vdots \\ y_{N_r} \end{bmatrix} = \begin{bmatrix} h_{11} & \dots & h_{N_t 1} \\ \vdots & \ddots & \vdots \\ h_{1N_r} & \dots & h_{N_t N_r} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{N_r} \end{bmatrix} \Leftrightarrow \mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{2.6}$$

where $\mathbf{y} \in \mathcal{C}^{N_r \times 1}$ is the complex $m \times 1$ received signal vector , $\mathbf{b} = \begin{bmatrix} \hat{b}_1 & \cdots & \hat{b}_{N_t} \end{bmatrix}^T$ is $N_t \times 1$ data vector , $\mathbf{H} \in \mathcal{C}^{N_t \times N_r}$ is $N_t \times N_r$ complex channel matrix which assumed to be available at the receiver, $\mathbf{x} \in \mathcal{C}^{N_r \times 1}$ is $N_t \times 1$ complex transmitted symbol vector and $\mathbf{n} \in \mathcal{C}^{N_r \times 1}$ is $N_r \times 1$ vector of i.i.d complex AWGN with each element having σ^2 variance. Eq (2-34) is a linear set of equations with N_t variables and N_r equations. A solution for this equation exists as long as $N_r \geq N_t$ and $\boldsymbol{H}$ is linearly independent or has full algebraic rank.

In other words, the number of streams that can simultaneously transmitted using SU-MIMO is limited by the by $\min(N_t, N_r)$ and the availability of uncorrelated channels or the lack of dominant LOS. Sufficient separation between antennas is therefore essential to avoid fading correlation. At the BS antenna separation in the order of 10 wavelengths

(1.5m at 2GHz) is required; while more than half a wavelength at the mobile handset (7.5cm at 2GHz) is required [44] [45].

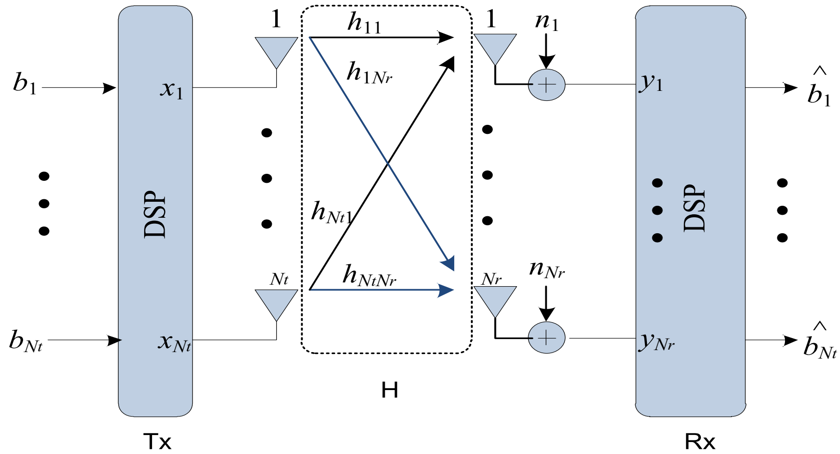


Figure 2- 9 Illustration of a SU-MIMO system

Depending on the average received SNR, SU-MIMO can be used either to increase the reliability of data transmission through maximising spatial diversity gain or increase the system capacity through spatial multiplexing. The first is usually referred to in literature as D-BLAST while the second is called V-BLAST architecture [3][55][56].

The essential difference between the two architectures lies in how data streams are encoded. ***In D-BLAST***, redundancy between the data streams is introduced through the use of specialized space-time block coding. In other words, the same data are transmitted from different spatial streams (antennas) after being encoded by a suitable space-time code and interleaved in time. High diversity gain attained by space-time coding allows the transmitter to use high order modulation and to reduce the redundancy from error reduction coding which leads to high spectral efficiency. The choice of different space time coding schemes offers a trade-off between diversity gain obtained and complexity of encoding and detection. For example space-time trellis code (STTC) can offer maximum diversity gain in order of $N_t \times N_r$. However decoding at the receiver requires the extensively complex multidimensional Viterbi algorithm. Space-time block codes (STBC) on the other hand attains only a diversity order equal to N_t but only requires simple ML detection [46][47].

In V-BLAST on the other hand, divides serial data streams into parallel data streams which are independently modulated and coded before being transmitted from different transmit antennas. However, the orthogonally among the transmitted streams totally depends on the fading correlation. Hence, the receiver can separate then decode and merge bit streams to the original transmitted data. An example of 2×2 spatial multiplexing scheme using V-BLAST is shown in Figure 2- 10**.** in addition to spatial multiplexing gain, V-BLAST can retain a diversity gain with an order up to N_r which varies according to which detection scheme is employed. For example, zero-forcing ZF has the lowest complexity of all schemes however it offers no diversity gain while the optimum ML detection can retain a diversity order equal to N_r on the expense of high computational complexity [49].

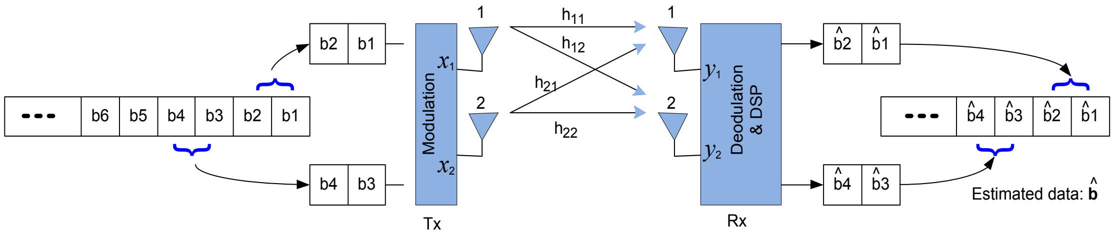


Figure 2- 10 an example of Spatial multiplexing in 2×2 SU-MIMO communication system

Optimal performance can be achieved by switching between the two schemes to achieve high spectral efficiency without comprising BER performance also referred to adaptive MIMO switch (AMS) [48]. A number of schemes have been proposed in literature to optimize this switching like [50]which is based on SNR information and time/frequency selectivity indicators and [51] which exploits the spatial selectivity of the channel.

2.4.2 Multiuser MIMO (MU-MIMO)

MU-MIMO allows multiple users equipped with a single or multiple antennas to communicate with a BS equipped with a multiple antenna by exploiting the spatial dimension between users who transmit simultaneously and over the same bandwidth [3][52][53]. MU-MIMO shares many of the principles and technologies used in SU-MIMO especially in uplink communication. However since users can't jointly decode their data streams in the downlink and are unaware of each other CSI, precoding at the BS becomes necessary to implement SM. In Figure 2- 11 an example of MU-MIMO system where N active users each equipped with u_k antennas chosen from a set of U users communicate with m antenna at the BS. At the uplink, the received signal $\mathbf{y}$ at the BS can be defined as

$$\mathbf{y} = \sum_{i=1}^{N} \mathbf{H}_i \mathbf{x}_i + \mathbf{n} \tag{2.7}$$

where $\mathbf{x}_i \in \mathcal{C}^{u_i \times 1}$ is transmitted signal vector of the i^{th} user. $\mathbf{H}_k \in \mathcal{C}^{m \times u_k}$ is complex Rayleigh flat fading channel matrix of the i^{th} user and assumed to be available at both communication ends, and $\mathbf{n} \in \mathcal{C}^{m \times 1}$ is vector of i.i.d complex AWGN with each element having variance of σ_n^2.

Each user is subject to an individual power constraint of P_i which implies $tr(\mathbf{Q}_i) \leq P_i\ ; i = 1, \dots, N$ where the transmit covariance matrix of the i^{th} user is defined to be $\mathbf{Q}_k \triangleq \mathbb{E}[\mathbf{x}_i \mathbf{x}_i^{\mathrm{H}}]$.

At the MU-MIMO, the received signal vector $\mathbf{y}_i \in \mathcal{C}^{u_k \times 1}$ at the i^{th} user's is given as

$$\mathbf{y}_i = \mathbf{H}_i^{\mathrm{T}} \mathbf{x} + \mathbf{n}_i \ ; \ i = 1, \dots, N \tag{2.8}$$

where $\mathbf{x} = \sum_{i=1}^{N} \mathbf{x}_i \in \mathcal{C}^{m \times 1}$ is the superposition of modulated users' symbols transmitted from BS . $\mathbf{H}_i \in \mathcal{C}^{m \times u_k}$ is complex Rayleigh flat fading downlink channel matrix for user i and assumed to be available at both communication ends, and $\mathbf{n} \in \mathcal{C}^{u_i \times 1}$ is vector of i.i.d complex AWGN at i^{th} user with each element having variance of σ_n^2 . The BS is under power constraint of P=$\sum_{i=1}^{N} P_i$ which is defined $tr(\mathbf{Q}) \leq P$ where $\mathbf{Q} \triangleq \mathbb{E}[\mathbf{v}\mathbf{v}^{\mathrm{H}}]$ is the transmit covariance matrix.

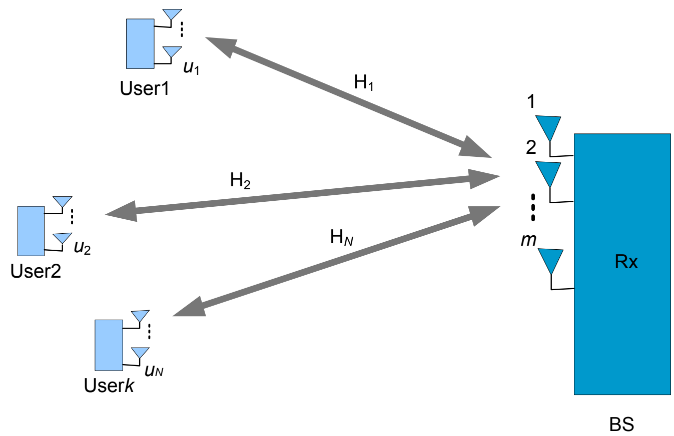


Figure 2- 11 An example of MU-MIMO system

MU-MIMO has many important advantages over SU-MIMO:

- It can provide multiple access gain allowing a number of users equal to that of the number of antennas at the BS to simultaneously access the network without consuming extra band or bandwidth.
- Geographical separation of users makes MU-MIMO less vulnerable to high channel correlation or LOS propagation than SU-MIMO.
- SM can be realised using a single-antenna mobile terminals which reduces the complexity, size, and cost of mobile terminals.

Unfortunately realizing the full benefits of MU-MIMO is constrained by a number of factors [64][65][66][67]

- Unlike SU-MIMO, MU-MIMO requires the availability of CSIT for the downlink; this places a significant burden on users which have to feedback their CSI to the BS, the overhead per user increases with the number of users which ultimately can reduce the capacity of the uplink and the number of users that can be served.

- MU-MIMO requires cross-layer design and cross-user optimisation to perform user scheduling, antenna selection, precoding and detection. These processes often involve exhaustive search and iterative process which increase exponentially with the number of users.

2.5 Conclusion

In chapter two, technical background and literature review of the related work to this thesis was provided. The fading channel principles including parameters, classifications and statistical distributions, estimation, and fading mitigation techniques were studied. Next the principles and features of the most important wireless multiple access techniques were presented and finally an overview of MIMO communication was presented.

3 Collaborative Modulation Multiple Access (CMMA)

3.1 Introduction

In this chapter, we propose a new non-orthogonal multiple access scheme that combines the functionalities of modulation and multiple access referred to as collaborative modulation multiple access (CMMA). It employs collaborative modulation precoding using unique modulation sets jointly designed at the base station to remove ambiguity and minimize interference. The received composite signal belongs to a higher constellation set with a rate equal to the sum rate of all users and with a structure that aims to maximize the minimum Euclidian distance. Users utilises a simple common pilot feedback to adjust their transmission adaptively to maintain the desired received composite signal. CMMA provides a practical solution for implementing the multiple access adder channel (MAAC) in fading environments. Our results show that CMMA can achieve a linear increase in link spectral efficiency on the expense of graceful degradation in BER performance. It can also be easily integrated with conventional multiple access techniques to extend user capacity and improve link utilization. Furthermore, a new CMMA antenna selection is proposed to improve performance while preserving the same simple precoding and without the need for pilot-aided channel estimation. Diversity gain is attained at any channel correlation and increase with transmit high correlation contrary to MIMO systems.

The remainder of this chapter is organized as follows. In section 3.2, we present related work and motivation. Then in Section 3.3, we introduce the principles and operation of CMMA. In Section 3.4 to 3.5, we describe system and signal model and how feedback and synchronizations is provided. This is followed in Section 3.6 by a description of how multiuser constellations are formed and their main properties. In Section 3.7, An CMMA antenna selection algorithm is proposed. We then analyse the BER of CMMA in Section 3.8 and present simulation results and discussion in section 3.9, and end with concluding notes.

3.2 Motivation and Related work

Multiple access schemes (MAS) perform a fundamental function in wireless networks, allowing users to share resources fairly while maximizing network throughput. Two major approaches to MAS exist. Orthogonal MAS aims to eliminate user interference by distributing finite resources such as time division multiple access (TDMA), frequency division multiple access (FDMA) and orthogonal frequency division multiple access (OFDMA) [31], or effectively the number of receive and transmit antennas and the availability of uncorrelated channels in space division multiple access (SDMA). However, these resources are limited in nature, which restricts cell ability to accommodate a big number of users with a high data rate. Non-orthogonal MAS (NOMAS) allow non-zero cross correlation among users. Examples of such schemes are random waveform code-division multiple-access (CDMA), trellis-coded multiple-access (TCMA) and interleave-division multiple-access (IDMA) [31]. Relaxing the orthogonality requirement for these schemes enables a soft limit on the number of users at the expense of increased interference and receiver complexity that limits the quality of service and user data rate - making the systems interference limited.

NOMAS can also be achieved using multiple access coding, also widely referred to as collaborative coding multiple access (CCMA) [34]. The majority of these codes are constructed for the multiple access adder channel model (MAAC). In CCMA, each user is provided with a unique codebook to insure that the sum transmission of users over a common channel form uniquely decodable codewords that can be jointly decoded at the receiver to unscramble individual user's data. Since Coherent combining of signals over a baseband common channel is fairly straight forward, CCMA has been successfully employed in [40] on the downlink of CDMA to extend users capacity by allowing two users to share the same spreading sequence. However on the uplink side, when signals from multiple users are transmitted in fading environments, fading causes independent distortion and delay to users' signals making coherent combining and synchronization extremely challenging. Few works has been done to address this issue such as complex-valued CCMA (CV_CCMA) in [37] which proposed joint channel estimation and detection as well as utilising receive spatial diversity to implement CCMA in flat fading channels.

NOMAS can also be realized without any form of coding by exploiting the spatial or/and temporal disparities in the received SNR of multiple users using superposition coding (SPC) [57][61][62]. SPC employs multistage detection technique referred to as successive interference cancellation (SIC) [62]. SPC with effective power control and scheduling has been proven to increase the system capacity and throughput when used in conjunction with other MAS [57][61] especially in the downlink of CDMA [57]. However, SIC error propagation and the requirement for large power separation has limited its application to only a handful of users. Signals from multiple users spatially multiplexed over rich fading channels can be separated by employing multiple receive antennas. Spatial multiplexing (SM) in multiple input multiple output (MIMO) systems offers a linear increase in system capacity without incurring additional resources in terms of power and bandwidth [63][52]. However, it has some fundamental limitations. Firstly, the number of users that can be simultaneously served is limited by the less number of transmit and receive antennas [63]. Secondly, the orthogonality among the transmitted streams depends on correlation among users' channels therefore high correlation due to insufficient antenna separation and/or poor scattering environment leads to a significant degradation in the sum rate capacity and bit error rate (BER) performance [64]. Thirdly, the amount of overhead increase with the number of users both in terms of pilots needed for channel estimation [68][69] and for user scheduling and precoding [65].

In this chapter, we propose a bandwidth efficient NOMAS called CMMA that utilises well known technologies like SPC, adaptive modulation, precoding, and joint maximum likelihood (ML) detection in an innovative manner. The novelty aspect of CMMA is the use of modulation to provide multiple access functionality and how it can integrate the above mentioned techniques together in a practical and low-overhead manner. The proposed scheme addresses many limitations of conventional NOMAS mentioned earlier and can be integrated within OMAS such as OFDMA. CMMA assigns users with unique modulation sets designed by the Base-station (BS) so that their sum transmission belongs to a higher constellation with full decodability. Users need to adjust the power and phase of their signal so that it is received according to users' assigned unique modulation sets. The main contributions of the paper are summarized below:

- A new model is proposed to exploit superposition coding by departing from user-specific power control and SIC receivers to a different approach that optimises power, phase, and/or constellation mapping using common feedback and collaborative precoding. CMMA offers higher capacity and can accommodate more users (even with equal power) than that of conventional SPC.
- CMMA maintains capacity and robust BER performance in highly correlated channels without the need for multiple receive antennas, channel state information (CSI) at the receiver or excessive feedback between the BS and individual users.
- A new simple uplink multiuser MIMO based on CMMA with antenna selection that maintains CMMA common feedback and simple precoding while achieving high diversity gain that is resilient to channel correlation and increases with high correlation. Furthermore, a low complexity iterative sphere decoding is designed to fully exploit the remaining receive antennas. This offers substantial performance improvement and is able to accommodate more users than the available number of receive antennas.
- A practical low-overhead scheme for coherent combining of multiple signals in fading channels essential for the implementation of joint ML detection and composite constellation design in SPC and in the multiple access adder channels.

3.3 Principles of CMMA

The main design philosophy for CMMA is the notion that users can share a common channel as long as any combination of their data combined over the channel produces a unique interference pattern that belongs to a valid composite constellation known at the receiver. Also the minimum separation between these unique interference patterns (composite constellation points) measured by the minimum distance (d_{min}) should be sufficient to mitigate noise and enable successful detection. In other words, CMMA combines signals from *N* different users each using a linear modulation set of size 2^{k_i} to form a composite signal that belongs to an M-QAM constellation *R* formed from the sum of all the possible mutation of signals from these *N* users. To ensure that the new composite signal is non-ambiguous, uniquely decodable, and has a data rate equal to the sum rate of all individual users, *R* must contain *M* unique constellation points given by

$$M = 2^{\sum_{i=1}^{N} k_i} \tag{3.1}$$

where k_i is the *ith* user number of bits per symbol. The composite constellation *R* can be written as:

$$R = U \times W \tag{3.2}$$

where *U* is a $M \times N$ matrix whose rows represent the possible combinations of *N* signals and *W* is a precoding complex matrix $1 \times N$ whose entries represent the power and phase of these *N* users' signals.

An important question remains, can a composite constellation *R* that satisfies Eq(1) be formed from any number of users. The answer is yes only if a precoding matrix *W* exists for any *N*. Note that for any value of *N*, *R* can take infinite number of choices. However, *U* always stays the same for a given user modulation set and has a row rank of *M/2* and a full column rank, hence there always exists a left inverse to *U* and any M-QAM constellation *R* can be constructed for any *N* users. Nevertheless, in practice the size of *R* increases with that of the number of users; hence as expected with M-QAM modulation, the BER performance degrades as the modulation order increases, however this is partially offset in CMMA by the coherent addition of users' signals which leads to a linear increase in average symbol power.

Now let's summarize the basic operation of CMMA systems:

The base station in cellular systems holds a lot of useful information about users in its cell (such as number of active users, their average channel gain, location and mobility) and conventionally, it is responsible for resource allocation. Furthermore, it is the sink for all uplink communications. Therefore, the task of designing the composite constellation and decoding table is better done at the BS.

So first, the BS station uses its knowledge of users 'average channel gain' to divide users into subgroups. A Monte-Carlo type simulation is used to calculate the average SNR and d_{min} corresponding to each possible formation and the one with the highest number of users and/or highest sum rate that satisfy a specific BER requirement is chosen.

The BS then assigns users with unique modulation sets and waiting periods to compensate for delay. Each user then waits for the common pilot to synchronize its transmission and extract CSI. Due to channel reciprocity and assuming channel coherent time is long enough for CSI to remain valid at the receiver. Precoding converts the fading channel into a Gaussian channel by averaging the transmit power around the mean channel gain over a suitable time-cycle. The aim is to find the maximum data rate that maintains fixed average transmit power and SNR at the receiver. This approach is similar to adaptive modulation where users vary their modulation and code rate according to channel conditions to maximise data rate [70]. But in CMMA, channel inversion rather than water filling is used to combine maximising rate with collaborative precoding.

Each user utilizes CSI to adjust the phase and power of its signal so that the received signal corresponds with the modulation set assigned by the BS. Users act independently unaware of channel correlation levels. Individual users act independently from each other and are unaware of how many users are simultaneously transmitting in their group or correlation levels between their channels, thus there are no requirements for any feedback between users in the group.

Then the BS station will simultaneously receive a combined signal corresponding to the sum transmission of all users. This signal will belong to the predesigned higher composite constellation *R*. Because the BS determines R, the receiver decodes users' signals simultaneously without CSI at the receiver (CSIR) and with a single RF circuit at the same complexity of a single user with the same modulation level. This is an advantage in over multiuser detection like SIC where the detection process has several serial stages equal to the number of users causing latency and unfairness due to error propagation.

3.4 An Illustrative Example of CMMA Operation

1. The BS uses its knowledge of users 'average channel gain, fading characteristics, and data rate requirement to divide active users within its cells into subgroups. A Monte-Carlo type simulation is used to calculate the average SNR and d_{min} corresponding to each possible group formation to identify the formation with the highest number of users and/or highest sum rate; where the composite group constellation at the resulting average SNR will satisfy a predefined BER performance. For example the optimum joint constellation for a group of two users each transmitting a QPSK signal will be achieved when the average power ratio between them is 0.25, so choosing one of users near the BS with strong channel and the other at the edge of the cell will be optimum.

2. The BS then assigns each user with a phase rotation/power control precoding parameters, modulation level to be used and the delay period from the recovering of the common pilot signal initial frame to compensate for different delays among users and synchronise their transmission.
3. Each user then listens to the common pilot channel to synchronize the start of its transmission and extract instant CSI information (channel gain and phase). Due to the of channel reciprocity in Time-division duplex systems and assuming that in slow fading the coherent time of the channel is long enough so this information will still be valid by the time the transmitted packets reach the receiver. The user then adjusts the phase and power of its transmitted signal according to the CSI so that its received signal at the BS station will be the same as the precoding parameters set by the BS. For example , if the instant channel gain is 0.5 and the phase induced by the channel is -60 ,let's assume that the predefined power/phase precoding parameters set by the BS to this user is 0.75/45 and the user uses BPSK then , the corresponding constellation set for this user will be 0.75/45 ,0.75/-135. Thus Taking account of the CSI, this user need to transmit at (0.75/0.5=1.5)/(-60+45=-15) , (0.75/0.5=1.5)/(-60-135=-195) .
4. Finally the BS receives simultaneously a combined signal corresponding to the sum of transmission of all users; this signal will correspond to a higher composite constellation (16-QAM rectangular constellation in our example) which the BS will decode as if it belongs to a single user.

3.5 System Model

As shown in Figure 3- 1, we consider the uplink of a cellular system consisting of *N* single-antenna users transmitting to a single-antenna BS.

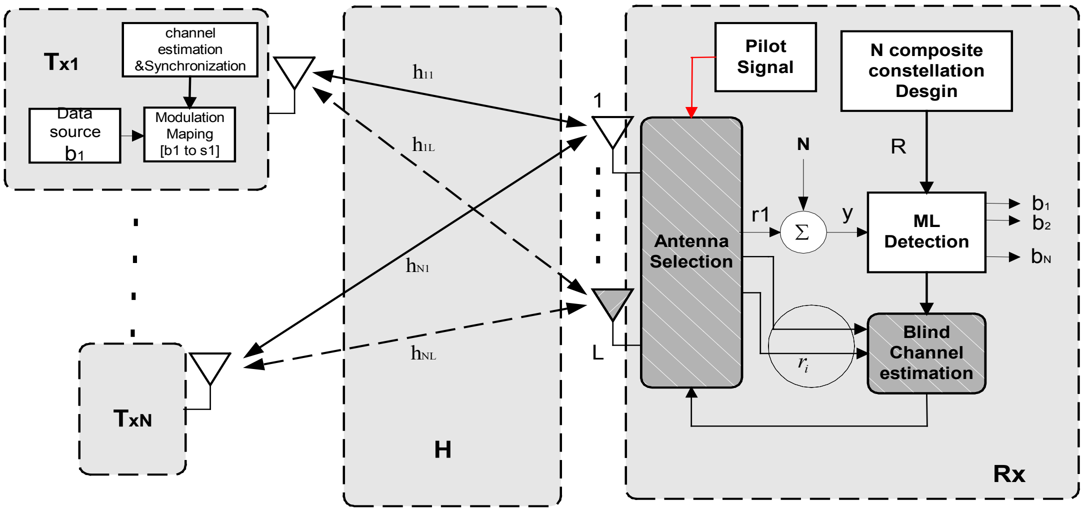


Figure 3- 1 System architecture of a CMMA system with *N* users. The two headed arrows refer to data traffic from users to BS and for common pilot from BS to users where both are sent through the same channel. The highlighted boxes at the receiver side are only needed for CMMA with antenna selection system.

3.5.1 Channel Model

Typically the BS is notably elevated relative to users which are located in a rich scattering environment causing their channels to experience Rayleigh multipath fading. This channel is modelled as a complex Gaussian-distributed with zero-mean and unit variance. We will generate *N* uncorrelated fading channels with Rayleigh distribution using improved sum of sinusoids [78] where a complex Gaussian noise is generated by finite sum of weighted sinusoids. The baseband representation of H_i for user *i* is:

$$H_i(t) = H_{xi}(t) + jH_{yi}(t) = \alpha_i(t)e^{-j\,\emptyset_i(t)} \tag{3.3}$$

where $\alpha_i(t), \emptyset_i(t)$ are respectively the fading amplitude and phase of user *i* channel at *t*. $H_{xi}(t)$ and $H_{yi}(t)$ are in-phase and quadrature samples of zero mean Gaussian random processes with σ_o^2 variance given by :

$$H_{xi}(t) = \sqrt{\frac{2}{G}}\sum_{i=1}^{G} \cos\left(w_d t\cos(\beta_i) + \psi_i\right) \tag{3.4}$$

$$H_{yi}(t) = \sqrt{\frac{2}{G}} \sum_{i=1}^{G} \cos\left(w_d t \sin(\beta_i) + \varphi_i\right) \tag{3.5}$$

$$\beta_i = \frac{2\pi i - \pi + \theta_i}{4G} \tag{3.6}$$

where G is the number of sinusoids, w_d is the angular Doppler frequency.

φ_i and ψ_i are the wave initial phase related to the quadrature components and are statistically independent and uniformly distributed on $[-\pi, \pi]$, $\forall i \in \{1,\ldots,G\}$.

The mean channel gain for a user i over a period of time T is defined as

$$\overline{H_{iT}} = \sqrt{\frac{1}{T} \sum_{t=0}^{t=T} \left|\alpha_i(t)^2\right|} \tag{3.7}$$

3.5.2 Signal model

The baseband presentation of transmitted signal from user i at time instant t is:

$$s_i(t) = \sqrt{P_i(t)} e^{-j\theta_i(t)} c_i(t) \tag{3.8}$$

where $c_i(t)$ is a complex signal representing data symbol chosen from a set of 2^{k_i}-QAM constellation $C_i = [c_1, c_2, \ldots, c_{2^{k_i}}]$ where k_i is the number of bit/symbol for user i and the average constellation power is fixed to one, and $P_i(t)$ and $\theta_i(t)$ are respectively the power weight and phase shift of user i at time instant t to ensure that its received signal corresponds to the precoding indexes G_i, ϑ_i assigned by the BS at the beginning of the data session. $P_i(t)$ and $\theta_i(t)$ are defined as

$$P_i(t) = \begin{cases} \left[\frac{G_i}{\alpha_i(t)}\right]^2, & \alpha_i(t) < \mu \\ 0, & \alpha_i(t) \geq \mu \end{cases} \tag{3.9}$$

$$\theta_i(t) = v_i - \phi_i(t) \tag{3.10}$$

G_i is chosen by the BS not to exceed H_{iT} to ensure that precoding is sustainable and does not deplete user's battery therefore.

$$G_i \leq \frac{1}{H_{\iota T}} \rightarrow \frac{1}{T}\sum_{t=0}^{T}\sqrt{P_i(t)} \leq \frac{1}{H_{\iota T}} \tag{3.11}$$

The channel inversion performed by precoder provide a simple way to compensate for fading locally while minimizing interference enabling multiuser modulation (MU) using only a small common periodic feedback. However, to ensure that the majority of power is not spent only during deep fading which may exceed peak power permitted in the transmitter, we consider a truncated inversion that only compensates for fading above a certain cut-off fade μ defined by the user's peak power. Although waterfilling is proven to be the optimum adaptive modulation strategy in point to point single user systems; it is very difficult to apply for a multiuser case as considered in CMMA. Because this will require EITHER users to change their constellations independently which may result in ambiguous composite constellation for the group in addition to the need for CSI at the BS, OR the BS has to adaptively update the design of the composite constellation based on CSIs from all users then feedback changes to users which will result in an excessive overhead and delay.

The baseband representation of the received signal of all users at the BS at time instant *t* is

$$y(t) = r(t) + n(t) = \sum_{i=1}^{N} h_i(t)s_i(t) + n(t) \tag{3.12}$$

where, $h_i(t)$ represents the complex channel gain of user *i* at time *t*, *n(t)* represents white Gaussian noise vector at *t* and is modelled as complex Gaussian-distributed signal with zero mean and variance σ_n^2 and *r(t)* is the composite received signal at time *t*. In order for *r(t)* to be decodable, the BS should choose a subset *N* from total active users in the cell to form a combined constellation *R* that satisfies the following conditions:

$$\text{if } r_i \,\&\, r_j \in R \text{ and } i \neq j \text{ then } r_i \neq r_j . \tag{3.13}$$

$$\frac{1}{4}d_{\min}^2 \geq \sigma_n^2 \qquad (3.14)$$

3.5.3 Joint Maximum Likelihood Detection

Since fading is compensated in the transmitter side, the detection process is reduced to that of ML detection in AWGN channels. Furthermore, as the received constellation R is designed by the BS, ML detector uses R as a reference to compare with the received signal $y(t)$ with no CSIR required. The detector performs an exhaustive search between the received signal $y(t)$ and all constellation points in R to find the constellation point which is the closest to $y(t)$ in terms of Euclidean distance as follows

$$\hat{r} = \arg\{\min_{y_i}(\| R - y(t) \|_2)\} \qquad (3.15)$$

The number of calculations needed to perform joint ML detection for a group of N users each transmitting with a modulation level 2^{k_i} is $\prod_N 2^{k_i}$. This is the same detection complexity for a single user (SU) QAM using the same order constellation as that of MU-QAM. However, various schemes proposed to reduce the complexity of ML in point to point communication or for MIMO like sphere decoding [71] and multistage ML detection [72] can greatly reduce the complexity of ML for CMMA with a very modest reduction in BER performance. For example, for 6x6 MIMO system employing QPSK modulation, [72] can achieve the BER performance close to that of the ML scheme with only 0.01 times complexity of the ML.

3.6 Common Pilot Channel (CPC)

Users acquire CSI from pilots sent from the BS to perform collaborative precoding over B symbols. We assume the channels are reciprocal which is widely accepted in TDD systems where uplink and downlink share a common frequency [68][69]. we consider a three-stage TDD transmission scheme, in which the total duration for transmission of B symbols is less than the minimum coherent time of users' channels to ensure that channel remain constant over B symbols (usually B ranges from 10s to 100s of symbols depending on channel fading statistics [68]) as shown in figure 3.2. In the first stage, the BS broadcasts a common pilot with power $\mathcal{P}r$ to users which estimate their channels using LMMSE estimator. Let's denote the channel estimates and the estimation errors by $\hat{h}$ and $\tilde{h}$ respectively where $h = \hat{h} + \tilde{h}$. $\tilde{h}$ is modelled as a random variable with complex Gaussian distribution with zero mean and Variance $\sigma_e^2 = 1/(1 + \mathcal{P}r/N_o)$. In the second stage, users use $\hat{h}$ to precode their data, we assume that the duration of the precoding stage is negligible. Finally, users transmit B-1 symbols. The channel estimation accuracy depends on the effective SNR during the estimation period. At low SNR, the estimation quality is poor which leads to degradation in channel capacity [68]. Therefore, the number of pilots, their placement, and how much power is allocated to them should be optimised to sustain a high SNR. In systems with multiple transmitters, the orthogonality of pilots to symbols from other users must be considered as well. Bearing in mind that users are hand-held devices with low gain antennas and limited batteries, while BS is connected to the grid (the downlink power is usually 20 dB higher than that of the uplink in Mobile Wimax IEEE 802.16e), therefore our reversed pilot can be transmitted with more power than that of forward link pilots achieving higher SNR with lower number of pilots. Not only accurate estimation due to higher power is achieved through reversed training but also 20-25% of total transmit power typically spent on training on the uplink of MIMO systems [69] can be reused for data transmission. The number of required pilots in CMMA is independent of the number of users, since pilots are broadcasted to users allowing more data to be transmitted each frame, while with forward training the minimum number of pilots is equal to the number of users in high SNR and when the power of data and pilots symbols are allowed to be different, while in low SNR and when the power of pilots and data is the same, pilots/data ratio can jump to 50% of transmitted symbols [16-17].

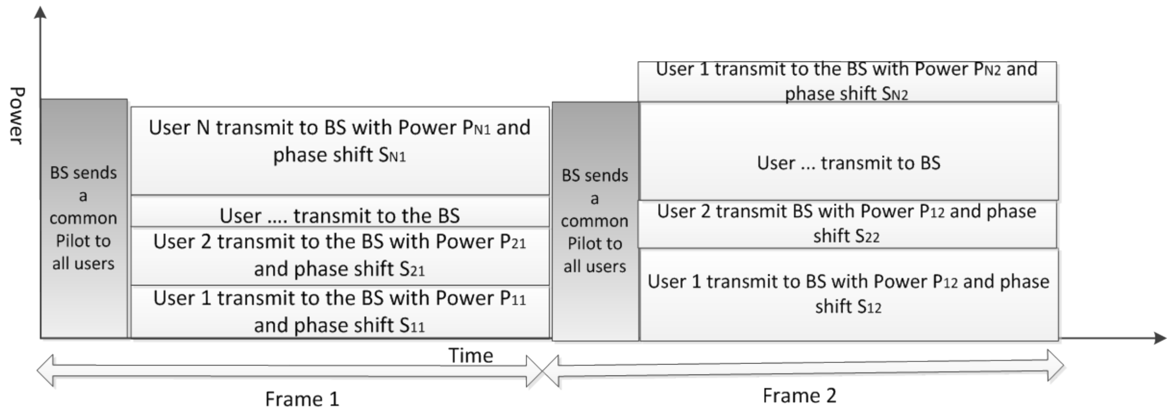


Figure 3- 2 Frame structure of a CMMA system with N users. The power and phase shift of users change every frame according to their instantaneous channel condition obtained from the common pilot.

The accuracy of channel estimation and hence precoding and detection is limited by two factors. Firstly, the accuracy of CSI obtained from the common pilot (CP) by the users and secondly the validity of the estimation at the BS. The first requirement can be addressed by increasing the power of the CP to guarantee that it is received at high SNR. The second requirement however requires a fairly accurate estimation of the coherent time (CT) of the channel and adjusting the size of frame accordingly. The channel's CT is directly and closely related with the relative speed between communication ends. This speed can be measured at the users for example by tracking the Doppler shift of one of the control channels transmitted from the BS and then feeding a quantized value to the BS whenever a significant change in coherent time occurs. The BS then can use this speed to estimate the coherent time of the frequency channel used by users and adjust its frame size to be at least twice that of the shortest coherent time between users' channels and the BS. It is also quite important to allocate users with similar level of mobility to the same group. Finally, while the use of pilots to obtain CSI is well used and studied technique, CMMA's common pilot design is different than conventional piloting schemes in several ways: a) our pilot is common to all users, unlike user-specific power control used in conventional SPC. b) the common pilot is not only used for channel estimation but also to achieve and maintain synchronization and as a control flag informing users when to send their next burst of data.

3.7 Synchronization in CMMA

Synchronization is essential to ensure that signals arrive simultaneously to form the designed composite signal and enable joint detection. Therefore, users should take into account the relative delay between them and adjust their transmission accordingly. Most synchronization schemes are based on an initial acquisition of reference time between the BS and users followed by a closed-loop tracking control procedure for maintaining synchronisation [73][74]. For CMMA, users transmit in flat fading environment, i.e. their respective signals arrive by a single resolvable path. The delays between arriving paths are considered independent and identically distributed. As part of the communication session setup, the BS broadcasts synchronization request (syn-r) to users, upon receiving the syn-r, each user waits for a predefined time before transmitting a reply to the BS. The BS then measures the delay and assigns each user with an initial transmit delay (ITD) which is defined as the time period that a user has to wait after it receives the common pilot before it starts transmitting. This value is initial due to delay changes caused by user mobility and/or channel variations. However, even though the relative delay between users should be calculated centrally by the BS, any delay changes can be measured locally. Since the BS broadcasts pilots at fixed intervals, users calculate delay changes by measuring time differences between consecutive pilots and adjust their ITDs accordingly.

3.8 CMMA Composite Constellation Design

For a given power constraints on average transmit power per user, the main objective of composite constellation design is to maximise the number of users who can simultaneously access the network while maintaining a minimum QOS or BER performance.

CMMA assumes a fixed design for the composite constellation throughout the communication session in order to eliminate the need for the two-way feedback required for coherent detection and the updating of composite constellation design that may seriously reduce the net data rate of the system. In the following sections a step by step guide for the design of composite constellation is provided.

3.8.1 Calculation of the average received power per user

Since users perform a truncated channel inversion to maintain a fixed received power of their assigned modulation set, the first task required in constellation design is to calculate a sustainable level of average received power that maintains the users' transmit power constraint. This level corresponds to the average channel gain or path loss which is determined by the location of the user, the distance between the user and the BS, and the geometry of the path profile between that user and the BS. The average path loss of a mobile user is proportional to $G_A/{d_i}^{\vartheta}$ where d_i is the distance between that user and the BS, G_A captures the effects of antenna gain and carrier wavelength, and ϑ is a constant whose measured value typically lies in the range $3 > \vartheta > 5$ [79].

In reality the location of the mobile user is available at the BS by measuring the difference in times of arrival (round trip time), angle of arrival, and received power between that mobile user and a number of nearby BSs. Alternatively, a mobile user equipped with a GPS receiver can locally calculate its location and then forward it to the BS [80]. Once the location of that user is obtained, field measurement stored at the BS can be used to obtain the average channel gain associated with that location.

3.8.2 Minimum distance selection criteria based on BER performance

The size of the composite constellation or the number of users that can be multiplexed within a single constellation is limited by the minimum QOS or BER that should be maintained for all constituent users who form the composite constellation.

The minimum SNR ($\lambda_{min,M}$) required for a QAM modulation with rate M bits/channel use transmitting over a bandwidth W to maintain a specified bit error rate BER under channel inversion adaptation policy can be obtained by modifying Eq. 26 in [81] and is given by

$$\lambda_{min,M} = \frac{2}{3}\left[1 - 2^{\frac{M}{W}}\right]\ln(5BER) \tag{3.16}$$

The mapping (structure) of the composite QAM constellation is often irregular and varies considerably depending on the power correlation between constituent users. However, regardless of the structure of the resulting QAM constellation, the BER performance of any QAM constellation depends primarily on the minimum Euclidian distance (d_{min}) between any two constellation points. Therefore, the effective SNR $\lambda_{eff,M}$ of a composite QAM constellation with rate M is equivalent to that of a rectangular QAM constellation with the same rate and minimum distance and is given by

$$\lambda_{eff,M} = \begin{cases} \sum_{j=1}^{j=(M)/2} 4^{j-1} d_{min,i}^2 \Big/ 2\sigma_n^2 & even\ M \\ (1 + \sum_{j=1}^{j=(M-1)/2} 4^{j}) d_{min,i}^2 \Big/ 4\sigma_n^2 & odd\ M \end{cases} \tag{3.17}$$

Equation 3.17 was obtained by calculating the average symbol power derived in relation to minimum distance of a regular rectangular QAM constellation with size of 2^N and a minimum distance equal to d_{min}.

In summary, in order to maintain a minimum BER for all constituent users whose signals are combined to form a composite QAM constellation with rate M, the effective SNR $\lambda_{eff,M}$ of that constellation should fulfil the following condition:

$$\lambda_{eff,M} \geq \lambda_{min,M} \tag{3.18}$$

3.8.3 Initial rate allocation per user

The average received powers for user i is $\overline{H_i}^2 P_i$ where $\overline{H_i}$, P_i respectively are the average channel gain and average transmit power for user *i*.

Hence, according to Shannon capacity, the maximum rate ($\mathcal{R}_{max}$) that can be realized from the superposition of *N* users is

$$\mathcal{R}_{max} = log_2\left[1 + \sum_{i=1}^{N} \overline{H_i}^2 P_i/\sigma_n^2\right] \tag{3.19}$$

It follows that individual rates $k_i, i = \{1, \dots, N\}$ assigned to consistent users should fulfil the following two conditions:

$$\mathcal{R}_{max} \geq \sum_{i=1}^{N} k_i \tag{3.20}$$

$$k_i \leq \log_2\left[1 + \overline{H_i}^2 P/\sigma_{n\,i}^2\right] \tag{3.21}$$

Equations (3.20) and (3.21) show that although CMMA is flexible with regards to allocating users with different rates, allocating high rate to users with a strong channel (closer to the BS) will reduce the rate that can be allocated to other users and ultimately reduce the number of users that be served within a single CMMA group.

3.8.4 Multi-stage successive composite QAM constellation design algorithm

In order to simplify the design of composite constellation, we propose a *N-1* stage composite constellation design where a single user at each stage is added to the composite constellation formed from the superposition of all users in the preceding stages. A step by step summary is shown below.

1) Sort all active users in the cell in a descending manner according to their average received power. This sorting is optimal as the effect of phase optimization between users on the d_{min} of their composite constellation becomes more critical as the power differences between the users gets smaller.

2) Assign users 1 and 2 respectively with modulation sets C_1, C_2 of size $2^{k_1}, 2^{k_2}$ and an average symbol power of $\overline{H_1}^2 P_1, \overline{H_2^2} P_2$ where $k_{1,} k_{2,}$ are chosen to satisfy the conditions in Eq. (3.20) and (3.21).

3) Depending on the power ratio between users 1 and 2, the power ratio between them $\rho_{12} = \overline{H_1^2} P_1 / \overline{H_2^2} P_2$ and the size of constellation sets used, find the optimum phase rotation for C_2 to maximize the Euclidian minimum distance $d_{min,1}$ of stage one composite constellation R_1 of size $2^{k_1+k_2}$ formed from the superposition of all possible combinations of C_1, C_2.

4) Assign user 3 with modulation set $C_3 = [c_{31}, c_{32}, \dots, c_{32^{k_3}}]$ of size $2^{k_3}$and an average symbol power of $\overline{H_3^2} P_3$, find the optimum phase rotation of C_3 that maximize the minimum distance $d_{min,2}$ of stage two composite constellation R_2 of size $2^{k_1+k_2+k_3}$ formed from the superposition of all possible combinations of R_1 and C_3.

5) Repeat step 4 for all the remaining users as long as the effective SNR of the resulting composite constellation at the output of each stage satisfies the minimum QoS criteria set in Eq. (3.18).

6) If the effective SNR of the resulting composite constellation R_j at the output of stage *j* doesn't satisfy the QoS criteria in Eq. (13) then skip user *j+1* and repeat step 4 for user *j+2* and composite constellation R_{i-1}.

Finding the optimum phase rotation at each stage can be performed using exhaustive search over a range of phases $[0{-}1/2\varphi_{j,min}]$ where $\varphi_{j,min}$ represents the minimum phase separation between any two constellation points that belongs to the composite constellation formed at the preceding stage.

This optimum phase rotation depends on two factors: the modulation set assigned to each user and the power ratio between users' signals. Therefore, an offline exhaustive search can be performed for different number of users with different rates and power distribution to find the optimum phase and d_{min}associated with each possibility and a look-up table can then be stored at the BS to reduce complexity and enable a quick phase optimization.

3.8.5 Design Consideration

To show the importance of phase rotation between users' constellations, Figure 3- 2 shows the minimum distance of composite constellation vs. phase rotation of individual constellations for two users employing QPSK with different power correlation and with total transmit power equal to two in all three scenarios. In all three manifestations of power correlation between the two constellations, the minimum distance of the composite constellation varies greatly depending on the value of phase rotation. Even when the power separation between users are equal to 6dB, the square minimum distance of the resulting 16-QAM constellation can vary by up to 9 dB depending on the value of phase rotation. Further in case of equal power between the two QPSK constellation, the d_{min} can fall to zero causing ambiguity and making detection impossible at any SNR value.

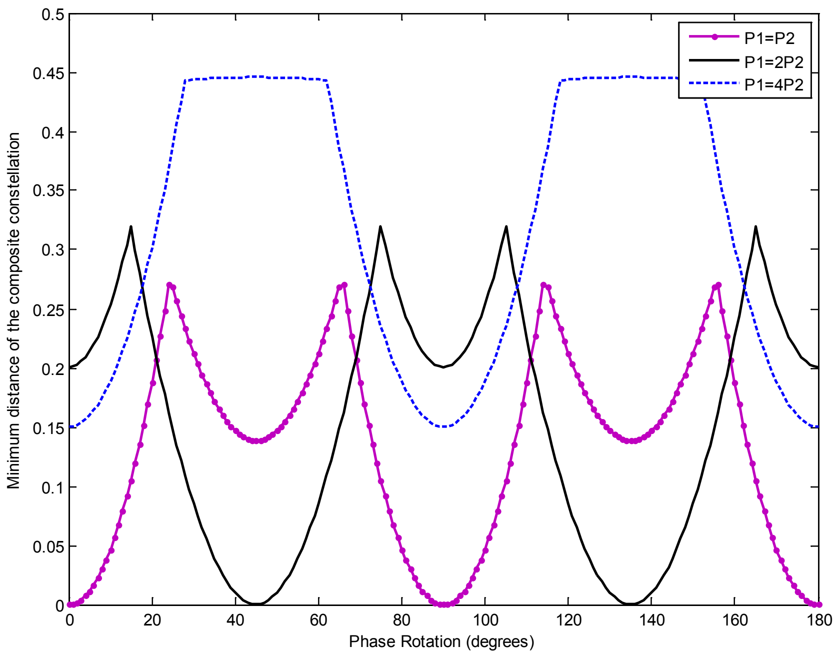


Figure 3- 3 Minimum distance of composite constellation vs. phase rotation of individual constellations for 2-users employing QPSK with different power correlation and with total transmit power equal to 2

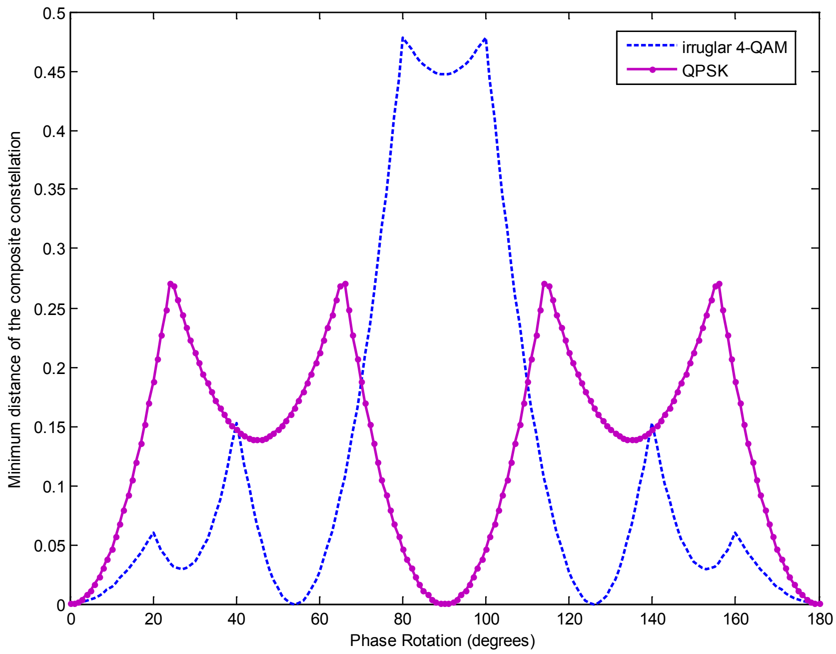


Figure 3- 4 Minimum distance of composite constellation vs. phase rotation of individual constellations for 2-users with equal power employing (a) QPSK and (b) 4-QAM {0°,180°,54°,234°} with total transmit power equal to 2 and equal symbol power of 1 for all symbol

With the right phase rotation, users with any power allocation can be combined to form non-ambiguous composite constellations. However, when the choice of users' constellations is confined to regular constellation sets like QPSK, the resulting composite constellation in most cases have irregular structure and suboptimal BER performance compared with rectangular constellation with the same average power and constellation size. For example, two regular QPSK with equal power and phase rotation of 30 degrees yields the best possible performance for equal power distribution as shown in Figure 3- 3. However, the d_{min} of resulting composite constellation shown in Fig 3.4 is 18% lower than that of rectangular 16-QAM which translates into a 3dB loss. This significant drop in performance can be avoided by replacing regular QPSK with irregular 4-QAM constellations with equal power and phase allocation {0°, 180°, 54°, 234°}. Even though this 4-QAM constellation are suboptimal in terms of minimum distance when users transmit orthogonally, combining these two constellations together with a phase rotation of 90° yields a 16-QAM regular constellation as shown in Figure 3- 5 which is easier to detect and has better Performance.

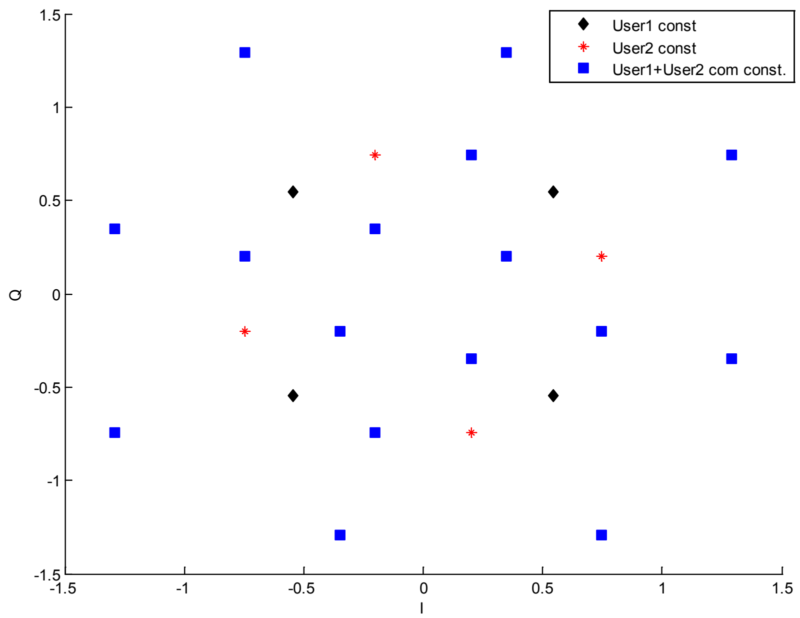


Figure 3- 5 16-QAM Composite constellation formed from the superposition two users with equal power employing regular QPSK constellation with average symbol power equal to 1

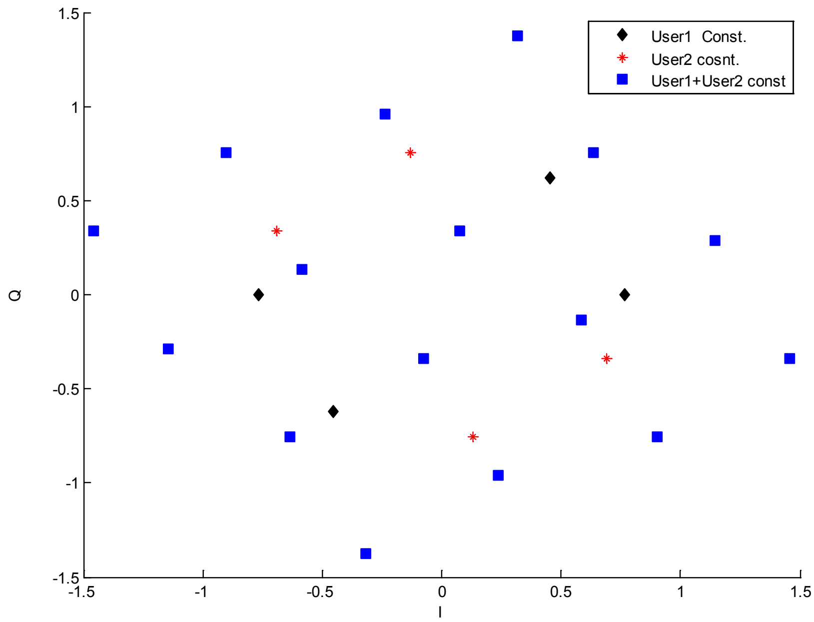


Figure 3- 6 16-QAM Composite constellation formed from the superposition of two users with equal power employing 4-QAM {0o,180o,54o,234o} with total transmit power equal to 2 and equal symbol power of 1 for all symbols

It is worth noting that 16-QAM regular constellation shown in Figure 3- 6 can also be formed from two QPSK users with power allocation ($P_1 = 4P_2$) and zero phase rotation, or from one QPSK user and two BPSK users with power allocation ($P_1 = 8P_2, P_3 = P_2$) and phase rotation of {0^o,0^o,90^o}, or from a 8-QAM and BPSK user with power allocation (P_1

$=5P_2$) and phase rotation 135°. Since composite constellations can be formed from users with different modulation levels, CMMA provides differential user treatment to adapt to channel quality, required data rate and QoS.

The d_{min} of composite constellation formed from N users' signals, is equal or less than that of any composite constellation formed from any subgroup of $N_1 \leq N$ constituent users. Hence, if one or more users leave the group or temporarily stop transmitting during deep fading, the composite constellation formed from the remaining N_1 remains non-ambiguous and maintains at least the same QoS compared with that of N users. Also, adding a new user to a group of N users can by achieved by optimising the existing composite constellation with that of the new user without the need for changing the unique modulation sets assigned to existing users. Hence the multi-stage composite design can allow the BS to add or remove users without affecting other active users. While it is possible to add users in this way while maintaining non-ambiguous composite constellations; all users suffer some degradation in their BER performance compared with the case before adding the new user. Also, while this method of adding users requires very small feedback involving only the new user, it might not always result in the best possible new composite constellation. Therefore it can be a trade-off between complexity and performance.

3.9 CMMA with Selective Diversity

3.9.1 Principle

With a single receive antenna, precoding can always fix the received constellation regardless of channel correlation. Therefore, users' precoding indexes remain unchanged during the communication session and only a common pilot feedback is required. However with multiple receive antennas, users experience multiple channels with random correlations - hence they are unable to fix the composite constellation at each receive antenna which varies in structure and $d_{\min}$ according to the random phase and gain channel correlation. To optimise the d_{min} across receive antennas, individual precoders now need to be aware not only of CSIT at their users but also of the transmit channel correlations across all users as in [64]. Also, the variation in constellation structures makes it necessary to have CSIR for detection. The diversity gain (DG) therefore comes at the expense of substantial increases in complexity, overheads, and requires two-way feedback. These reasons make selection diversity where only a single antenna is chosen from a group of L antennas, an attractive choice to achieve DG. However, conventional selective combining (SC) isn't optimal for CMMA. Since unlike SU transmission where the received constellations only change in intensity but never in structure among diversity branches, our received signal is composite consisting of N signals transmitted over independent fading channels per receive antenna causing both the intensity and structure of the received constellation to vary. In addition, one user may suffer deep fading in one antenna while the other suffers on another. If one of these users is much stronger, conventional SC favours this user which lead to unfairness. For these reasons designing an antenna selection algorithm should optimise overall group performance to provide fairness among users with different power and channel conditions.

We propose an effective selection algorithm that satisfies these conditions while preserving the structure, complexity, and overhead of CMMA. Our selection process consists of two stages. First, each receive antenna j calculates the total power $P_{tot,j}$ required by users to transmit their composite signal

$$P_{tot,j}(t) = \sum_{i=1}^{N} \frac{P_{ij}(t)}{\left|h_{ij}(t)^2\right|} \tag{3.22}$$

where $P_{ij}(t)$ *and* h_{ij} are the *ith* user power needed for precoding and the complex channel gain at *jth* receive antenna, respectively. Then the BS selects the antenna s that requires the least total transmit power. The total transmit power at the selected antenna s is given by:

$$P_{tot,s}(t) = arg \min_{j=1 \to L} \{P_{tot,j}(t)\} \quad (3.23)$$

By reducing the instantaneous transmit power, the average received power increases enabling composite constellations with higher d_{min}. Furthermore, the probability that users will suffer fading levels below μ is reduced, increasing system capacity for truncated channel inversion. To guarantee fairness when users have different power allocation, quantile normalization is employed.

3.9.2 Selection evaluation through blind channel estimation

The BS tracks changes in channel conditions to ensure that the best antenna is always selected. This is carried out by using the detected data from the output of the selected antenna s as a training sequence to estimate the channel gains for the other L-1 antennas. Since the same channel estimation process is performed at each receive antenna, we only need to consider estimation at one receive antenna. The received signal at the receive antenna j at time t is

$$y_j(t) = \sum_{i=1}^{N} g_{ij}(t)c_i(t) + n_j(t) \quad (3.24)$$

where $g_{ij}$is the channel gain between user i and antenna j weighted by the power and phase adjustments required for the selected antenna s given by

$$g_{ij}(t) = h_{ij}\sqrt{P_{is}(t)}e^{-j\theta_{is}(t)} \quad (3.25)$$

where $P_{is}(t)$ and $\theta_{is}(t)$ are respectively the power weight and phase shift of user i at time instant t to ensure that its received signal at the selected antenna s corresponds to the precoding indexes G_i and ϑ_i assigned by the BS. We assume the channel h_{ij} remains constant over a period of B symbols.

The joint estimation problem is to extract individual users' channel gains h_{ij} from the received composite signal y. To enable joint channel estimation, a subgroup of symbols B_p must be chosen from the available B symbols to satisfy the following condition: the cross correlation of the individual user's data sequence formed from these B_p symbols is zero or low. Sequences with such properties are widely used for CDMA like pseudorandom binary sequences (PRBS). Since $N \leq B_p \ll B$ therefore there is high possibility of finding such sequences within B. Let's state Y_P as $B_P \times 1$ matrix representing the received composite signal of B_p disjoint symbols chosen from a block of B symbols

$$Y_p = C_p g_p + n_p \tag{3.26}$$

where g_p is $N \times B_p$ matrix defined as $g_p = \begin{bmatrix} g_{p,1} \\ \vdots \\ g_{p,N} \end{bmatrix}$ where $g_{p,j} = [g_{1,j} \quad \cdots \quad g_{B_{p,j}}]$ and $C_p = [C_1, C_2, \dots C_N]^T$, where C_j is the circulant training matrix derived from $c_j = \begin{bmatrix} c_{1,j} \\ \vdots \\ c_{B_{p,j}} \end{bmatrix}$.

The least square (LS) channel estimates can be found simultaneously for the N CMMA users by minimising the square error quantity, which produces the following solution:

$$\widehat{g_p} = argmin\left\|Y_p - C_p g_p\right\|^2 = \left({C_p}^H C_p\right)^{-1} {C_p}^H Y_p \tag{3.27}$$

where $(\ )^H, (\ )^{-1}$ represent the Hermitian and inverse matrixes respectively.

3.9.3 CMMA with selective diversity and iterative decoding (SC-CMMA-ID)

SC-CMMA provides an effective mechanism to achieve diversity gain and good performance even at the presence of high channel correlation and without the need for pilot-based channel estimation at the receiver or any form of feedback between users and the BS. However in SC-CMMA, detection is only performed at the selected antenna where the predesigned composite constellation is formed; while the composite signals received from the *L-1* remaining antennas are not used for decoding and only utilised for maintaining selection which results in a low-complexity but sub-optimal performance. Therefore in this section, an iterative decoding (ID) process that preserves the structure and simple precoding of SC-CMMA but achieves a superior performance is proposed. The number of iterations is always limited to two regardless of the number of users involved or the number of receive antennas available. Hence SC-CMMA-ID consists of two successive stages.

The first stage is identical to that of SC-CMMA explained in sections 3.8.1 and 3.8.2 respectively whereby joint ML detection is performed at the selected antenna and the output of the decoder is used for blind channel estimation as explained in section 3.8.2.

Once the complex values of g_{ij} are obtained by blind channel estimation, the BS can attain the random composite constellation formed from all users at the remaining *L-1* antennas. Let's assume that R_j is the composite constellation formed from the superposition of signals from *N* users at antenna j where $j \in \{1,2,..,L\}, j \neq s$ then :

$$[R_j] = [C] \times [g_j] \tag{3.28}$$

Where $[C]$ is a $M \times N$ matrix representing all the possible combinations of *N-1* transmitted signals. When users employ BPSK and assume the average symbol power is unity, the entries on Ge will be either +1 or -1. And $[g_j]$ is a $1 \times N$ matrix representing complex channel coefficients between antenna j and N users weighted by the power and phase adjustments required for the selected antenna.

The second stage of SC-CMMA-ID is identical to that of MIMO with ML equalization which involves finding the distance squared d_{ij}^2 between the received signal at each antenna j and the i^{th} possible combination signals $r_i \in [R_j]$ then calculating the mean square distance $\overline{d_i^2}$ across all the received antennas

$$d_{ij}^2 = \left|y_j - r_i\right|^2, \qquad 1 \leq i \leq M;\ 1 \leq j \leq L \tag{3.29}$$

$$\overline{d_i^2} = mean\{d_{i1}^2, d_{i2}^2, \dots, d_{iL}^2\} \tag{3.30}$$

Using the set of M calculated mean distances, the receiver makes its decision based on d_{min} criterion. The possible transmitted signals are selected as a symbol r_j which produces the minimum mean distance as

$$\{\hat{r}_1, \dots, \hat{r}_M\} = \arg \min_{i=1,\dots,M} \overline{d_i^2} \qquad (3.31)$$

However, the complexity of joint ML detection at the second stage grows exponentially not only with the number of users but also with the number of received antennas. Therefore in order to maintain the optimum performance of joint ML while reducing its complexity to a manageable level, we propose a sphere-based detection that uses the output of the selected antenna at the first stage to determine the number of calculations required for the second detection stage as follows:

Lets $\hat{r}_{is} \in [R]$ be the estimated composite symbol of the selected antenna obtained from the output of the decoder at the first stage. Now lets $[R_{sub,s}] \in [R_s]$ by a sub constellation that contains $\hat{r}_{is}$ and all other constellations points directly adjacent to $\hat{r}_{is}$, then at the second stage limit the process described at equation's 24 and 25 to calculate the distance between the received composite signal at each antenna and the $[R_{sub,j}] \in [R_j]$; $1 \leq j \leq L$. Using the detected data from the selected antenna to determine the sphere of detection at the second stage and across all remaining receive antennas can greatly reduce the complexity of iterative decoding. For example, in the case of regular rectangular MQAM constellation, the maximum number of constellation points contained in a sphere is seven. For 4x4 communication system where users employ QPSK, the number of calculations required for SC-CMMA-ID is 277 compared with 1024 for MIMO with ML equalization. This amounts to a reduction of 73% in total number of calculations.

3.10 Analysis OF BER and Outage Probability for CMMA

3.10.1 BER for CMMA

The average probability of error in an AWGN channel for M-QAM using coherent detection can be approximated [29] to

$$\Pr_e \cong 4\left(1-\frac{1}{\sqrt{M}}\right)Q\left(\sqrt{\frac{3E_{av}}{(M-1)N_o}}\right) \tag{3.32}$$

where E_{av} is the average signal energy. For a CMMA scheme with N users forming a regular constellation, the $E_{av,reg}$ can be defined as

$$E_{av,reg} = \sum_{i=1}^{N}\int_{\mu}^{\infty} (\Pr(\lambda_i)/\lambda_i)\, d\lambda = \frac{\mathrm{E}_1\left(\mu/N\bar{\lambda}\right)}{N\bar{\lambda}} \tag{3.33}$$

However since the mapping and the resulting d_{min} of a composite QAM constellation can vary greatly according to user's power correlation. In general, the average signal power E_{av} for a composite QAM constellation with mapping $\pi(\cdot)$ and minimum distance $d_{min,\pi}$ can be derived from that a regular QAM constellation with the same rate and a minimum distance $d_{min,reg}$ as:

$$E_{av} = \frac{\mathrm{E}_1\left(\mu/N\bar{\lambda}\right)}{N\bar{\lambda}} - \left(\frac{d_{min,reg}}{d_{min,\pi}}\right)^2 \tag{3.34}$$

To show the power gain of CMMA compared with a single user transmission, if the average transmits power per user is fixed to P then the minimum distance of the multiuser CMMA constellation will be

$$d_{\min,mu} = \sqrt{N} d_{\min,su} \tag{3.35}$$

where N is the number of users and $d_{\min,su}$ is the received constellation's minimum distance for single user case. It can be proven that for any 2^M-QAM:

$$P_{av} = \frac{1}{2}\sum_{i=1}^{i=M/2} 4^{i-1} \times d_{\min}^{2} \tag{3.36}$$

$$P_{av} = \frac{1}{4}d_{\min}^{2} + \sum_{i=1}^{i=(M-1)/2} 4^{i-1} \times d_{\min}^{2} \tag{3.37}$$

where equations (3.36) and (3.37) are respectively for even and odd M values.

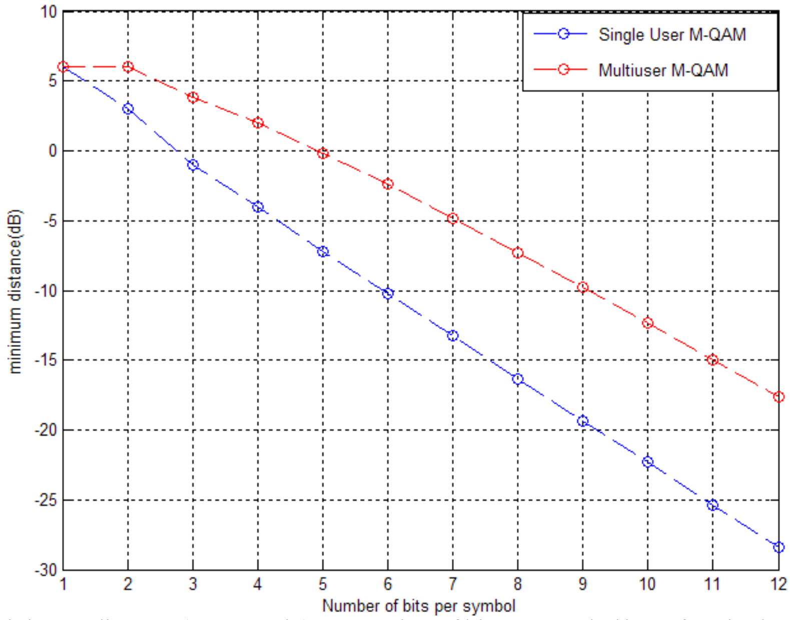


Figure 3- 7 Minimum distance (Power gain) vs. number of bits per symbol/user for Single user M-QAM and Multiuser M-QAM

Figure 3-7 shows the power gain of CMMA constellation over that of a SU when the average power per user is fixed to one. CMMA bandwidth efficiency increases with the number of users due to combined higher modulation at the expense of a reduction in BER performance since the power gain of multiuser modulation is not sufficient to compensate for the drop in $d_{\min}$. However, due to the multiuser nature of CMMA, the burden of increase in symbol power required to sustain a fixed BER is distributed. Conventionally, due to limited mobile power, higher-order modulation is restricted to users with good channel located near the BS, while those on the edge of the cell use lower-order modulation. However, since dedicated resources are assigned to users irrespective of their location, links assigned to users on the cell edge have lower bandwidth efficiency compared with those near the BS. With CMMA, several users located at the cell edge with only a modest BER degradation can share one channel and quadruple bandwidth efficiency compared with a single user case freeing more channels for new users.

3.10.2 CMMA outage probability with antenna selection

The total power required to sustain a specific SNR λ for *N* users in CMMA can be written as:

$$P_{tot}(t) = \sum_{i=1}^{N} \frac{G_i}{|h_i(t)|^2} \tag{3.38}$$

As shown in (3.38), P_{tot} has a chi-square distribution with *N* degrees of freedom, therefore the outage probability of a CMMA system with a single receive antenna at threshold λ can be written as

$$\Pr_{out}(1,\lambda) = \Pr\{P_{tot} < \lambda\} = \int_{-\infty}^{\lambda} \frac{P_{tot}^{N-1} e^{-\frac{P_{tot}}{2}}}{2^N \Gamma(N)} dP_{tot} = \frac{\gamma(N,\lambda)}{\Gamma(N)} \tag{3.39}$$

where γ denotes the lower incomplete gamma function and Γ denotes the Gamma function. For *L* receive antennas with uncorrelated channels, the probability that P_{tot} for all of *L* branches is below λ is simply the product of individual probabilities of *N* users with single receive antenna.

$$\Pr_{out,\lambda,L} = \left[\frac{\gamma(N/2,\lambda/2)}{\Gamma(N/2)}\right]^L \tag{3.40}$$

DG is defined as the reduction in total transmit power for a CMMA group with *L* receive antennas compared with single antenna case when both have equal outage probability therefore.

$$\Pr_{out}(1,\lambda_1) = P_{out}(L,\lambda_L) \Rightarrow G_d = \frac{\lambda_L}{\lambda_1} = \lambda_L - \lambda_1[dB] \tag{3.41}$$

where λ_1, λ_L are respectively the SNR of a single and L receive antennas required to produce the same outage probability. In Figure 3-8, we calculated the DG as a function of the outage probability. As expected, the DG decreases as the number of users' increases, since the probability that most users experience their strongest channel at the same antenna decrease.

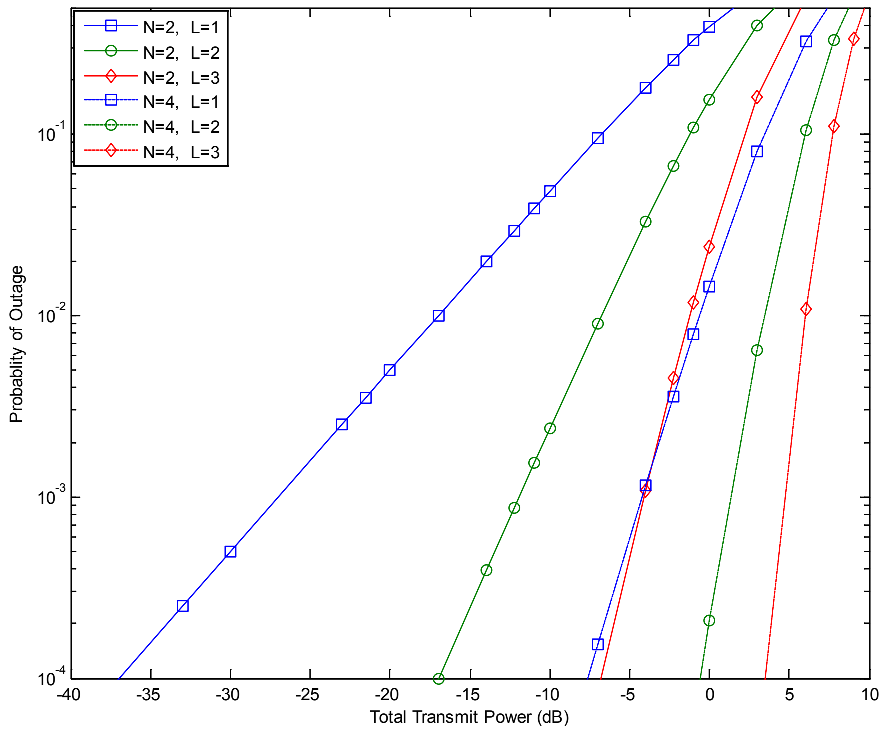


Figure 3- 8 Comparison of CMMA Selective diversity gain for different number of users

3.11 Simulation Results

This section presents the results of our Monte Carlo simulations using several possible CMMA formations constructed according to Table 3.1.

Table 3.1. Best possible formation of composite QAM constellations for different number of users (N) employing BPSK with different power distribution. The SNR field in the table refers to the total power increase required to achieve the same performance as a single user employing BPSK.

N	Power Allocation	Phase Rotation In degrees	P_{total}(watt) /sum rate (bits/sec)	Composite QAM order / Bandwidth efficiency	d_{min}	SNR(dB) at any fixed

				/Complexity		BER
2	$P_1 = P_2$	$\theta_1 = 0,\ \theta_2 = 90$	2	4	1.1120	0
3	$P_1 = P_2 = P_3$	$\theta_1 = 0,\ \theta_2 = 90$ $\theta_3 = 60$	3	8	0.5870	5.5
3	$P_1 = P_2 = 2P_3$	$\theta_1 = 0,\ \theta_2 = 90$ $\theta_3 = 45$	3	8	0.8875	2
4	$P_1 = P_2 = P_3 = P_4$	$\theta_1 = 0,\ \theta_2 = 90$ $\theta_3 = -30,\ \theta_4 = 60$	4	16	0.5788	5.7
4	$P_1 = P_2$ $P_3 = P_4 = 4P_1$	$\theta_1 = \theta_3 = 0$ $\theta_2 = \theta_4 = 90$	4	16	0.7057	4
5	$P_1 = P_2$ $P_3 = P_4 = 4P_1$ $P_5 = 2P_3$	$\theta_1 = \theta_3 = 0$ $\theta_2 = \theta_4 = 90$ $\theta_5 = 135$	5	32	0.5217	6.6
6	$P_1 = P_2$ $P_3 = P_4 = 4P_1$ $P_5 = P_6 = 4P_3$	$\theta_1 = \theta_3 = \theta_5 = 0$ $\theta_2 = \theta_4 = \theta_6 = 90$	6	64	0.4225	8.4

Our model assumes transmission over block Rayleigh fading channel with a channel memory of 50 consecutive symbols. For the case of two users, we multiply the channels by a colouring matrix to generate arbitrary channel correlation levels. We compared CMMA with the conventional SPC where *N* users send their data over a common channel using SIC or joint ML detection. We also compared our scheme with theoretical results for TDMA system where every user sends its information during its time slot with a rate equal to the sum rate of equivalent CMMA group. We assume perfect CSIT for CMMA and perfect CSIR otherwise and we restricted the average power per user in all cases to unity.

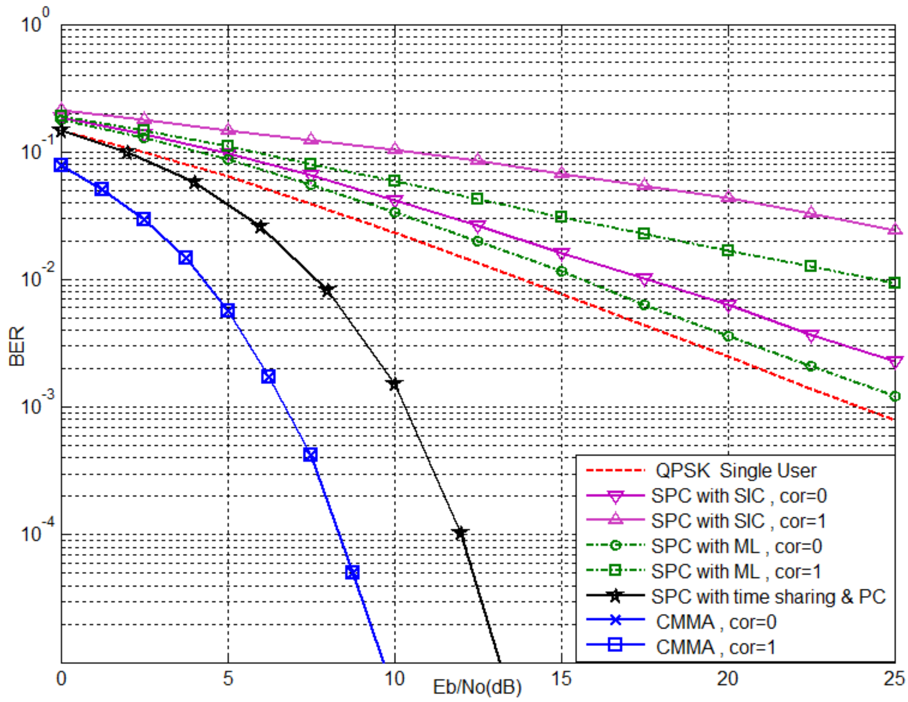


Figure 3- 9 BER Performance of equal power 2-user CMMA compared with superposition coding with SIC and ML, all employing BPSK for correlated (cor=1) and uncorrelated (cor=0) channels. The single user QPSK presents the performance of orthogonal MAS with same rate as 2-user CMMA.

Figure 3- 8 presents the simulation results for two BPSK users, which clearly shows that the performance of SPC schemes drops considerably with high channel correlation. Even with uncorrelated channels, the BER performance drops by 1.6 dB compared with the single user case. This degradation worsens for higher number of users, dropping to 2.6 dB for the case of four users compared with a single 16-QAM user (Figure 3- 12) and 3.5dB for six users compared with 64-QAM (Figure 3- 10). This happens because not only the intensity of the composite constellation fluctuates due to fading but also its structure due to channel correlation. As can be seen in Figure 3- 5, CMMA is not affected by channel correlations as precoding fixes the constellation structure to that of a regular QAM at any correlation level. Another inherent advantage of precoding is the significant gain from power control on the expense of a small common feedback that is fixed to one pilot regardless of the number of users. By optimizing the available transmit power according to channel variation, a feedback gain of 18 dB and 14 dB at BER of 10^{-4} is achieved respectively for two and four BSPK

users as shown respectively in Figure 3- 9 and Figure 3- 12. In the two BPSK users case and due to the orthogonally between users, the BER performance remains unchanged compared with a single BPSK user with perfect power control while the bandwidth efficiency doubles.

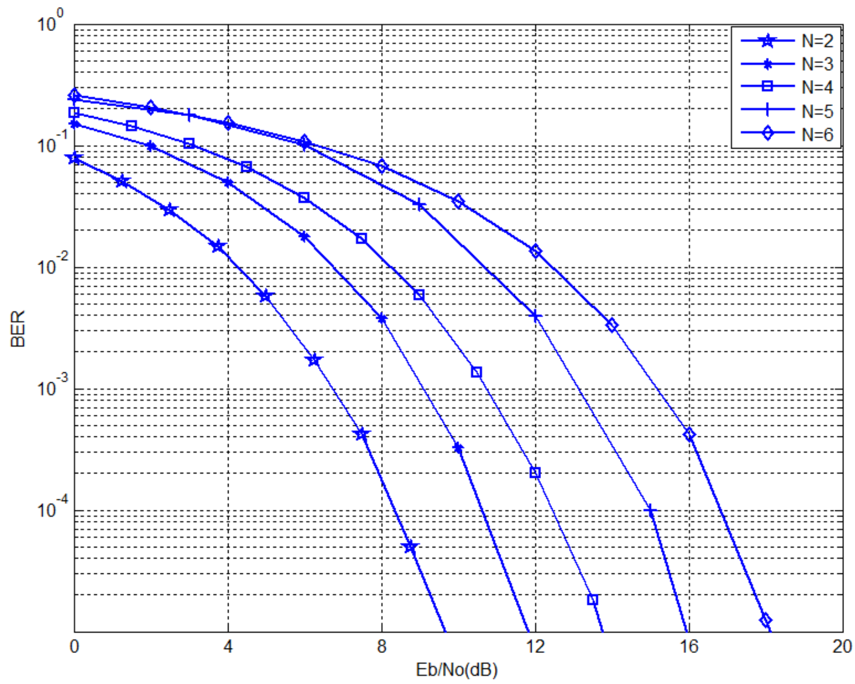


Figure 3- 10 Comparison of BER performance for CMMA with different number of users employing BPSK forming regular QAM constellation

CMMA bandwidth efficiency increases with the number of users due to combined higher modulation. However, this is achieved at the expense of a reduction in BER performance as shown in Figure 3- 9 where performance drops by 6 dB at BER of 10^{-5} when the number of user increase from 1 to 5 BPSK users since the power gain of multiuser modulation is not sufficient to compensate for the drop in $d_{\min}$.

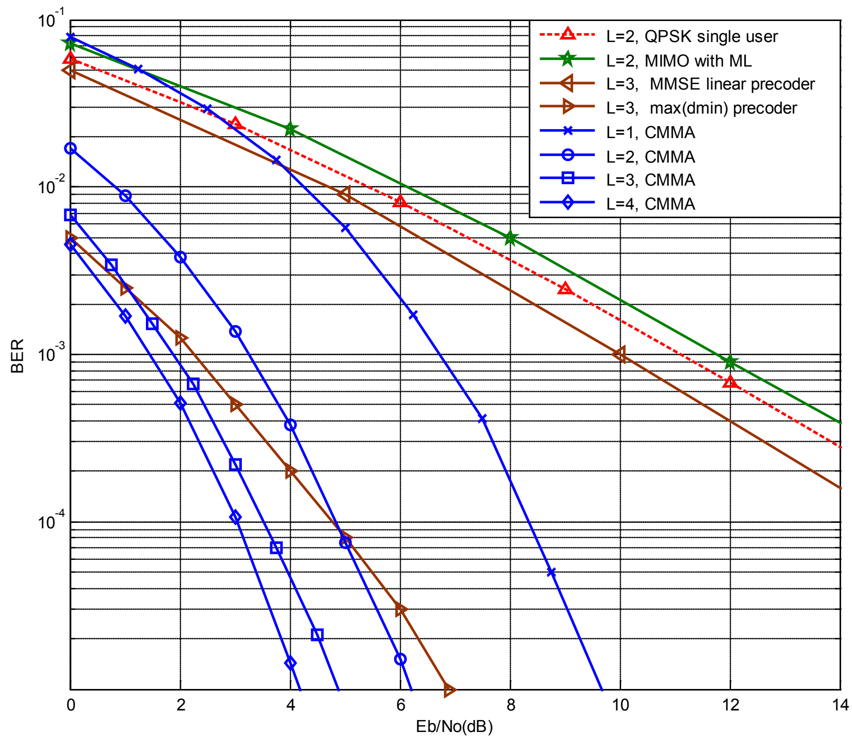


Figure 3- 11 Comparison of BER Performance of 2-User CMMA with selective diversity and different MIMO linear and non-linear precoding schemes, all using BPSK

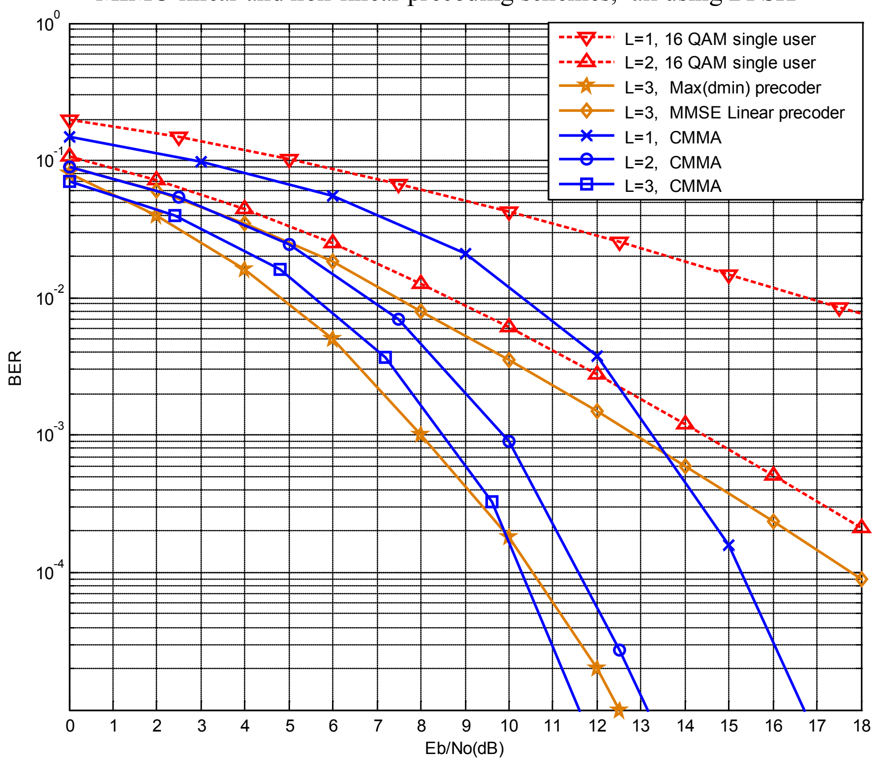


Figure 3- 12 Comparison of BER Performance of 2-users CMMA with selective diversity and different MIMO linear and non-liner precoding schemes all using QPSK . In the case of CMMA, Two irregular QPSK with phases of $\{0^o,180^o,54^o,234^o\}$ with equal power and 90^o phase rotation.

In Figure 3- 10 and Figure 3- 11 respectively, we compare the performance of two CMMA users using BPSK and QPSK modulation with selective diversity with that of 3 by 2 MIMO scheme over which 2 independent data streams are sent employing MMSE linear precoder [76] and max $d_{\min}$ precoder [77] with ML detection and assuming perfect CSI available at both transmitter and receiver side. Even with the reduced complexity and feedback overhead compared to [24-25], CMMA achieves a 0.9 dB gain over max $d_{\min}$ precoder at BER of 10^{-5} and a 10.5 dB over MMSE linear MIMO precoder for two QPSK users. As expected with spatial diversity, the highest DG is achieved from the second receive antenna and the addition of more receive antennas leads only to smaller increases. As shown in Figure 3- 10, adding a second antenna to two users yield a DG of 4 dB. The DG achieved by adding a third antenna only yields an additional 1.5 dB.

With fully correlated channels ,a maximum DG regardless of the number of users can be achieved as shown in Figure 3- 12 where 5dB can be achieved from two receive antennas serving four users. However with uncorrelated channels the diversity gain that can be achieved becomes dependent on the number of users dropping in the case of two receive antennas from 4 dB for two users (Figure 3- 10) to 2.6 dB for six users (Figure 3- 13).

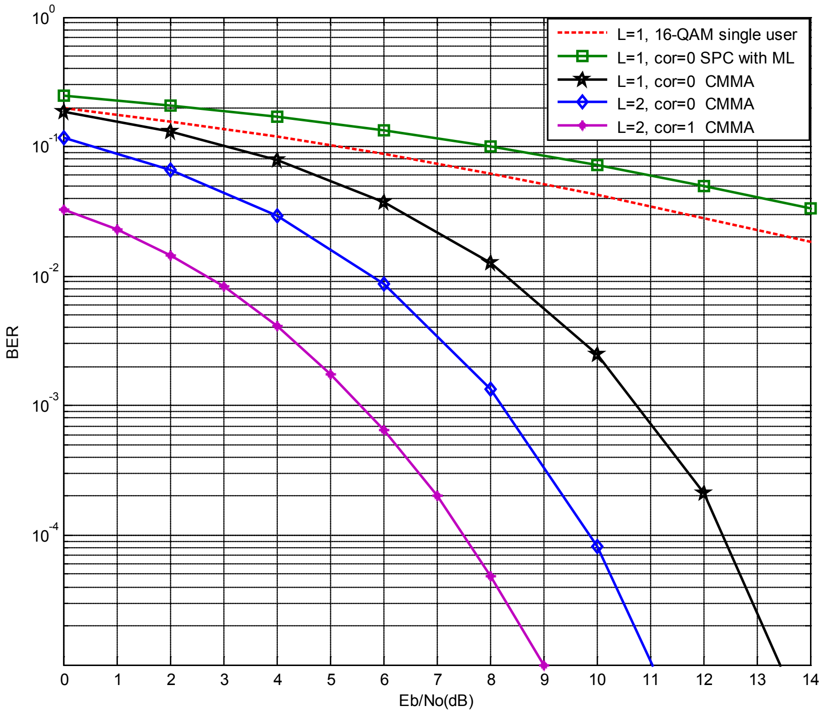


Figure 3- 13 BER Performance of 4-user CMMA with Unequal Power with selective diversity in the presence of high transmit correlation

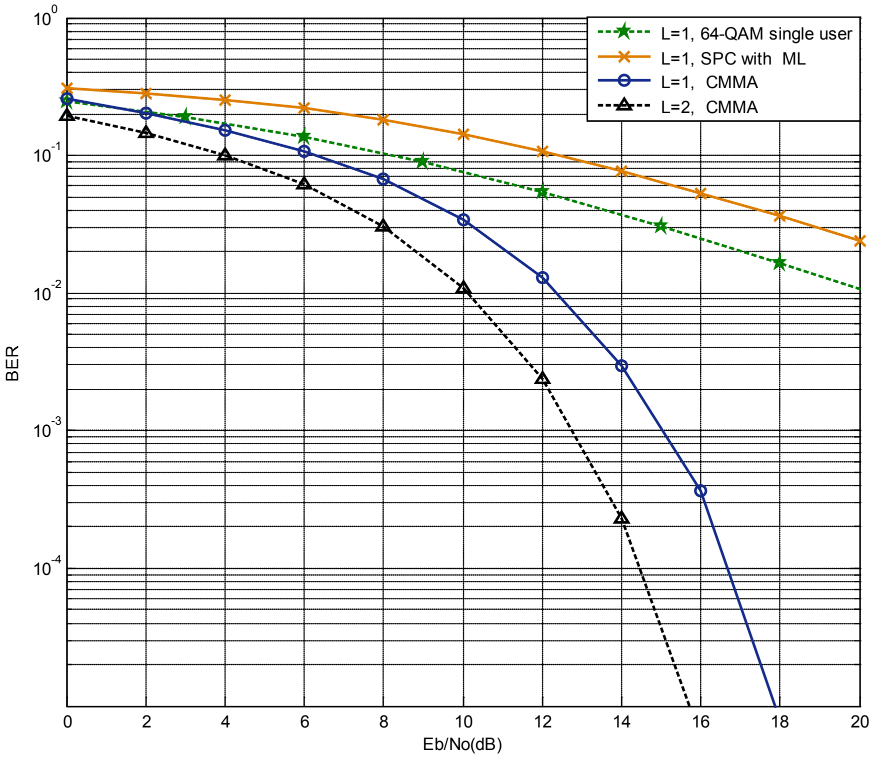


Figure 3- 14 BER Performance of 6-User CMMA with Unequal Power

Figs. 15 and 16 show the BER performance of five and six users, respectively using CMMA with selective diversity combining (SC) and iterative decoding (ID). It can be seen that on the expense of a small increase in complexity, ID significantly improve the performance of CMMA. For example, in the case of 5-user CMMA with two receive antennas, a BER performance improvement of 1.2 dB can be achieved with ID over that of SC-CMMA (Fig. 13). The gain of using ID over just SC-CMMA increase with the number of receives antennas. For example; for 6-user CMMA as shown in Fig. 16, ID improves BER over SC-CMMA by an extra 1.8 dB for three receive antennas and by 3.5 dB for four receive antennas. This is expected since as the number of receive antennas increase, the more likely that the random composite constellations formed at one or more them are non-ambiguous.

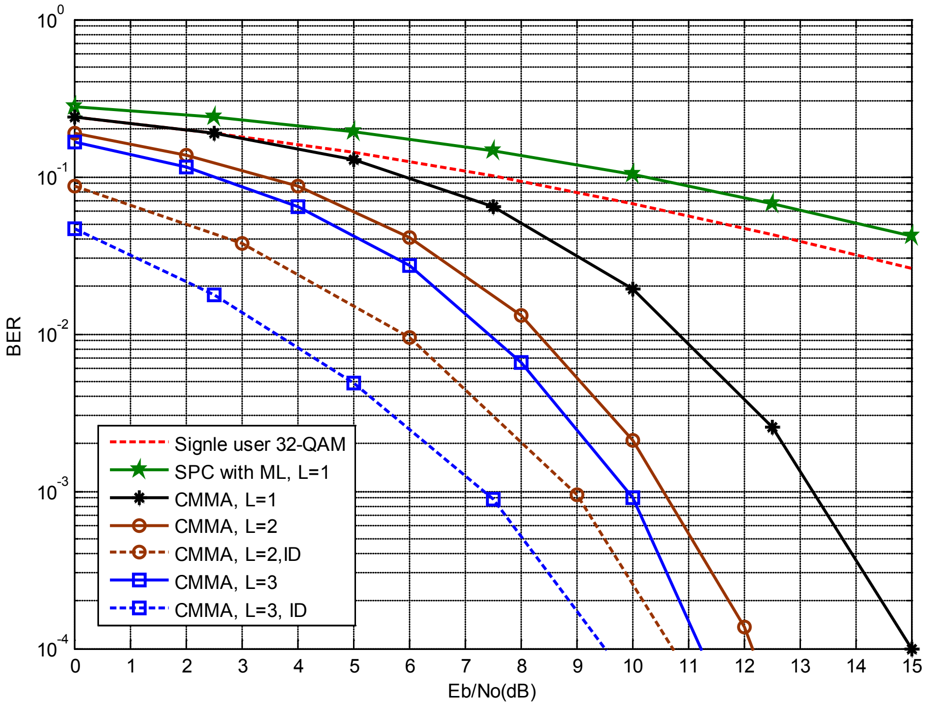


Figure 3- 15 BER performance of 5-user CMMA with unequal power, all CMMA and SPC using BPSK per user

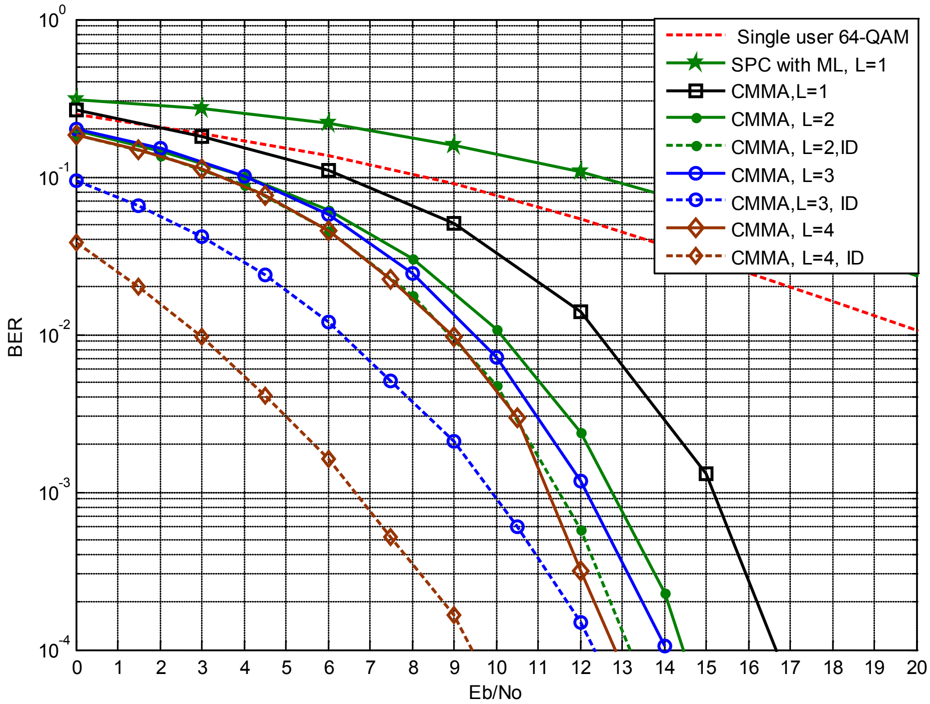


Figure 3- 16 BER performance of 6-user CMMA with unequal power, all CMMA and SPC using BPSK per user

3.12 Conclusion

A novel NOMAS employing collaborative modulation precoding, composite signal design and joint ML detection has been proposed. It has been shown that using only a small reverse common pilot, users with different channel conditions and rate requirements can share the same link without ambiguity achieving high spectral efficiency in every available link as well as flexibility on the number of users that can be admitted to the network. Due to power gain CMMA offers substantial increase in capacity with comparable orthogonal MAS scheme with TCI. Furthermore unlike SPC, results show that CMMA is resilient to channel correlation and the feedback diversity inherent in precoding provide a substantial gain in BER performance where up to 17.6 dB gain can be achieved in the case of two BPSK users. For a power constraint system, a higher order modulation can be achieved compared with a single user without degradation in performance. We also proposed a new a selection diversity combining algorithm for CMMA to benefit from spatial diversity without changing the simple pilot feedback, precoding, or detection methods. Furthermore a new iterative sphere decoding is designed to fully exploit the remaining receive antennas, the complexity of which is less than comparable MIMO with ML detection. This offers a low overhead alternative to uplink multiuser MIMO with diversity gain that increases with transmit channel correlation and is able to accommodate more users than the number of receive antennas. CMMA has also a wide range of applications. For example, it can be easily integrated with other conventional MAS such as OFDMA employed on LTE advance to increase the number of users beyond the number of orthogonal channels. It also provides a practical solution for schemes that require coherent combining of signals over fading channels such as multiple access adder channel and physical network coding.

4 Capacity of CMMA and SC-CMMA

4.1 Introduction

In this chapter, a thorough study of CMMA capacity using a single receive antenna and selection diversity combining will be carried out to find closed form expressions for spectral efficiency (capacity per unit of bandwidth) as a function of average received SNR. Next we will compare the performance of CMMA with that of Multiuser Diversity which is another multiuser adaptive modulation scheme widely used in cellular networks to provide multiple access for several users over the same bandwidth while trying to maximise the long term total throughput. Finally we will study the effect of channel correlation on the performance of CMMA.

4.2 Capacity of CMMA

The average symbol power for 2^M-QAM constellation with mapping $\pi_i(\cdot)$ and minimum distance d_i is equal whether this Constellation is transmitted from a single user with transmit power P_{su} or formed through the superposition of N different signals with total power $P_{tot} = NP = P_{su}$. Therefore, a CMMA system with N users whose signals are multiplexed to form a predesigned 2^M-QAM constellation with mapping $\pi_i(\cdot)$ and d_i is equivalent to a scheme where a single user with average power P transmits to N receive antennas using a 2^M-QAM constellation with mapping $\pi_i(\cdot)$ and where N received signals are coherently added before detection . However since users act independently to precode their signals and transmit constantly regardless of relative channel correlation, the probability density function (PDF) of the received signal amplitude assuming Raleigh fading is simply that of a single user given by [82] as

$$\Pr(\lambda) = e^{-\lambda/\lambda_x} \tag{4.1}$$

Where λ_x is the average SNR per receive antenna.

For CMMA, channel inversion using variable power and fixed rate is essential to enable the coherent combining of multiple signals from N different users experiencing N independent Rayleigh fading channels and to insure that users can fix the amplitude and phase of their received signal according with the unique modulation set assigned to that user by the base station. Channel inversion with variable power and fixed rate will convert the fading channel model into a time-invariant AWGN channel model therefore the channel capacity $\mathbb{C}$ follows that of the capacity of an AWGN channel and can be derived from [36] as :

$$\mathbb{C} = B\log_2\left(1 + \frac{1}{\sum_{i=1}^{N}\int_0^{\infty}(\Pr(\lambda_i)/\lambda_i)\,d\lambda_i}\right) \tag{4.2}$$

Replacing Pr in (4.2) with its value in (4.1) we find:

$$\mathbb{C} = B\log_2\left(1 + \frac{1}{N\int_0^{\infty}\lambda^{-1}e^{-\lambda/\lambda_x}d\lambda}\right) = 0 \tag{4.3}$$

As can be seen from (4.2) and conformed in [3-4]. Channel inversion by itself will yield zero capacity due to the fact precoding is done locally and independently at transmitters therefore most of the transmitted power will be used to compensate for deep fading. For these reasons, a truncated channel inversion is used instead where users only compensate for fading above a certain threshold μ . Any user experiencing fading below μ will stop transmitting.

To maximise the capacity per user, the optimal cut-off SNR level μ below which data transmission is suspended must satisfy [36]

$$\int_{\mu}^{+\infty}\left(\frac{1}{\mu} - \frac{1}{\lambda}\right)Pr_{su}(\lambda)d\lambda = 1 \tag{4.4}$$

Where $Pr_{su}(\lambda)$ is the probability density function (PDF) of the received signal amplitude for a single user under flat fading and is given in (4.1) .

It has been proven in [38] that there is a unique value for μ that satisfies (4.4) and μ always lies in the interval [0, 1] and $\mu \xrightarrow{yields} 1\ as\ \lambda_x \xrightarrow{yields} \infty$.

The capacity of a communication system with truncated channel inversion is given in [38] as:

$$\mathbb{C} = B \log_2 \left(1 + \frac{1}{\int_{\mu}^{\infty} (\Pr(\lambda)/\lambda)\, d\lambda} \right) (1 - Pr_{out}) \tag{4.5}$$

Where Pr_{out} is the probability of outage defined as the probability equal to the probability that received SNR falls below μ or in other words Pr_{out} is the probability of no transmission. Since precoding is performed locally at each user, the value of μ is chosen to satisfy (4.4) in order to maximise the capacity per user. This will insure that users transmit most of time to provide fairness and minimize delay. Hence the capacity of a CMMA scheme with *N* users at any one time is that of a CMMA system with *N-N1* where *N1* is the number of users whose channels falls below μ at time *t*.

Therefore the capacity of CMMA with *N* users under truncated channel inversion can be derived from (4.5) and defined as :

$$\mathbb{C} = \sum_{i=1}^{N} \frac{N!}{(N-i)!\, i!} \mathbb{C}_i (1 - Pr_{out})^i\, Pr_{out}^{N-i}) \tag{4.6}$$

Where $\mathbb{C}_i$ is the capacity of a CMMA system with *i* users and where all channels of all of the constituent users stay above μ therefore

$$\mathbb{C}_i = B \log_2 \left(1 + \frac{1}{\int_{\mu}^{\infty} (\Pr(\lambda)/i\lambda)\, d\lambda} \right) \tag{4.7}$$

Replacing *Pr* in (4.7) with its value in (4.1) we find:

$$\mathbb{C}_i = B \log_2 \left(1 + \frac{i}{\int_{\mu}^{\infty} \lambda^{-1} e^{-\lambda/\lambda_x} d\lambda} \right) \tag{4.8}$$

This is the exponential integral of first-order function $\mathrm{E}_1(x)$ as defined in [84]:

$$E_1(x) = \int_1^{\infty} x^{-1} e^{-x} dx \tag{4.9}$$

Lets

$$x = \lambda/\lambda_x \text{ then } dx = d\lambda/\lambda_x \tag{4.10}$$

Therefore replacing the value of (4.9) in (4.10) and changing the values of integration we find:

$$\mathbb{C}_i = B \log_2 \left(1 + \frac{\lambda_x i}{\mathrm{E}_1(\mu/\lambda_x)}\right) \tag{4.11}$$

Pr_{out} is the probability that a single user experience fading above a certain level μ and defined as

$$Pr_{out,su} = 1 - \int_{\mu}^{\infty} \mathrm{Pr_{su}}(\lambda)\, d\lambda \tag{4.12}$$

Replacing *Pr* in (4.12) with (4.1) and integrating we find:

$$\mathrm{Pr_{out,su}} = 1 - \int_{\mu}^{\infty} \frac{1}{\lambda_x} e^{-\frac{\lambda}{\lambda_x}} d\lambda = 1 - e^{\frac{-\mu}{\lambda_x}} \tag{4.13}$$

Fig. 4.1 shows the theoretical spectral efficiency as a function of average received SNR, λ_x for a CMMA system with truncated channel inversion for different number of users. These curves are obtained in MATLAB using the closed form expressions, (4.6), (4.11), (4.13). The capacity of CMMA increases with the number of users due to the power gain. However, due to the reduction in minimum distance of the composite receive constellation, this increase is not linear and the rate of increase drops when the number of users is increased. For example as can be seen in Fig.4.1 the capacity at SNR=25 dB increases from 7 bits/sec/Hz for two users to 9 for eight users. This is expected as at the absence of any diversity gain, the power gain brought by the new users is accompanied by increased interuser interference.

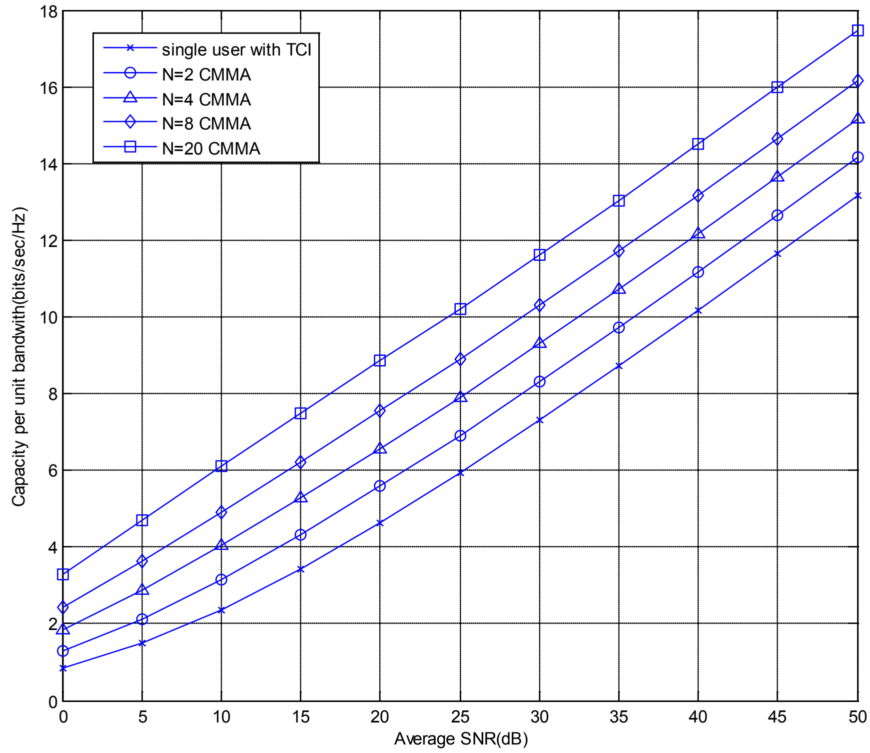


Figure 4-1 Capacity of CMMA with single receive antenna

4.3 CMMA Vs Multiuser Diversity (MUD)

In this section, we will compare the performance of CMMA with that of a well-known and widely implemented technique referred to as multiuser diversity (MUD) . Both CMMA and MUD aim to provide multiple accesses for several users over the same bandwidth while trying to maximise the long term total throughput (sum capacity) by exploiting the fading nature of the channel and feedback from the receiver to transmitter. However MUD achieves these goals by using a packet scheduler at the medium-access control (MAC) layer at the BS which always allocates the common radio resource to the user that has the best channel quality. In a system with large number of users, each experiencing independent fading, there is high probability that at least one user will have a very good channel at any one time. MUD therefore is equivalent to a system where single user transmits to N receive antenna and where selection combining is used to achieve diversity. However the challenge for implementing MUD is to exploit virtual diversity gain while sharing the benefits fairly and without excessive delay among users with asymmetric channel statistics. This is addressed by using a proportional fair scheduler [85] where users are served when they are near their peak within a fixed latency time-scale. Another important challenge for MUD is the rate of change in channel condition, the faster the channel changes, the lower the delay among users and the higher the possibility that users experience good channels. If the fluctuation in the channel is slow, more fluctuations can be induced artificially using opportunistic beamforming by employing dumb antennas which randomly sweep out a beam and opportunistically send data to the user closest to the beam. Dumb antenna can approach the performance of true beamforming when the number of users is large, but with much less feedback and channel measurements [86].

The capacity of a single input single output system using multiuser diversity and adaptive and adaptive transmission with variable rate and power is given in [83] by :

$$\mathbb{C}_{siso}^{MD} = B \log_2(e) \sum_{k=0}^{N-1} (-1)^k \binom{N-1}{k} \frac{E_1\left((1+k)\frac{\mu_{MD}}{\lambda_x}\right)}{1+k} \tag{4.14}$$

Where $E_1(x)$ is the exponential integral function and μ_{MD} is the optimal SNR cut-off value below which data transmission is suspended and is calculated using the approximation given in [83] as :

$$\mu_{MD} = N \frac{\sum_{k=0}^{N-1} (-1)^k \binom{N-1}{k} \frac{1}{1+k}}{1 + \frac{N}{\lambda_x} \sum_{k=0}^{N-1} (-1)^{k+1} \binom{N-1}{k} [\log(1+k) + E]} \tag{4.15}$$

in which E is the Euler constant (E=0.577215665)

Fig. 4- 2 shows the theoretical spectral efficiency (capacity per unit of bandwidth) as a function of average received SNR, λ_x for both a CMMA system with truncated channel inversion and multiuser diversity system with adaptive modulation using water filling with variable power and rate. These curves are obtained in MATLAB using the closed form expressions, (4.6), (4.11), (4.13) for CMMA and (4.14) and the approximation in (4.15) for MUD. As can be seen in Fig .4.2, the capacity of CMMA is higher than that of MUD in low

to medium SNR while MUD achieves higher capacity at high SNR. However, the difference in performance between the two schemes in high SNR decreases as the number of users increase and CMMA becomes superior to MUD. This is because the capacity of MUD is equivalent to that of a selection diversity combining [83] where only diversity gain is exploited while that of CMMA has power gain but no diversity gain. The increase in diversity gain for MUD tends to diminish as the number of users increase while the power gain in CMMA remains constant.

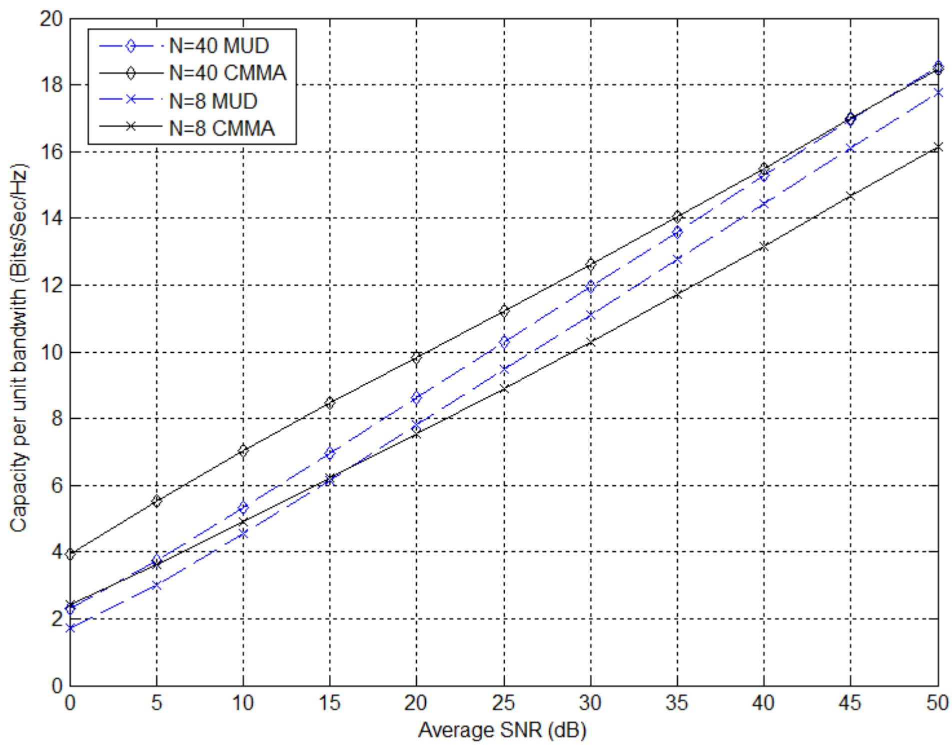


Figure 4- 2 Capacity of CMMA Vs. MUD

CMMA is superior to MUD in terms of feedback, fairness, and delay (especially when the number of users is large) since all users transmit at any time as long as their channel is above the cut-off SNR μ. In addition, for MUD , the BS needs to have partial or full CSI about all users in order for the scheduler to choose the one with best channel and select the user with the best channel. The receiver in CMMA does not require any CSI at the receiver and only a small common pilot feedback is required. Finally like other types of diversity MUD is sensitive to channel correlation among users' channels as the diversity gain diminish with higher channel correlation, whereas CMMA is unaffected by channel correlation.

4.4 CMMA capacity with antenna selection

In this section we will calculate the capacity of a CMMA system with selective diversity combining assuming that there are *L* receive antenna and the BS will select the antenna *S* that requires the least total transmit power over all.

The instantaneous total transmit power for a group of *N* CMMA users required to maintain a fixed receive SNR λ_x per user is defined as :

$$P_{tot}(t) = \sum_{i=1}^{N} \frac{\lambda_x}{\lambda_i(t)} \quad , where\ \lambda_i(t) = \frac{|h_i(t)|^2}{N_o} \tag{4.16}$$

λ_i has an exponential distribution with λ_x mean, it follows that since P_{tot} is the sum of *N* exponential variables, its probability distribution function will follow that of Erlang distribution given by :

$$\Pr(\lambda) = \frac{\lambda^{N-1} e^{-\lambda/\lambda_x}}{\lambda_x^N (N-1)!} \tag{4.17}$$

The probability of outage for a CMMA system of *N* users and a single receive antenna is defined as :

$$Pr_{out,CMMA} = 1 - \int_{\lambda}^{\infty} \Pr_{\mathrm{CMMA}}(\lambda)\, d\lambda \tag{4.18}$$

Substituting (4.17) into (4.18) and integrating we find :

$$Pr_{out,CMMA} = \int_{0}^{\lambda} \frac{t^{N-1} e^{-t/\lambda_x}}{\lambda_x^N \Gamma(N)} dt = \frac{\gamma(N, \lambda/\lambda_x)}{\Gamma(N)} \tag{4.19}$$

Where γ denotes the lower incomplete gamma function. For *L* receive antennae with uncorrelated channels, the probability of outage for all *L* branches that falls below a certain threshold λ is simply the product of individual probabilities of N users with single receive antenna.

$$Pr_{out}^{Sel} = \left(Pr_{out,CMMA} \right)^{L} \tag{4.20}$$

Pr_{out}^{Sel} also represents the PDF of the output SNR as a function of the threshold s. The probability density function is therefore

$$Pr^{Sel} = \frac{dPr_{out}^{Sel}(\lambda)}{d\lambda} \tag{4.21}$$

Substituting (4.20) into (4.21) and deriving we find :

$$Pr^{Sel} = \frac{L}{\lambda_x} \left[\Gamma(N)\right]^{-L} \left(\frac{\lambda}{\lambda_x}\right)^{N-1} e^{-\frac{\lambda}{\lambda_x}} \left[\gamma(N, \lambda/\lambda_x)\right]^{L-1} \tag{4.22}$$

The average total transmit power required to sustain a fixed SNR λ_x is given by :

$$\overline{P_{total}} = \int_{0}^{\infty} \frac{1}{\lambda} \Pr(\lambda) \;\; d\lambda \tag{4.23}$$

For a single receive antenna and replacing Pr in (4.23) with its value in (4.17) we find:

$$\overline{P_{tot}^{l=1}} = \frac{\int_0^{\infty} \lambda^{N-2} e^{-\lambda/\lambda_x} d\lambda}{\lambda_x^N (N-1)!} \tag{4.24}$$

Gamma function $\Gamma(N)$ is defined as [84] as :

$$\Gamma(N) = (N-1)! = \int_{0}^{\infty} x^{N-1} e^{-x} dx \tag{4.25}$$

Therefore replacing the value of (4.24) with (4.25) we find :

$$\overline{P_{tot}^{l=1}} = \frac{\Gamma(N-1)}{\lambda_x^N \Gamma(N)} \tag{4.26}$$

Finally from [84]

$$\Gamma(N) = (N-1)\Gamma(N-1) \tag{4.27}$$

It follows that the average total transmit power for a single receive antenna is :

$$\overline{P_{tot}^{l=1}} = 1/(N-1)\lambda_x \tag{4.28}$$

The average total transmit power required to maintain the same average received power $\lambda_x$will decrease as the number of receive antenna increase. In other words, using the same transmit power a higher average received SNR can be maintained as the number of receive antennas increase achieving higher capacity.

It is not possible to find a closed-form expression for total transmit power for any *N* number of user with any *L* receive antennas therefore we will derive a close form expression for any *N* when *L=2,3.*

4.4.1 Capacity of CMMA with two receive antennas

For *L*=2 , Lets x= λ/λ_x then substituting $\overline{P_{tot}^{l=2}}$ with its value from (4.22) and (4.23) we find :

$$\overline{P_{tot}^{l=2}} = \frac{2}{\lambda_x} [\Gamma(N)]^{-2} \int_0^\infty (x)^{N-2} e^{-x} \, \gamma(N,x) dx \tag{4.29}$$

From [84] $\gamma(n,x)$ and $d\gamma(n,x)$ can be written as:

$$\gamma(n,x) = (n-1)\gamma(n-1,x) - (x)^{n-1}e^{-x} \tag{4.30}$$

$$\frac{d\gamma(N,x)}{dx} = (x)^{N-1}e^{-x} \tag{4.31}$$

Then substituting (4.30) and (4.31) into (4.29) and integrating

$$\overline{P_{tot}^{l=2}} = \frac{2}{\lambda_x} [\Gamma(N)]^{-2} \left\{ \int_0^{\Gamma(N-1)} (N-1)\gamma(N-1,x) d\gamma(N-1,x) - \int_0^\infty 2x^{2N-3}e^{-2x} \, dx \right\} \tag{4.32}$$

$$\int_0^\infty x^{n-1}e^{-ax}dx = \frac{\Gamma(n+1)}{a^{n+1}} \tag{4.33}$$

Then substituting (4.32) into (4.33) and integrating

$$\overline{P_{tot}^{l=2}} = \frac{2}{\lambda_x}\,[\Gamma(N)]^{-2}\left\{\frac{(\mathrm{N}-1)\Gamma(N)^2}{2} - \frac{\Gamma(2N-2)}{(N-1)2^{2n-2}}\right\} \tag{4.34}$$

4.4.2 Capacity of CMMA with three receive antennas

Now For *L=3*

Substituting $\overline{P_{tot}^{l=3}}$ with its value from (4.22) and (4.23) we find :

$$\overline{P_{tot}^{l=3}} = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\int_0^\infty (x)^{N-2}e^{-x}\,[\gamma(N,x)]^2 dx \tag{4.35}$$

Then performing integration by parts yields

$$\overline{P_{tot}^{l=3}} = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{[\gamma(N,x)^2\gamma(N-1,x)]_0^\infty - \int_0^\infty 2\gamma(N,x)(x)^{N-1}e^{-x}\,\gamma(N-1,x)dx\right\} \tag{4.36}$$

Substituting (4.30) into (4.36) and performing integration by parts

$$\overline{P_{tot}^{l=3}} = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\Gamma(N)^2\Gamma(N-1) - \int_0^{\Gamma(N)} \frac{2\gamma(N,x)^2\,d\gamma}{(N-1)} - \int_0^\infty \frac{2\gamma(N,x)(x)^{2(N-1)}e^{-2x}\,dx}{(N-1)}\right\} \tag{4.37}$$

$$\overline{P_{tot}^{l=3}} = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\frac{\Gamma(N)^3}{(N-1)} - \frac{2\Gamma(N)^3}{3(N-1)} - \int_0^\infty \frac{2\gamma(N,x)(x)^{2(N-1)}e^{-2x}\,dx}{(N-1)}\right\} \tag{4.38}$$

From [84] $\gamma(n,x)$ can be written as :

$$\gamma(N,x) = \Gamma(N)\left[1 - e^{-x}\sum_{k=0}^{N-1}\frac{x^k}{k!}\right] \tag{4.39}$$

Substituting (4.39)into (4.38) and performing integration by parts

$$\overline{P_{tot}^{l=3}} = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\frac{\Gamma(N)^3}{3(N-1)} - \int_0^\infty \frac{2\Gamma(N)(x)^{2(N-1)}e^{-2x}\,dx}{(N-1)}\right.$$
$$\left. + \frac{2\Gamma(N)}{(N-1)}\int_0^\infty e^{-3x}\sum_{k=0}^{N-1}\frac{x^{2N-2+k}dx}{k!}\right\} \tag{4.40}$$

Substituting (4.33) into (4.40) and integrating we find :

$$\overline{P_{tot}^{l=3}} = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\frac{\Gamma(N)^3}{3(N-1)} - \frac{2\Gamma(N)\Gamma(2N-1)}{(N-1)2^{2n-1}}\right.$$
$$\left. + \frac{2\Gamma(N)}{(N-1)}\sum_{k=0}^{N-1}\frac{\Gamma(2N-1+k)}{k!\,3^{2n-1+k}}\right\} \tag{4.41}$$

4.4.3 Results and Discussion

Fig. 4- 3 shows the theoretical spectral efficiency as a function of average received SNR λ_x, for a CMMA system with selection diversity for different number of users and when up to three antennas are available at the receiver. These curves are obtained in MATLAB using the closed form expressions, (4.6), (4.34), (4.41). The probability of outage in CMMA follows that of a Poisson distribution also known as the law of small numbers. It defines the probability distribution of an event that happens rarely but has very many opportunities to happen. Therefore as the number of users in a CMMA group increases the difference in SNR between receive antennas tend to diminish; Therefore for a large number of users, a higher number of receive antennas is required to achieve the same improvement in capacity as will be the case with lower number of users and smaller number of receive antennas. For example for *N=L=2* the capacity an improvement of capacity of up to 3 dB is obtained; while three receive antennas are required to achieve this improvement … the same improvement for a group of three users.

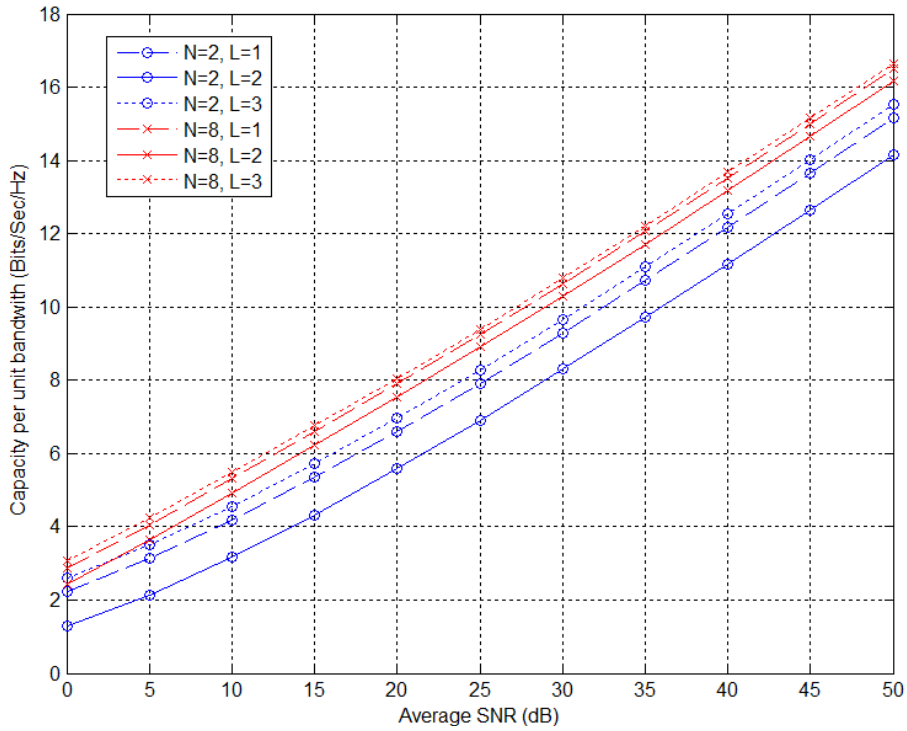


Figure 4- 3 Capacity of CMMA with selection diversity combining

4.5 Correlation effect on CMMA capacity

In this section we will analyse the effect of channel correlation on the capacity of CMMA by calculating the closed form expression for the CMMA capacity under fully correlated channels and comparing it with the capacity when all channels are uncorrelated, this will provide the lower and upper bound of CMMA capacity in regard to channel correlation.

4.5.1 Capacity of CMMA with fully correlated channels:

Let first consider the case for a group of N users each equipped with a single receive antenna assuming fully correlated channels among the users and the BS. When the channels are fully correlated they will all have the same envelopes or amplitude i.e. $|h_i| = |h|, where\ i = \{1,..N\}$. Therefore CMMA in this case can be remodelled as a single-input single-output (SISO) system where a single user equipped with a single antenna is transmitting using a 2^M-QAM constellation with mapping $\pi_i(\cdot)$ and minimum distance d_i

identical to that of the composite constellation formed from the superposition of the N users and with power equal to the total power of all users. The closed form expression of capacity of CMMA with fully correlated channel can be derived from that of a SISO system using truncated channel inversion with fixed rate and variable power is given in [37] as :

$$\mathbb{C}_{CMMA}^{cor=1} = B \log_2\left(1 + \frac{N\lambda_x}{E_1(\mu/\lambda_x)}\right) e^{-\mu/\lambda_x} \quad (4.42)$$

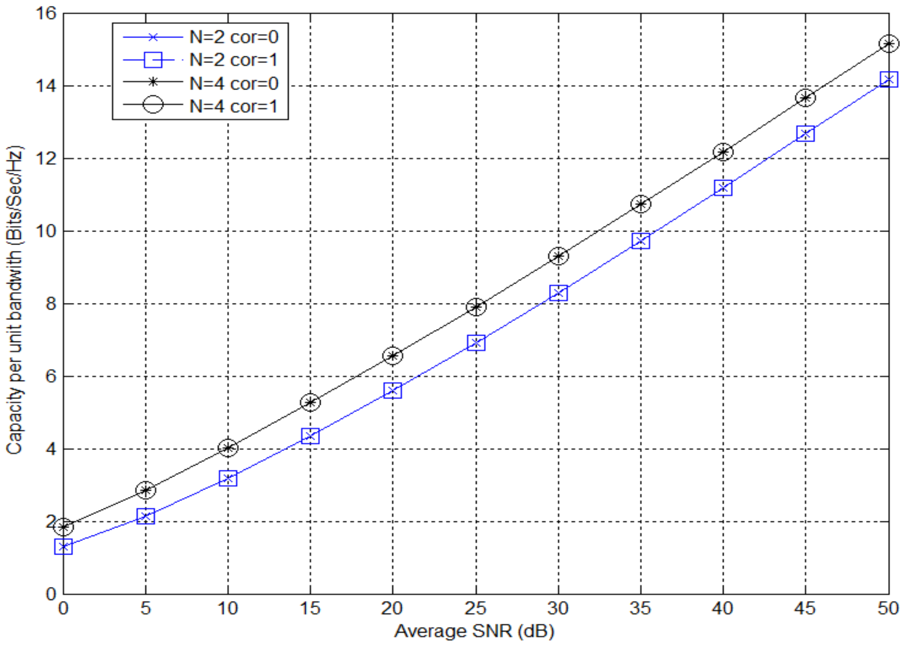


Figure 4- 4 Capacity of CMMA with uncorrelated and fully correlated channels

Fig. 4- 4 shows the theoretical spectral efficiency as a function of average received SNR λ_x for a CMMA system with uncorrelated and fully correlated Rayleigh fading channels. These curves are obtained in MATLAB using the closed form expressions, (4.6) and (4.42). It is clear that correlation does not have any effect on the capacity of CMMA with a single receive antenna. This result is expected since precoding is locally performed at transmitters acting independently of each other.

4.5.2 Capacity of SC-CMMA under full transmit correlation

Consider the case for a CMMA group of N users each equipped with a single receive antennas and a BS equipped with L receive antennas using selective diversity combining. We assume full correlation at the transmitters but the receive antennas to be uncorrelated. In other words, all the channels between users and any receive antenna will have the same envelope but the channels between any user and L receive antenna will vary independently. This models an environment where users are close together with poor scattering in their immediate proximity while the receive antennas are sufficiently spaced and users' signals experience a rich scattering environment before they are received at the BS. CMMA with selective combining can be in this case remodelled to a single user using a 2^M-QAM constellation with mapping $\pi_i(\cdot)$ and minimum distance d_i identical to that of the composite constellation formed from the superposition of the N users and with power equal to the total power of all users transmitting using truncated channel inversion with cut-off frequency $N\mu_{MD}$ to a multi antenna receiver with selective combining , whereμ_{MD} is the optimum cut-off SNR for a single user with L receive antennas calculated using the approximation in (4.15). The closed form expression of sum capacity in this scenario will follow that of a MISO system using truncated channel inversion with fixed rate and variable power at transmitters and selective combining at the receiver and can be derived from [37] as :

$$\mathbb{C}_{CMMA,Sel}^{cor=1} = B\log_2\left(1 + \frac{N\lambda_x}{L\sum_{k=0}^{L-1}(-1)^k\binom{L-1}{k}E_1\left(\frac{(1+k)\mu_{MD}}{\lambda_x}\right)}\right)(1 - Pr_{out,sel}) \quad (4.43)$$

Where $Pr_{out,sel}$ is given in [37] as :

$$Pr_{out,sel} = 1 - \sum_{k=0}^{L-1}(-1)^k\binom{L-1}{k}\frac{Le^{-(1+k)\mu_{MD}/\lambda_x}}{1+k} \quad (4.44)$$

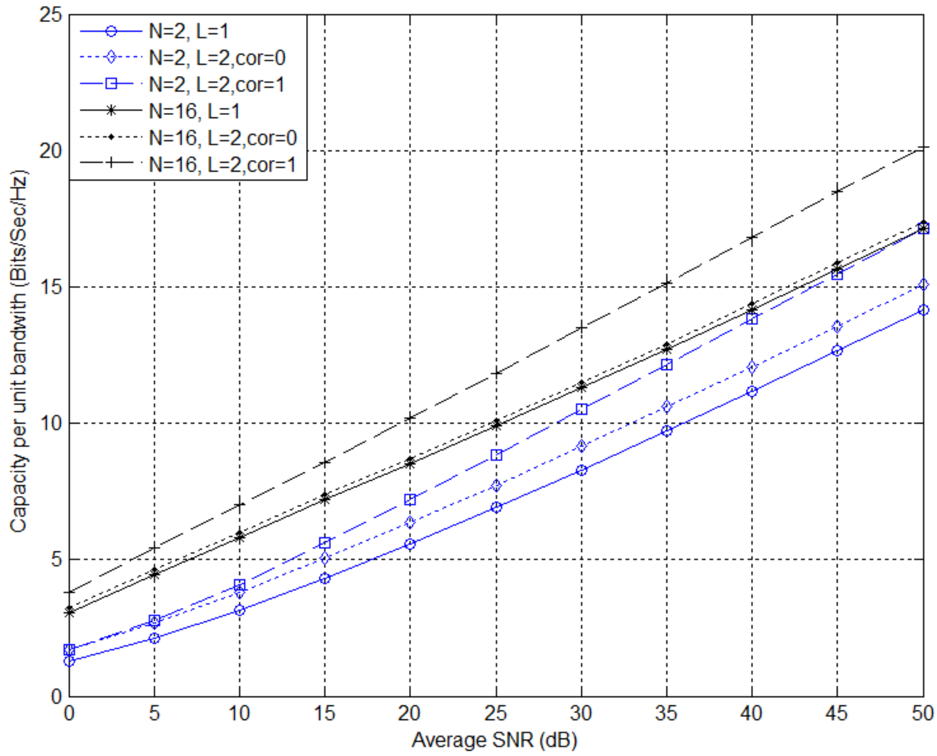


Figure 4- 5 Capacity of CMMA with selective diversity under full transmit correlation

Fig. 4- 5 shows the theoretical sum capacity per unit of bandwidth as a function of average received SNR (λ_x) for a SC-CMMA with two receive antennas under full transmit correlation. These curves are obtained in MATLAB using the closed form expressions (4.43) and (4.44). It is clear that the capacity increases with transmit correlation for example at an average SNR of 30 dB the sum capacity increase from 8.3 bits/sec/Hz to 9.3 when the channels are uncorrelated but with full transmit correlation the capacity increase further to 10.5 . It is also interesting that unlike the uncorrelated channel case, the diversity gain with full transmit correlation becomes independent of the number of CMMA users, as can be seen from Fig. 4.5 the increase in rate at 30 dB for a group of 16 CMMA users with two receive antennas drops to just 0.2 bits/sec/Hz when the channels are uncorrelated. However the increase remains constant at 2.2 bits/sec/Hz with full transmit correlation compared with the two users case. This is expected with transmit correlation since all users will experience their strongest channels at exactly the same receive antennas therefore achieving a diversity order equal to the number of receive antennas.

4.5.3 Capacity of SC-CMMA under full transmits and receives correlation

With full transmit and receive correlation, all channels between users and across receive antennas will have the same envelope. As a result the instantaneous total receive SNR at all receive antennas will be the same. This reduces the achievable diversity gain to null. However due to full channel correlation, the identical composite constellations will be formed at all receive antennas. Therefore it is possible to coherently combine all the received signals from L receive antennas to take advantage of the antenna gain (Power gain) as can be seen from Fig. 4-6.

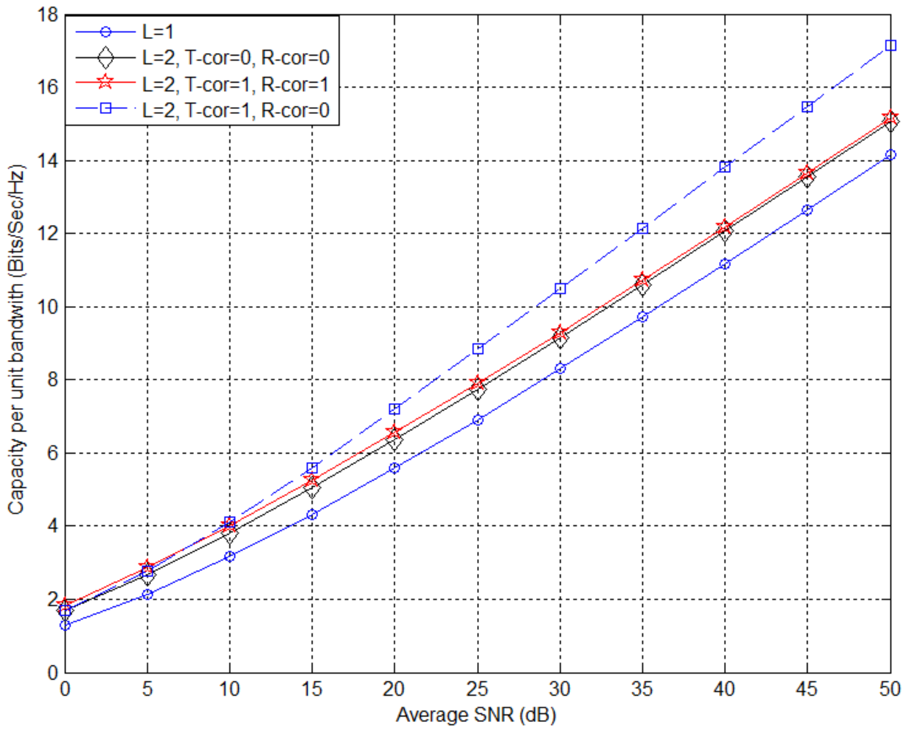


Figure 4- 6 Capacity of 2-User CMMA under different transmit and correlation scenarios

4.6 Conclusion

In this chapter, a thorough study of CMMA capacity using single receive antenna and selection diversity combining has been carried out. Closed form expressions for spectral efficiency (capacity per unit of bandwidth) as a function of average received SNR were found and the performance of CMMA was compared with that of equivalent system using TDMA with multiuser diversity (MUD).

It was shown that the capacity of CMMA increases with the number of users but so does the multiuser interference between them which leads to only non-linear logarithmic increase in capacity. The capacity of CMMA is not affected by channel correlation since users precode their signals independently. However, although very small latency and overheads can be achieved by independent precoding, this comes at the expense of not utilising the inherent multiuser diversity gain when users' channels are uncorrelated; therefore MUD can offer higher capacity than CMMA on the expense of latency and scheduling overheads. However when the number of users increases, the power gain due to superposition increases linearly while additional improvement in diversity gain tend to diminish. Hence the increase in power gain will be more significant therefore the difference in capacity between MUD and CMMA tends to become smaller.

Assuming uncorrelated channels between users, the increase in CMMA capacity due to selection combining for a fixed number of receive antennas tends to drop as the number of users increase. Therefore a higher number of receive antennas is required to achieve the same improvement in capacity. However the capacity of CMMA with selection combining improves remarkably with correlation and becomes independent of the number of users ; as with correlation more users tend to experience their strongest channel at the same receive antenna hence achieving full diversity order.

5 Improved CMMA using Opportunistic Scheduling and Collaborative Coding

5.1 Introduction

This chapter is divided into two main parts. In the first part of the chapter, a new scheme is proposed to combine CMMA with a low complexity opportunistic scheduling algorithm to exploit the multiuser diversity gain inherent due to the independence of users' channel. The second part of this chapter introduces a new scheme combining both collaborative coding and modulation referred to as hybrid CMMA (H-CMMA).

5.2 CMMA with Opportunistic Scheduling (CMMA-OS)

5.2.1 Motivation

In CMMA, the composite constellation is designed centrally at the BS which assigns users with static unique modulation sets that remain constant regardless of the instantaneous channel conditions by employing local precoding at transmitters using only CSI between individual users and the BS. This static assignment of unique modulation sets and local independent precoding was chosen to remove ambiguity and allow simultaneous multiple accesses with the minimum possible feedback and without CSI at the receiver. However this simplicity in design and implementation of CMMA comes at the expense of underutilization of the inherent multiuser diversity that arises from the independence of channels between users and the BS. It naturally follows that a dynamic assignment of modulation sets and code rates to users according to their instantaneous channel conditions and instantaneous correlation among their channels will result not only in the power gain achieved by conventional CMMA but also in diversity gain. However, this dynamic resource allocation using opportunistic scheduling requires both CSI at the transmitters (for precoding and channels) and at the receivers (for scheduling). Moreover, updating the mapping of the composite receive constellation in accordance with real-time CSI adds a significant complexity burden on the BS and requires updating of user's individual modulation sets through a feedback channel from the BS to individual users. This will translate into much higher overhead and require a sizable portion of the channel coherent time to be used for feedback reducing the time available for data transmission. To overcome the above-mentioned problems, in this section we will introduce a new opportunistic scheduling scheme for CMMA which achieves both power and diversity gain with low feedback using only partial CSI at the receiver.

5.2.2 System Model

5.2.2.1 Composite constellation design

To avoid the complexity and excessive feedback associated with the dynamic real-time update of the composite constellation mapping and the consequential requirement to feedback users individually with their new unique modulation sets. The BS will design the composite constellation at the beginning of the data session and this constellation and its constituent unique modulation sets will remain unchanged for the rest of data session. However, unlike conventional CMMA, the BS will take into account the multiuser diversity gain due to the independence of users' channels. Furthermore, although the resulting unique modulation sets will remain constant and will only be fedback to users once at the start of their data session. These modulation sets will no longer be associated with specific users as in conventional CMMA but with the user with a specific diversity order at every frame.

To illustrate how CMMA with opportunistic scheduling works, let's consider a group of N users with fully uncorrelated channels and an average received SNR per user of λ_x. If we sort users according to their instantaneous channel gain into a new equivalent group of N

virtual users where user one in the new group represents the user with the strongest channel at any one time and user N represents the user with the weakest channel at any one time, then the probability density function of user $i \in \{1, \cdots, N\}$ is

$$Pr_i(\lambda) = \frac{N}{\lambda_x} \sum_{k=i-1}^{N-1} (-1)^k \binom{N-1}{k} e^{-(1+k)\lambda/\lambda_x} \tag{5.1}$$

And the average received SNR for user i is:

$$\overline{\lambda_i} = \int_0^{\infty} \lambda \mathrm{Pr_i}(\lambda) d\lambda = \sum_{\mathrm{k=i}}^{\mathrm{N}} \frac{\lambda_{\mathrm{x}}}{\mathrm{k}} \tag{5.2}$$

In other words, the problem now is finding the optimum composite constellation for N users with average power $\{\overline{\lambda_1}, \overline{\lambda_2}, \cdots, \overline{\lambda_N}\}$. This can be achieved through a Monte Carlo search to find the optimum modulation sets and phase offsets for the new virtual N users that form a non-ambiguous composite constellation with the highest possible minimum distance and/or highest possible sum rate for a specific required BER.

The variation in the average received SNRs in the new group makes it easier to design a composite QAM constellation with regular mapping thus achieving higher minimum distance. In addition, assigning users with unique modulation sets according to their instantaneous CSI rather than their long term average reduces the user's probability of outage as when the users experience a weak channel, the corresponding unique modulation set has low average amplitude thus it no longer requires wasting a large proportion of the transmit power to compensate for deep fading.

Once the composite constellation has been designed, its constituent unique modulation sets are sent to all users before the data session starts. Although the N unique constellation sets used to construct the composite received constellation remains constant throughout the session and regardless of instantaneous channel conditions, they are no longer associated with specific users like conventional CMMA but with diversity order. In other words, at the start of each frame the user with the strongest channel always gets issued the unique modulation set containing 2^{k_1} constellation points with mapping $\pi_1(\cdot)$, the second strongest user will be issued unique modulation set containing 2^{k_2} constellation points with mapping $\pi_2(\cdot)$ and so on.

5.2.2.2 Scheduling using opportunistic feedback

In this section, we will introduce a novel mechanism to minimize the feedback required for opportunistic scheduling in CMMA by taking advantage of collusion-free and distributed nature of CMMA. First, we will present an overview of opportunistic scheduling in the first half of this section before moving to introduce our opportunistic feedback approach for CMMA-OS.

5.2.2.2.1 Related work

Excessive feedback, especially when the number of users is large, can outweigh any benefits derived from opportunistic scheduling [93], therefore the issue of reducing the amount of required feedback has been an active area of research. In [93], a simple threshold based scheme restricts feedback only to users whose channel gain is above a predefined threshold. This approach significantly reduces the amount of required feedback at the expense of a small reduction in the overall maximum throughput.

The assumption in [93] is that resources used to feedback CSI are not shared among users. However, this is not the case for most practical systems where feedback is usually done in a TDMA manner thus the feedback period increases linearly with the number of users.

To address this issue, opportunistic splitting was proposed in [94] where each data transmission is preceded by a number of mini slots, which the BS uses to obtain the current CSI of users in a distributed manner. Once the user with strongest channel is identified, data transmission begins. Initially, a number of thresholds depending on the number of users are set and each threshold is assigned to one mini slot. At the start of the first mini slot, every user with current channel gain between the pair of thresholds transmits to the BS. The BS then broadcasts to all the users whether no user transmitted, exactly one user transmitted, or a collision occurred. Depending on the broadcast message received, each user modifies its threshold according to a binary search like algorithm and users whose channel gain is between the new thresholds transmit in the next mini slot. This process continues until collision is eliminated, therefore the number of mini slots before a transmission vary. It was shown that an average of only 2.5 mini slots are required for the algorithm to find the user with the strongest channel. This is significant reduction compared to the linear number of slots required for a centralized feedback scheme.

However, opportunistic splitting requires two way feedback which may constitute a high overhead, especially with the channel coherent time is small or/and the number of users are large. To overcome this coordination problem, a random access based feedback protocol called static splitting was proposed in [91][92], where only users transmit to the BS during the feedback stage. Here, each data transmission is preceded by a fixed number of mini slots. In each mini slot, users with instantaneous channel gain above a predefined threshold transmit with some probability. When no collision occurs the identified user is selected, otherwise one user is selected at random. As expected, opportunistic splitting outperforms static splitting. However, it requires a higher feedback especially when the number of users is large.

5.2.2.2.2 Opportunistic feedback algorithms for CMMA

As in conventional CMMA, the BS will broadcast a common pilot at the start of each frame to enable users to track their CSI and perform precoding. However, in this case, users need to know the relative strength of their channel compared to other users in order to choose which one out of N unique modulation sets they ought to use. To achieve this, we will divide each frame into two periods: a scheduling-period (SP) followed by a data transmission period (TP). Before the scheduling-period (SP) and at the start of every frame, the BS broadcasts a common pilot to all users, so users can use it to locally synchronize their transmission and estimate their channel gain (due to reciprocity property of a wireless channel). The probability density function (pdf) of the channel-gain is divided into regions with identical probability measure defined by a set of thresholds λ_i, $i = 1,...,N$ such that $\lambda_1 \geq \lambda_2 \geq ... \lambda_N$, where N is the total number of unique modulation sets. These regions and their associated thresholds can be computed locally at the users in a distributed manner using CSI obtained from the common pilot. If the channel gain $|h_i|$ of user i satisfies $\lambda_i \leqslant |h_i| < \lambda_{i-1}$, then the user will quantize its channel gain and send a message i out of N possible messages to the BS during the scheduling period using the modulation set assigned to that user in the previous frame. Employing collaborative precoding to send the quantized channel gain messages in the scheduling period will reduce the time required for feedback as all users will send their quantized channel gains simultaneously. Furthermore, if two users happen to transmit the same quantized message (i.e. their channel gains are in the same region), then their feedback messages will not collide, since each user uses a unique modulation set. That is contrary to the commonly used approach of Opportunistic Feedback (OF) in [95] [96], where the SP is divided into a number of time slots and the pdf of the channel gain is quantized into one of these slots. The BS will then simply arrange users in the order of their channel gains and choose one out of $N!$ ordering-combinations to feedback to users. However, as the number of ordering-combinations increases significantly with the number of users, the amount of feedback required becomes prohibitive for a large number of users. Fortunately, since the CSI are already available at the transmitters, users can associate each channel gain region with a specific modulation set out of N possible sets. Therefore, the BS task is no longer informing all users of which modulation sets to be used, but only to correct the choice of modulation set when more than one user experience an instantaneous channel gain in the same region and thus choose the same unique modulation set causing ambiguity in the composite constellation. Since the pdf of the channel gain is divided into *N* regions with equal probability, the probability that a user i falls within a specific region at time t is *1/N.* The probability that N_x (where $N_x < N$) users falls within the same region is $(1/N)^{N_x}$. Therefore, the collusion probability decreases with the number of users in this case making the feedback manageable. The BS will resolve any collision by broadcasting the identities of $N_x - 1$ followed by the new order (modulation set) to be assigned to these users. All other users will assume that their prediction is correct. Then the BS will broadcast a short flag to indicate the end of the SP and to inform users to start sending their data using their new unique modulation sets for the remaining duration of the frame.

5.2.3 Numerical Example

In this section we will demonstrate through simulation how opportunistic scheduling can improve the BER performance of CMMA without incurring any power penalties. We assume that all users and the BS are each equipped with a single antenna. Users transmit over uncorrelated flat-fading Rayleigh channels modelled as a complex Gaussian-distributed with zero-mean and unit variance. Channels change at a rate much slower than the data rate. Therefore, they remain constant over hundreds of symbols. Finally we assume perfect CSI at the transmitters and the BS has perfect knowledge of the order of users' channels.

Let's consider the case where three users transmit simultaneously to a BS employing QPSK modulation with an average symbol power of one per user. Using exhaustive Monte-Carlo search, we will obtain the optimum value for the amplitude and phase rotation between the three users to achieve non-ambiguous composite constellation with the highest possible minimum distance giving the users' power constraint and the average channel gain per user.

For conventional CMMA, the BS allocates a single unique modulation set per user and the precoding is performed locally and independently of other users. Figure 5-1 shows the unique modulation set assigned to the three users and the resulting composite constellation formed from the superposition of these sets. Although the composite constellation is non-ambiguous, it has irregular mapping where constellation points on the periphery enjoy a large separation compared with central points where the majority of constellation points are packed close together. This irregular mapping leads to small overall minimum distance and a considerable difference in error protection between constellation points.

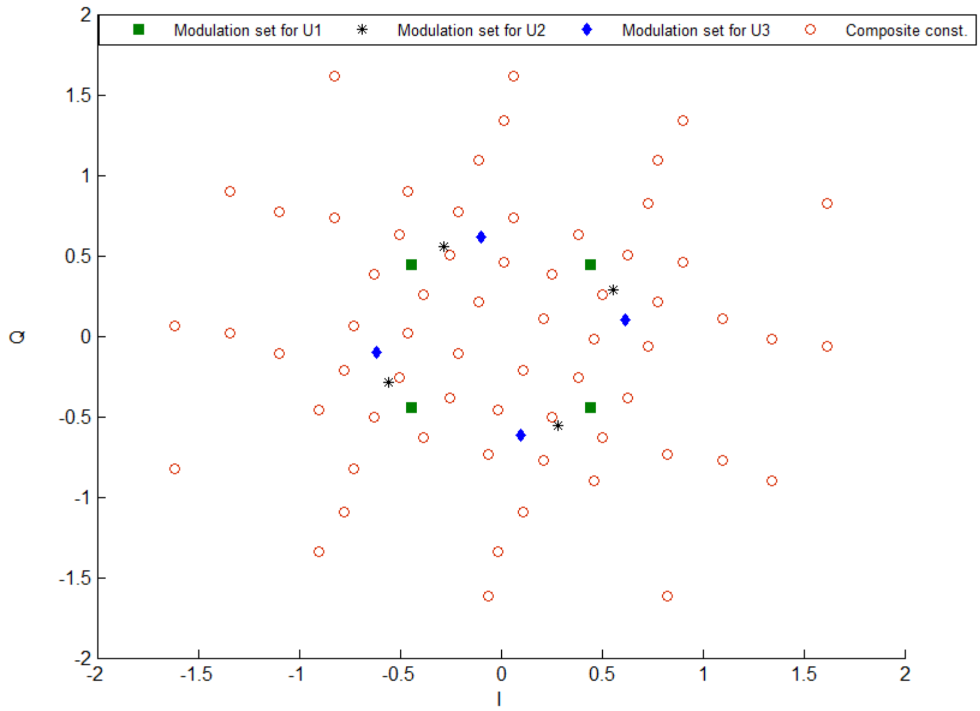


Figure 5-1 composite constellation for three equal power QPSK users with CMMA

CMMA-OS on the other hand, allocates three unique constellation sets to all the three users and the BS ensures that no more than one user employs the same modulation set at any one time. Using the same power constraint and average channel gain of unity per user as before, each user will partition its channel into three virtual independent sub-channels by assuming i.i.d. fading statistics. Each sub-channel is associated with a particular order of that user's channel at any one time compared to other users. One fixed modulation set is assigned to each sub-channel. The average sub-channel gains for users from strongest to weakest according to (5.2) are 1.83, 0.83 and 0.34. The optimal transmit power adaptation is the well-known water-filling where more power is allocated to "better" sub-channels with high SNR, so as to maximize the sum of data rates in all sub channels. Therefore, the average symbol power per modulation set for the three sub channels set are chosen respectively as 1.56, 0.86 and 0.53. This power distribution is chosen to enable the formation of a regular 64-QAM constellation which in turn maximises the minimum distance of the composite constellation for a given power constraint.

Figure 5-2 shows the unique modulation set assigned to each sub-channel and the resulting composite constellation formed from the superposition of these sets. Contrary to conventional CMMA and even though the same power constraint and average channel gain are used, opportunistic scheduling enabled the formation of a non-ambiguous composite constellation with regular mapping. Although the error protection of constellation points on the periphery is still higher than central points, the difference is greatly minimized, leading to 56% increase in minimum distance compared with the case in Figure 5- 1 where no opportunistic scheduling is employed.

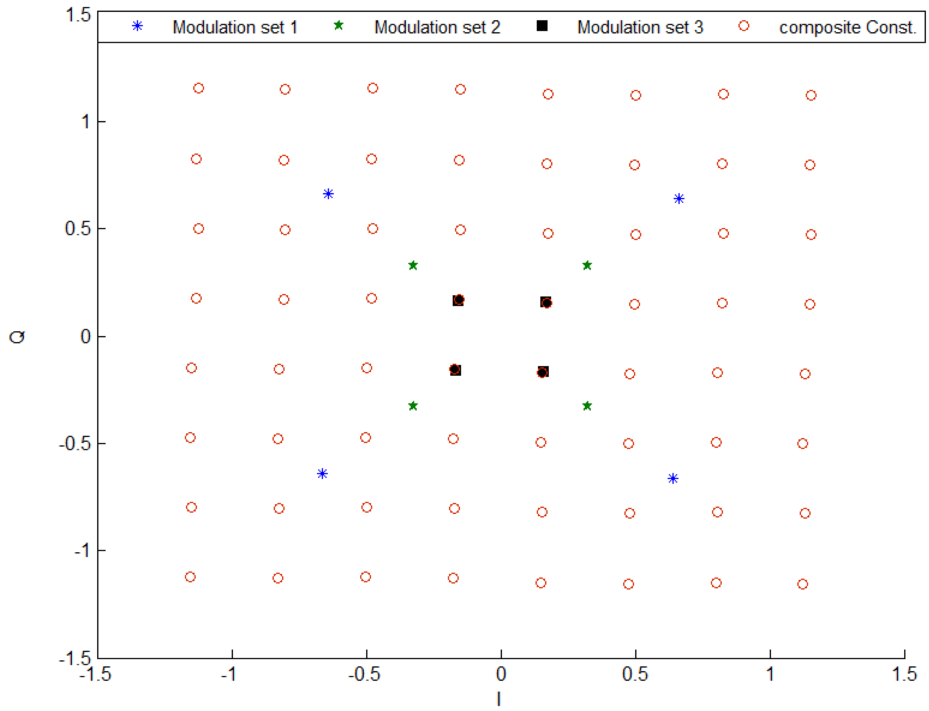


Figure 5- 2 Composite constellation for three equal power QPSK users with CMMA-OP

Figure 5-3 presents the simulation results for three equal power QPSK users simultaneously transmitting to BS using both CMMA and CMMA-OS. The results show that opportunistic scheduling provides a significant improvement of BER over a system where only CMMA is employed. As can be seen from Figure 5-3, the power gain of CMMA-OP is 7dB at BER of 10^{-5}. This increase in power is due both to multiuser diversity gain and constellation mapping gain since CMMA-OS allow the formation of regular constellation.

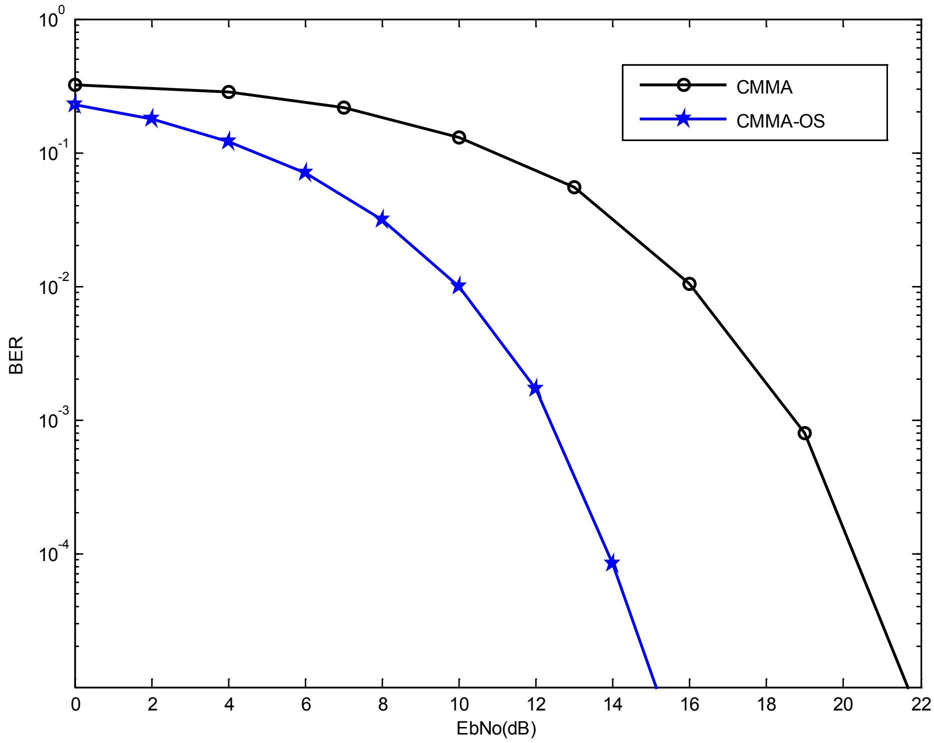


Figure 5-3 BER performance of three equal power QPSK users with CMMA-OP and CMMA

5.2.4 Capacity of CMMA-OS

In CMMA with opportunistic scheduling, the amount of instantaneous transmit power required for precoding varies not only with the channel gain per user but also with the correlation between users' channels. In other words, precoding is no longer local and independent per user but takes account of correlation among users' channel for optimum recourse allocation, hence the total instantaneous transmit power required for channel inversion in this case is linearly related to the sum of channel gains for all users.

Assuming flat Rayleigh fading channel, the average received SNR per user has an exponential distribution with mean λ_x. The probability distribution for a CMMA system with N users with opportunistic scheduling is the sum of N exponential variables which follows a Erlang distribution whose probability density function is given in [84] as

$$\Pr(\lambda) = \frac{\lambda^{N-1} e^{-\lambda/\lambda_x}}{\lambda_x^N (N-1)!} \tag{5.3}$$

where λ_x is the average SNR per user.

In conventional CMMA, the capacity with total channel inversion is zero since precoding is done locally and independently at each user with a fixed modulation set, based on the average channel gain at each user leading to a large portion of the transmit power being used to compensate for deep fading. However, when opportunistic scheduling is used with CMMA, the modulation set for each user depends on its instantaneous channel gain, hence when the user experience a weak channel, the corresponding modulation set will have a low average symbol power as well as limiting the amount of transmit power needed to compensate for the weak channel, and thus making total channel inversion feasible.

Channel inversion with variable power and fixed rate will convert the fading channel model into a time-invariant AWGN channel model. Therefore, the channel capacity $\mathbb{C}$ follows that of the capacity of an AWGN channel is given in [36] as

$$\mathbb{C} = B \log_2 \left(1 + \frac{1}{\int_0^\infty (\Pr(\lambda)/\lambda)\, d\lambda} \right) \tag{5.4}$$

Replacing *Pr* in (5.3) with its value in (5.4) we find:

$$\mathbb{C} = B \log_2 \left(1 + \frac{\lambda_x^N (N-1)!}{\int_0^\infty \lambda^{N-2} e^{-\lambda/\lambda_x} d\lambda} \right) \tag{5.5}$$

Therefore, replacing the value of (4.25) in (5.5) we find:

$$\mathbb{C} = B \log_2 \left(1 + \frac{\lambda_x^N \Gamma(N)}{\Gamma(N-1)} \right) \tag{5.6}$$

Therefore the capacity of a CMMA system with N users using channel inversion and opportunistic scheduling is given as

$$\mathbb{C} = B\log_2(1 + (N-1)\lambda_x) \tag{5.7}$$

The capacity of N users CMMA with channel inversion and opportunistic scheduling given in (5.7) is equal to that of the capacity given in [83] for a system where a single user transmitting to N receive antenna with maximum ratio combining (MRC) equalization and total channel inversion. This is expected as in addition to the power gain provided by collaborative modulation through the coherent addition of users' signals. Opportunistic scheduling enables a diversity gain of order N through the dynamic allocation of unique modulation sets. In summary, a CMMA system with N users whose signals are multiplexed to form a predesigned 2^M-QAM constellation with mapping $\pi_i(\cdot)$ and d_i is equivalent to a scheme where a single user with average power P transmits to N receive antennas using a 2^M-QAM constellation with mapping $\pi_i(\cdot)$, where N received signals are coherently added before detection.

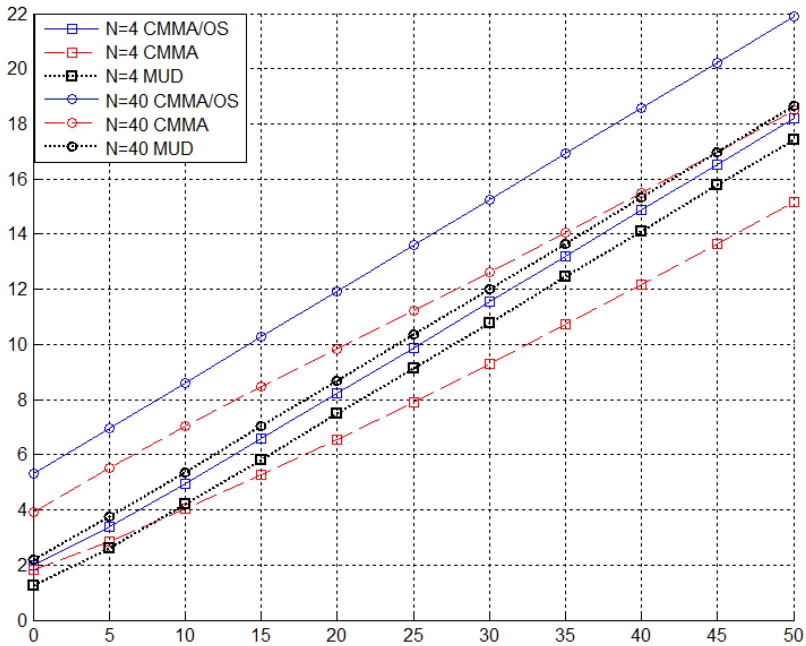


Figure 5- 4 Capacity of CMMA with opportunistic scheduling

Figure 5-4 shows the theoretical sum capacity per unit of bandwidth as a function of average received SNR, λ_x for a CMMA system with opportunistic scheduling and channel inversion for different numbers of users. These curves are obtained in MATLAB using the closed form expressions (5.7). To show the advantage of using opportunistic scheduling with CMMA, we also compared our new system with conventional CMMA using truncated channel inversion, closed form expression (4.6) and with multiuser diversity using water filling with adaptive rate and power using (4.14). As can be seen in Figure 5- 4 the capacity of CMMA with opportunistic scheduling is higher than that of MUD and the difference in performance between the two schemes increases with the number of users. This is because the capacity of MUD is equivalent to that of a selection diversity combining [83] where only diversity gain is exploited, while that of CMMA-OS resembles that of MRC where both power and diversity gain are exploited.

5.2.5 Selective diversity combining for CMMA-OS

In this section, we propose a new simple selection diversity combining (SC) to improve the BER performance and capacity of CMMA with opportunistic scheduling by exploiting the spatial receive diversity, made available by having multiple antennas at the receiver. Selection diversity combining is ideal for CMMA-OS for two main reasons. Firstly, our scheme requires only a single RF chain to operate which greatly reduces the cost of the BS in terms of size, power and hardware. Secondly, selective diversity where only a single antenna is selected is as a trade-off between performance and complexity as it ensures that the composite constellation remains fixed and eliminates the need for full CSI at the receiver.

At the start of every frame, the BS need to scan the L available receive antennas and select the one with the highest total channel gain across all N users. In other words, the BS does not really need to know the individual channel gain between users and every receive antenna but only the sum channel gain at every receive antenna. Therefore, if users ‘signals can be coherently added at each receive antenna, then the BS only needs to measure the SNR at each antenna and choose the one with highest SNR, or even simply use an envelope detector and select the branch with the highest signal plus noise. Embracing this principle, the BS will successively broadcast a pilot from each receive antenna to all N users. Users will use this pilot to extract CSI and then simultaneously transmit one symbol back to the BS all using the same power P while adjusting their phase using CSI, so that all their signals add coherently at the receiver. The BS will then simply measure the SNR of the combined receive signal and switch to the next antenna and repeat the same steps. At the end of the selection process, the BS broadcasts a short message indicating which antenna is selected to initiate the scheduling period (SP).

Since the duration of the selection process scales with the number of receive antennas, when the number of receive antennas is large or when the coherent time of the channel is small (and thus the frame duration is small), the BS can reduce the antenna scanning period by switching to the first receive antenna where a predefined SNR threshold for total channel gain is observed.

It is also worth noting that in a system, the BS limits the number of users per CMMA group to N and divide all active users within the cell into T groups with N users each. If the BS has a single receive antenna and only the group with highest total channel gain is allowed to transmit at any one time, then the BS can use our proposed selection algorithm to select the best group to transmit with relatively small amount of feedback achieving the same capacity and BER performance as a system where N CMMA users are transmitting to a BS with T receive antennas and a single RF chain.

5.2.6 Capacity of CMMA-OS with selective diversity combining

In this section, we will calculate the capacity of a CMMA-OP system with selective diversity combining assuming that there are L receive antennas and the BS will select the antenna S with the highest average channel gain.

The probability of outage for a CMMA-OP system of N users and a single receive antenna is calculated by replacing the value of (5.3) in (4.18) and integrating

$$Pr_{out,CMMA-OP} = \int_0^{\lambda} \frac{t^{N-1} e^{-t/\lambda_x}}{\lambda_x^N \Gamma(N)} dt = \frac{\gamma(N, \lambda/\lambda_x)}{\Gamma(N)} \tag{5.8}$$

where γ denotes the lower incomplete gamma function. For L receive antennas with uncorrelated channels, the probability of outage for all of L branches below λ is simply the product of individual probabilities of N users with single receive antenna.

$$Pr_{out}^{Sel} = \left(Pr_{out,CMMA} \right)^L \tag{5.9}$$

Pr_{out}^{Sel} also represents the pdf of the output SNR as a function of the threshold s. The pdf of the output SNR is therefore obtained by substituting (5.8) into (5.9) and deriving

$$Pr^{Sel} = \frac{dPr_{out}^{Sel}(\lambda)}{d\lambda} = \frac{L}{\lambda_x} [\Gamma(N)]^{-L} \left(\frac{\lambda}{\lambda_x}\right)^{N-1} e^{-\frac{\lambda}{\lambda_x}} [\gamma(N, \lambda/\lambda_x)]^{L-1} \tag{5.10}$$

It follows that for a CMMA-OP scheme with N users and L receive antennas using channel inversion and selection diversity combining, the channel capacity follows that of the capacity of an AWGN channel given in [48]. It is not possible to find a closed-form expression for the capacity for any N number of users with any L receive antennas where we will derive a closed form expression for any N when L=2, 3.

5.2.6.1 Capacity of CMMA-OP with two receive antennas

For L=2

$$\mathbb{C}^{Sel,2} = B \log_2 \left(1 + \frac{1}{y_2}\right) \tag{5.11}$$

Let x= λ/λ_x, substitute y_2 with its value from (5.10) and (5.4) we find:

$$y_2 = \frac{2}{\lambda_x}\ [\Gamma(N)]^{-2} \int_0^{\infty} (x)^{N-2} e^{-x}\ \gamma(N, x) dx \tag{5.12}$$

Then substituting (4.30) and (4.31) into (5.12) and integrating

$$y_2 = \frac{2}{\lambda_x}\ [\Gamma(N)]^{-2} \left\{ \int_0^{\Gamma(N-1)} (N-1)\gamma(N-1, x) d\gamma(N-1, x) - \int_0^{\infty} 2x^{2N-3} e^{-2x}\ dx \right\} \tag{5.13}$$

Then substituting (4.33) into (5.13) and integrating

$$y_2 = \frac{2}{\lambda_x}\ [\Gamma(N)]^{-2} \left\{ \frac{(\mathrm{N}-1)\Gamma(N)^2}{2} - \frac{\Gamma(2N-2)}{(N-1)2^{2n-2}} \right\} \tag{5.14}$$

5.2.6.2 Capacity of CMMA with three receive antennas

Now for *L=3*

$$\mathbb{C}^{Sel,3} = B \log_2 \left(1 + \frac{1}{y_3}\right) \tag{5.15}$$

Then substitute y_3 with its value from (5.10) and (5.4) we find:

$$y_3 = \frac{3}{\lambda_x}\ [\Gamma(N)]^{-3} \int_0^{\infty} (x)^{N-2} e^{-x}\ [\gamma(N, x)]^2 dx \tag{5.16}$$

Then perform integration by parts yields

$$y_3 = \frac{3}{\lambda_x}\ [\Gamma(N)]^{-3} \left\{ [\gamma(N, x)^2 \gamma(N-1, x)]_0^{\infty} - \int_0^{\infty} 2\gamma(N, x)(x)^{N-1} e^{-x}\ \gamma(N-1, x) dx \right\} \tag{5.17}$$

Substitute (4.30) into (5.17) and perform integration by parts

$$y_3 = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\Gamma(N)^2\Gamma(N-1) - \int_0^{\Gamma(N)} \frac{2\gamma(N,x)^2\,d\gamma}{(N-1)}\right.$$

$$\left. - \int_0^{\infty} \frac{2\gamma(N,x)(x)^{2(N-1)}e^{-2x}\,dx}{(N-1)}\right\} \tag{5.18}$$

$$y_3 = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\frac{\Gamma(N)^3}{(N-1)} - \frac{2\Gamma(N)^3}{3(N-1)} - \int_0^{\infty} \frac{2\gamma(N,x)(x)^{2(N-1)}e^{-2x}\,dx}{(N-1)}\right\} \tag{5.19}$$

Substitute (4.39) into (5.19) and perform integration by parts

$$y_3 = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\frac{\Gamma(N)^3}{3(N-1)} - \int_0^{\infty} \frac{2\Gamma(N)(x)^{2(N-1)}e^{-2x}\,dx}{(N-1)}\right.$$

$$\left. + \frac{2\Gamma(N)}{(N-1)}\int_0^{\infty} e^{-3x} \sum_{k=0}^{N-1} \frac{x^{2N-2+k}dx}{k!}\right\} \tag{5.20}$$

Substitute (4.33) into (5.20) and integrate it, we find:

$$y_3 = \frac{3}{\lambda_x}\,[\Gamma(N)]^{-3}\left\{\frac{\Gamma(N)^3}{3(N-1)} - \frac{2\Gamma(N)\Gamma(2N-1)}{(N-1)2^{2n-1}}\right.$$

$$\left. + \frac{2\Gamma(N)}{(N-1)}\sum_{k=0}^{N-1} \frac{\Gamma(2N-1+k)}{k!\,3^{2n-1+k}}\right\} \tag{5.21}$$

5.2.6.3 Results and Discussion

Figure 5- 2 shows the theoretical spectral efficiency as a function of average received SNR, λ for a CMMA-OP system with selection diversity for different number of users and when up to three antennas are available at the receiver. These curves are obtained in MATLAB using the closed form expressions, (5.20), (5.13) and (5.4). Since the probability of outage in CMMA follows that of a position distribution, therefore as the number of users increase, the differences in SNR between receive antennas tend to diminish. Therefore, for a large number of users, a higher number of receive antennas is required to achieve the same

improvement in capacity as will be the case with lower number of users and smaller number of receive antennas.

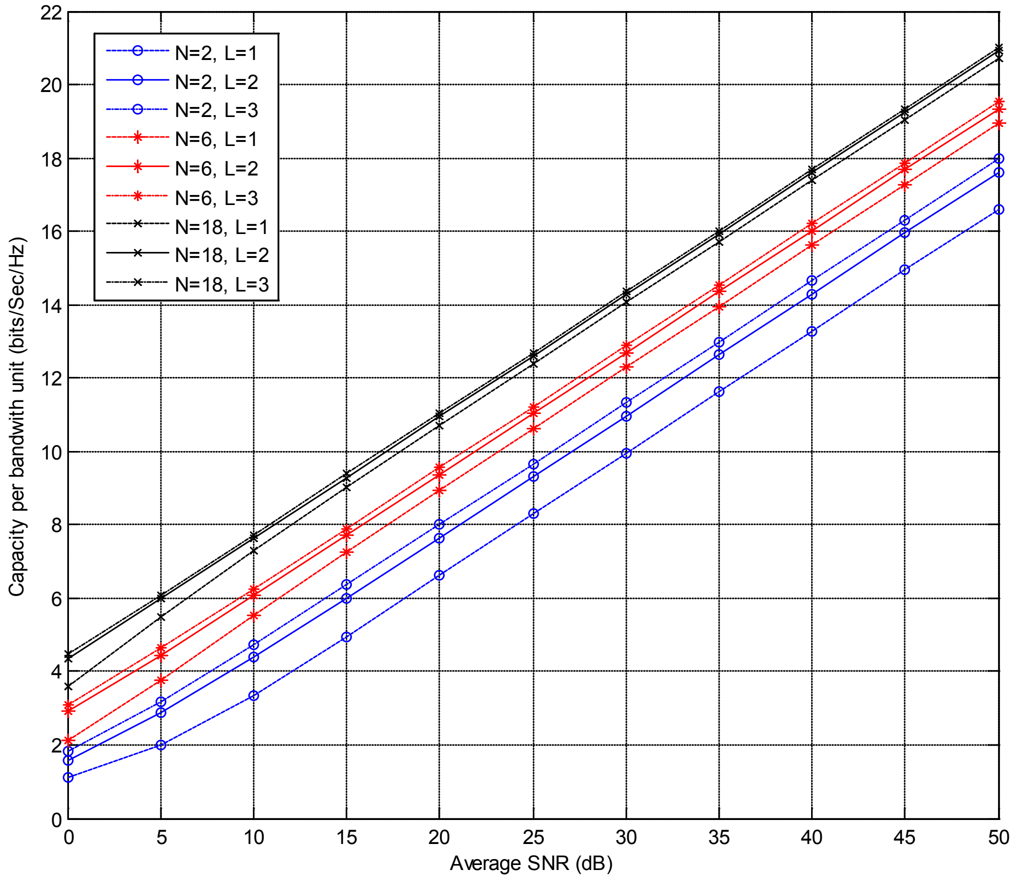


Figure 5- 5 Capacity of CMMA-OP with selection diversity combining

5.3 Hybrid CMMA/CCMA (H-CMMA)

5.3.1 Motivation

CMMA allows a linear increase in sum rate without any reduction in individual rate per user by ensuring the formation of non-ambiguous composite constellation at the receiver. However, the number of constellation points increases exponentially with the number of users while the power gain from the coherent addition of users' signals only increase linearly. In addition, the optimum mapping of the composite constellation is highly related to the average distribution of users' channels (i.e. their large-scale fading and location within the cell). Users located near each other in respect to the BS are likely to have correlated channel with similar average channel gain which in return leads to the formation of composite constellation with irregular mapping and sub-optimal minimum distance. Reduction in the minimum distance due to number of users or channel distributions will lead to degradation in BER performance compared with a single user transmission.

Hence while CMMA is very bandwidth efficient, it is power limited, since more power is needed to compensate for the drop in BER performance when the number of users increases. In addition to the BER performance degradation, the complexity of the joint ML detection in CMMA increases significantly in an exponential manner with the number of users.

These two issues raise some important questions: how can CMMA maintain an acceptable QoS while serving large number of users without increasing the users' transmit power? And how can the BS limit the complexity of ML detection when the number of users is large?

The answer to these questions lies in the flexible design of composite constellation that, while making use of all the available transmit power of users and maintaining the simple one-way feedback structure of CMMA can also vary the size of the composite constellation, and thus the resulting minimum distance according to the required QOS.

To avoid the above mentioned problems and contrary to CMMA, Collaborative Coding Multiple Access (CCMA) allows ambiguity in the received composite constellation, i.e. the number of unique constellation points is less than all the possible mutations of users' data. This ambiguity makes the power gain resulting from the coherent addition of users' signals sufficient to compensate for the reduced expansion in constellation size thus maintaining the same minimum distance for the composite constellation compared with a single user. However, this ambiguity is resolved using multiple access codes which in turn reduce the rate per user compared with a single user. Hence, although CCMA has robust BER performance, the length and/or size of code words increases with the number of users, thus reducing the rate per user and leading to a diminishing gain in sum rate.

However, the implementation of CCMA in Rayleigh fading channels is difficult since the varying gain, phase and delay of the fading channel makes the coherent addition of users' channels challenging. However, the centralized composite constellation design and the distributed independent local precoding strategy proposed to implement CMMA can also be used for the coherent combining of codewords in CCMA.

Both the synergies and contrasting characteristics of CCMA and CMMA make them quite easy to integrate and very compatible to provide both a power and bandwidth efficient collaborative multiple access, especially in environments with low-to-medium SNR and/or when the number of users that need to access the network is large.

A hybrid CCMA/CMMA scheme which will be referred to as H-CMMA can increase the minimum distance of composite constellation, reduce the complexity of ML detection and provide a robust BER performance without any increase in transmit power at the expense of a small reduction in rate per user. H-CMMA allows the BS to adapt to changes in SNR and number of users by adjusting the ratio between the number of unique collaborative codes and unique modulation sets. For example, for a group of *N* users each employing BPSK modulation, H-CMMA can switch from a system with *N* unique collaborative codes and a single modulation set when the SNR is low (to maximise the minimum distance) to a system with *N* unique modulation sets and no collaborative coding when the SNR is high (to maximise the rate). An example of H-CCMA is shown in Figure 5.6 where four users are divided into two groups. Users inside each of the two groups in Figure 5.6 use the same modulation set to precode the amplitude and phase of their data according to the value of the received forward pilot transmitted from the BS. Before performing precoding, both users inside each group encode their data with a unique MAC code. Modulation sets used in groups A and B are designed at the BS to form non-ambiguous fully decodable constellations according to composite constellation design explained in the third chapter.

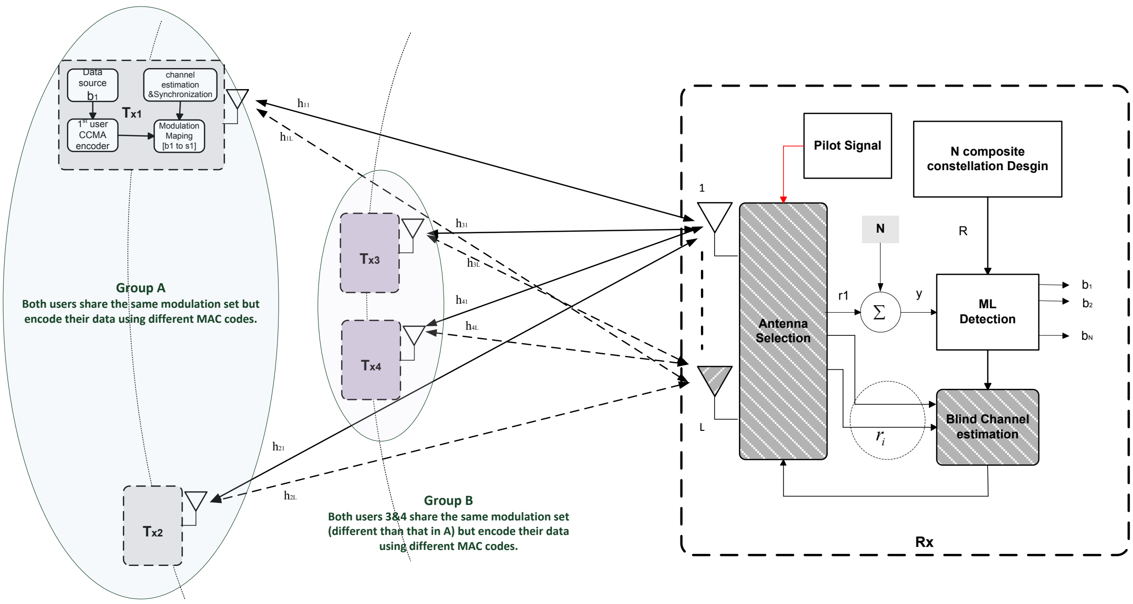


Figure 5- 6 Example of 4-user H-CMMA

5.3.2 System model

Below is a summary of the basic operation of H-CMMA:

- The BS station uses its knowledge of users' average channel gain to divide users into T subgroups. Users with similar average channel gain (i.e. similar distance to the BS) will be grouped together. The number of users in each subgroup can also be different.
- Users within a single subgroup will be assigned unique collaborative codes of length z to guarantee full decodability. These codes can be reused for users in other subgroups. Since the length of collaborative codes increases with the number of users within a subgroup leading to a reduction in individual users' rate, the number of users per subgroup should be kept to a minimum.
- The BS will treat each subgroup as a single CMMA user and assign all users within that subgroup with the same collaborative modulation set. Unique modulation sets will be used for different subgroups designed by the BS to remove ambiguity among different subgroups and to maximise the minimum distance of the composite constellation.
- The data session will be divided into a number of frames where the duration of each frame is less than the coherent time of the channel so that the channel can be assumed to remain static for the duration of at least one frame and change independently between frames
- Each frame is preceded by a common pilot broadcasted from the BS to enable users to extract their CSI to adjust their transmission and maintain synchronization.
- Users will first encode their data using their assigned collaborative codebook (if one is assigned) and then perform collaborative precoding to adjust the amplitude and phase of their transmitted signal according to their CSI to ensure that their received signal belongs to the unique modulation set assigned to that user by the BS.

- During every symbol interval, the received symbol value $y(t)$ formed from the superposition of all signals from N users will belong to the composite constellation predesigned by the BS.
- The number of unique constellation points within this composite constellation will be less than the sum rate of all users, since users belonging to the same subgroup use the same modulation set which leads to ambiguity. However, due to collaborative coding any sequence of z consecutive composite signals will form a unique code word. Therefore, the optimum detection technique is joint ML detection which finds the nearest valid code word of length z out of all permissible code words.

5.3.3 Code and Constellation Construction

A collaborative multiuser codebook of length z is said to be fully decodable if all the received composite code words resulting from users' transmission are unique. Various code constructions for the synchronous MAAC have been proposed over the years assuming full bit and block synchronisation [1-4]. Codes with short block length were found to be the simplest and proven to give the highest sum rate [33]. The most widely used uniquely decodable collaborative codes are the two-user and three-user [82][33] codes given below in Table 5- 1 and Table 5- 2, respectively. For the two users case, a widely used code is proposed by [82] where user one has two code words C_1= *(00, 11)* and user two has three code words C_2= *(00, 01, 10)* where the subscripts represent the user number. The individual rates for users one and two are R_1=*0.5* and R_2=*0.792*, respectively. The composite coding scheme, shown in Table 5-1, has therefore a sum rate R_{sum}=R_1+R_2=*1.292* (bits/channel use).

Table 5- 1 Two-user uniquely decodable code

User1/User2	00	01	10

00	00	01	10
11	11	12	21

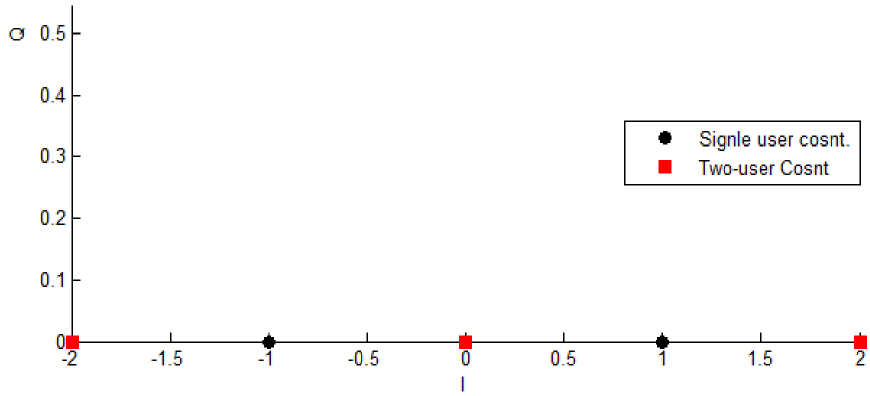


Figure 5- 7 Composite constellation for two users using collaborative coding as in Table 5.1

For three active users, we consider the coding scheme introduced in [33] where the uniquely decidable code C_1 = (11, 00), C_2 = (10, 01), C_3 = (10, 00) are used. Table 5.2 represents the encoding table for the three-user scheme where User 1 and User 2 codes have already been combined. Since only two code words of length *z=2* are assigned per user in this scheme, the individual rate is $R_1 = R_2 = R_3 =$ 0.5 bits/channel use, and the total rate sum in this case is R_{sum} = 1.5 bits/channel use.

Table 5-2 Three-user uniquely decodable code

User3/User1+User2	21	10	12	01
10	31	20	22	11
00	21	10	12	01

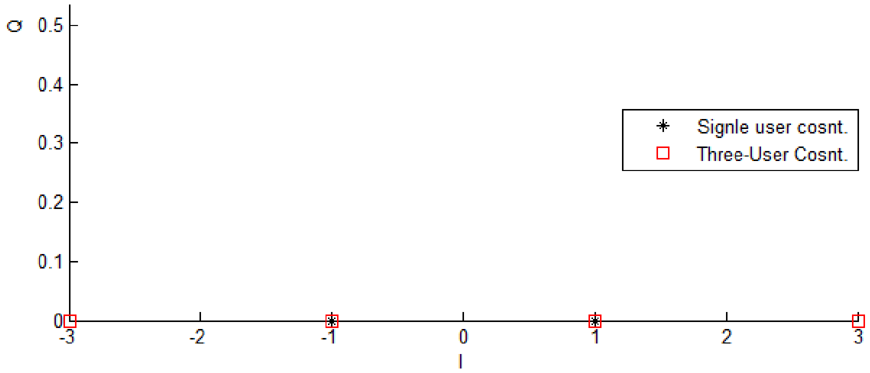


Figure 5- 8 constellation for three users using collaborative coding as in Table 5.2

A collaborative coding schemes for five users where *z=3* and sum rate R_{sum} = 1.67 has been proposed in [36].

In [37], a new set of collaborative codes was introduced for various numbers of users *N* using multi-level digital modulation of order *M*, it was shown that the minimum codeword length in this case will be *N+1* and the number of unique code words per user is *M.*

Figures 5.6 and 5.7 respectively shows the composite constellations formed from the coherent addition of two and three users with equal power and BSPK modulation, the number of unique constellation points in this case is *N+1* as opposed to 2^N unique constellation points required for full decodability without the need for collaborative coding. However, the interesting observation from these figures is that the minimum distance between the unique constellation points remain unchanged when compared with a signal user case, this combined with optimum joint ML detection and short code lengths imply the BER performance of these composite constellations will not degrade when more than one users are multiplexed together using CCMA in contrast to that of CMMA.

Let's now consider an uplink communication system where *N* users each employing BPSK modulation simultaneously transmits to a BS with a single receive antenna using H-CMMA. We divide users into *T* subgroups where the number of users for each subgroup is $\sum_{j=1}^{T} Nc_j = N$. Each user within a subgroup is assigned with a unique collaborative code of length z_j then added coherently with the rest of the users within that subgroup to form a composite constellation consisting of $Nc_j + 1$, $j=\{1,2,....T\}$ unique constellation points. Each subgroup will then be treated as a single user and a Monte Carlo search will be carried out to find the optimum power and phase rotation between the *T* composite constellation that ensures both full decodability and a maximum achievable minimum distance for a given total average transmit power. The number of unique constellation points for the received composite constellation formed from the *N* users will be $\prod_{j=1}^{T}(Nc_j + 1)$ compared to 2^N for CMMA.

In Table 5- 3, we compared the size of the received composite constellation for different number of users under CMMA and H-CMMA with a variable number of subgroups *T* assuming equal number of users in each subgroup. It can be clearly seen that for the same number of users and total transmit power, the number of constellation points in H-CMMA can be reduced significantly compared with CMMA which in turn significantly reduce the number of calculations required for ML detection and increase the minimum distance of the composite.

Table 5- 3 : Number of unique composite constellation points for N users employing BPSK modulation under CMMA and H-CMMA with variable number of subgroups

N	**4**	**8**	**12**
CMMA	16	256	4096
H-CMMA (*T*=*N/2*)	9	81	729
H-CMMA (*T*=*N/4*)	5	25	125

5.3.4 Simulation Results

In this section, we will demonstrate through simulation how H-CMMA improves the BER performance of CMMA. We assume that users and the BS are each equipped with a single antenna. Users transmit over uncorrelated flat-fading Rayleigh channels are modelled as a complex Gaussian-distributed with zero-mean and unit variance. Channels change at a rate much slower than the data rate, therefore remaining constant over 100s of symbols. We assume perfect CSI at the transmitters.

5.3.4.1 Example 1: Four equal-power users

Let's consider four users transmitting simultaneously employing BPSK modulation with an average symbol power of one per user. Using exhaustive Monte-Carlo search, we obtained the optimum value for amplitude and phase rotation between users to achieve non-ambiguous composite constellation with the highest possible minimum distance giving the users' power constraint and the average channel gain per user. Figure 5-8 shows the received composite constellation formed from the superposition of four users' signals at SNR of 15 dB. Now let's divide the four users into two groups where users within the same group use the same unique modulation set (coherently combined) and are separated by the collaborative coding scheme shown in Table 5-1. Figure 5-9 shows the received composite constellation in this case where the minimum distance of composite constellation formed using H-CMMA scheme remain unchanged compared with that of a single user while in the CMMA it drops by 48%. Figure 5-10 shows the BER performance of the two different scenarios. CMMA can achieve a rate of 4 bits per channel use on the expense of 5.7 dB drops in BER performance compared with a single user case. H-CMMA on the other hand achieved only a sum rate of 2.584 bits per channel use while preserving the BER performance of a single user. It is worth noting that the BER performance can also be reserved by dividing the users in a TDMA fashion into two time slots and where two users with a 90 degree phase rotation transmit per time slot but the achievable sum rate in this case is 2 bits/channel use (22.6 % reduction compared with H-CMMA).

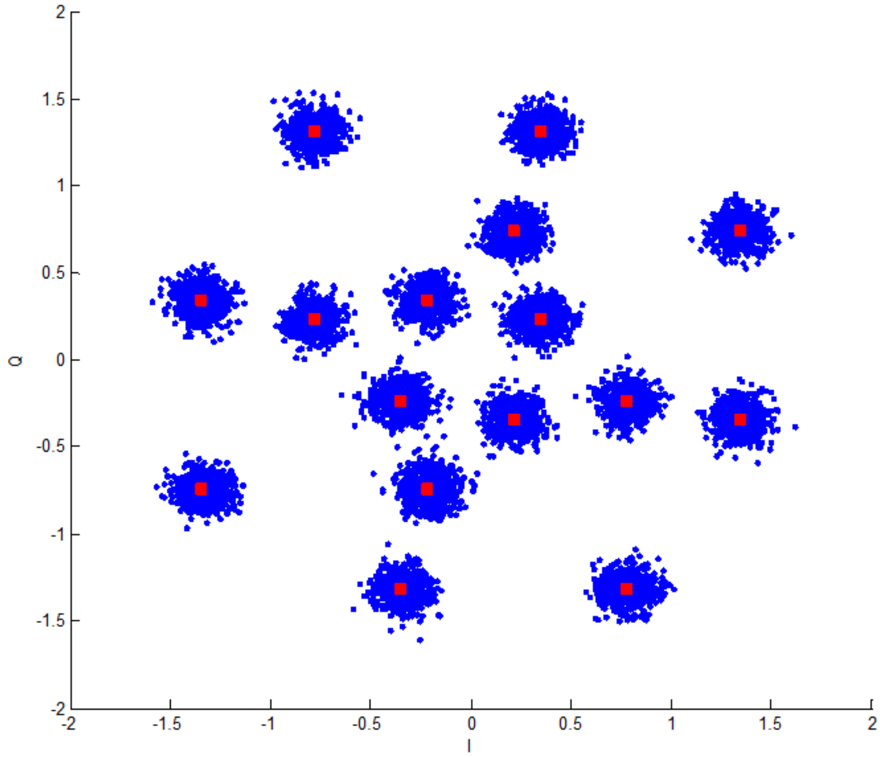


Figure 5- 9 Receive composite constellation of four equal- power users using CMMA at SNR of 15 dB

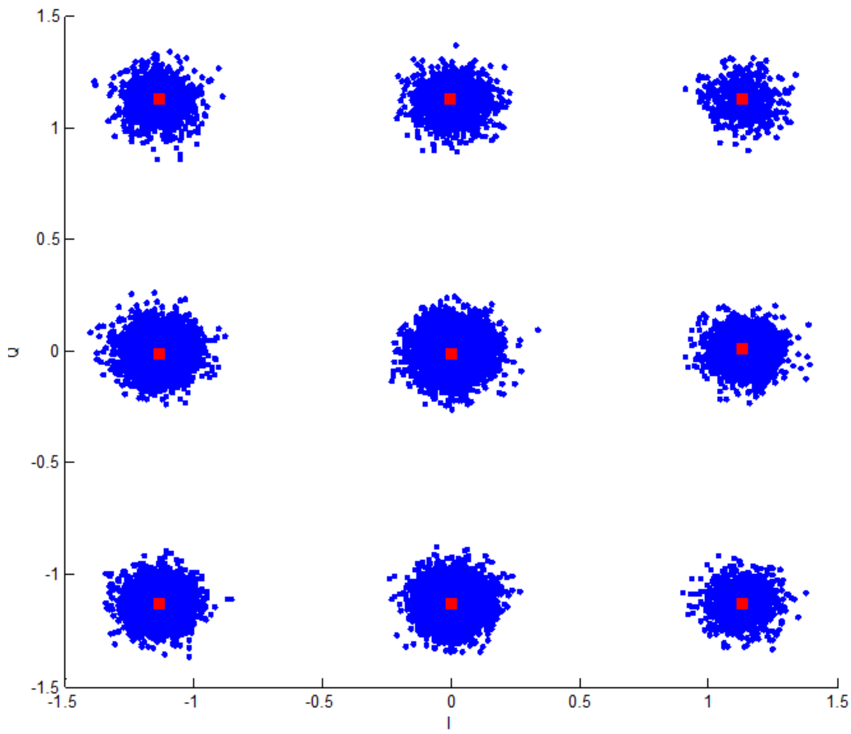


Figure 5- 10 Receive composite constellation of four equal-power users using H-CMMA at SNR of 15 dB

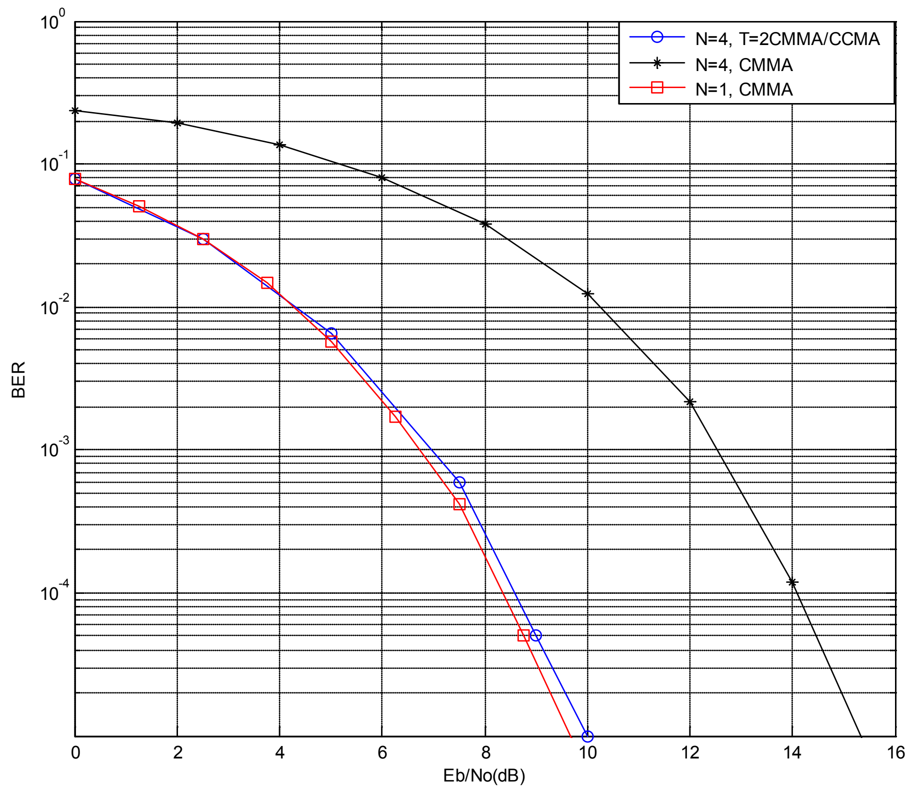


Figure 5- 11 BER performance of four users with equal powers using CMMA and H-CMMA

5.3.4.2 Example 2: Six equal-power users

Let's consider the case where six users transmit simultaneously employing BPSK modulation with an average symbol power of one per user. Using exhaustive Monte-Carlo search, we obtained the optimum value for amplitude and phase rotation between users to achieve non-ambiguous composite constellation with the highest possible minimum distance giving the users' power constraint and the average channel gain per user.

As the number of users increases, H-CMMA becomes even more effective as more combinations of subgroups can be formed from the main group and the rate vs. BER performance can be varied more flexibly depending on the received SNR and QOS requirement for different users. Table 5-4 shows a number of possible combinations for a group of six users ranging from a rate of 3 bits/channel use with no degradation in BER performance to a maximum rate of 6 bits/channel use on the expense of 12.5 dB in BER performance. It can also be seen that users can be allocated different rates depending on their QOS requirement. For example, if one or more users require a higher rate, no collaborative code is assigned to these users and they are directly multiplexed with other subgroups employing only collaborative modulation. Figures 5-11 to 5-14 shows the received composite constellations and their constituent modulation sets for H-CMMA combinations configured as in Table 5-4. As expected the number of unique constellation points and the mapping of the composite constellation can be varied to achieve the required minimum distance and manageable complexity. For example, the number of constellation points can be reduced by four folds compared with the 64 constellation points formed from using only CMMA as can be seen in Figure 5- 11.

Table 5- 4 Different group configuration of six BPSK users employing CMMA, CMMA/TDMA, and H-CMMA showing trade off between sum rate and required SNR to achieve a fixed BER compared with a single BPSK user (non-collaborative case).

Scheme	*Collaborative Code (CC)*	***R*(bits/sec) *per user***	R_{sum} (bits/sec)	*cosnt. size*	d_{min}	***SNR*(dB)**
CMMA	*None*	R_i=1, $i=\{1,2...,6\}$	6	64	0.345	12.5
CMMA/TDMA (*T*=2)	*None*	R_i=0.5, $i=\{1,2...,6\}$	3	8	1.05	5.5
CMMA/TDMA (*T*=3)	*None*	R_i=0.34, $i=\{1,2...,6\}$	2	4	2	0
H-CMMA (*T*=2)	$C_1 = C_4$ = (11,00); $C_2 = C_5$ = (10,01); $C_3 = C_6$ (10,00)	R_i=0.5, $i=\{1,2...,6\}$	3	16	2	0.2
H-CMMA (*T*=3)	$C_1 = C_3 = C_5$=(00,11) $C_2 = C_4 = C_6$=(00,01,10)	$R_1=R_3=R_5$ =0.792 $R_2=R_4=R_6$ =0.5	*3.876*	27	1.1	5.2
H-CMMA (*T*=3)	C_1 = (11,00); C_2 = (10,01); C_3 = (10,00) C_4=(00,11) ; C_5=(00,01,10) C_6=None	$R_1=R_2=R_3=R_4$ =0.5 R_5=0.792 R_6=1	*3.792*	24	1.528	2.35
H-CMMA (*T*=4)	$C_1=C_2$=None; $C_3=C_5$=(00,01,10); $C_4 = C_6$=(00,11)	$R_1=R_2$=1 $R_3 = R_5$=0.792 $R_4 = R_6$=0.5	*4.584*	36	1.04	5.6

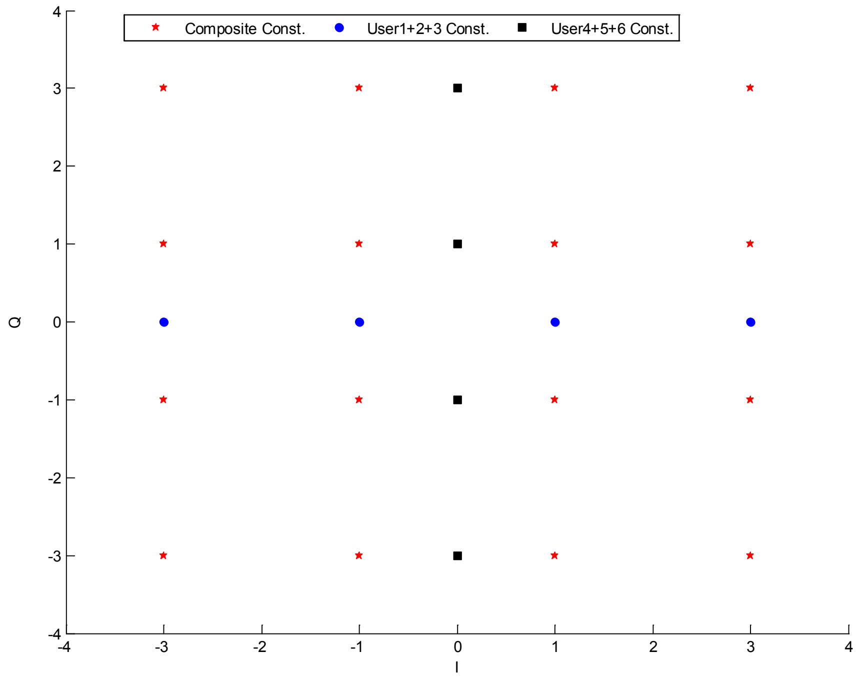


Figure 5- 12 composite constellation for six equal power BPSK users with H-CMMA (T=2 (3, 3))

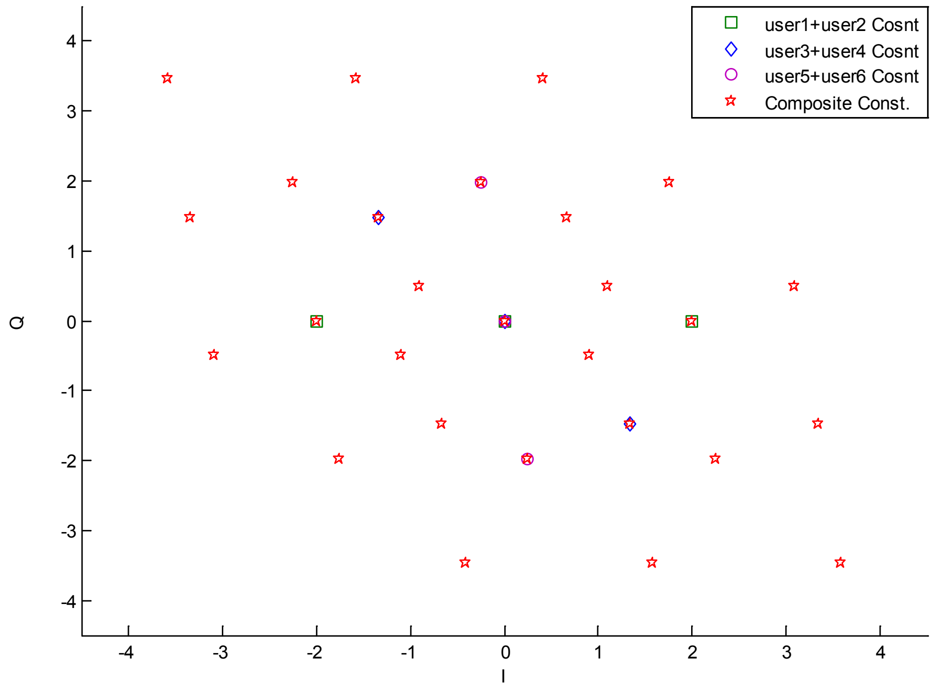


Figure 5- 13 Composite constellation for six equal power BPSK users with H-CMMA (T=3(2, 2, 2))

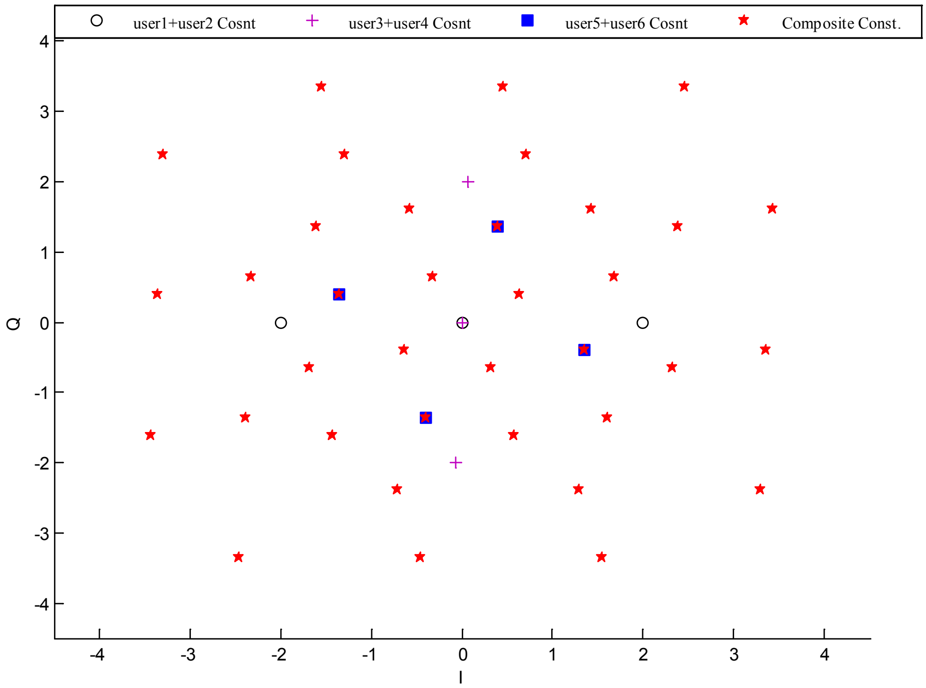


Figure 5- 14 Composite constellation for six equal power BPSK users with H-CMMA (T=4(2,2,1,1)) as configured by Table 5- 4

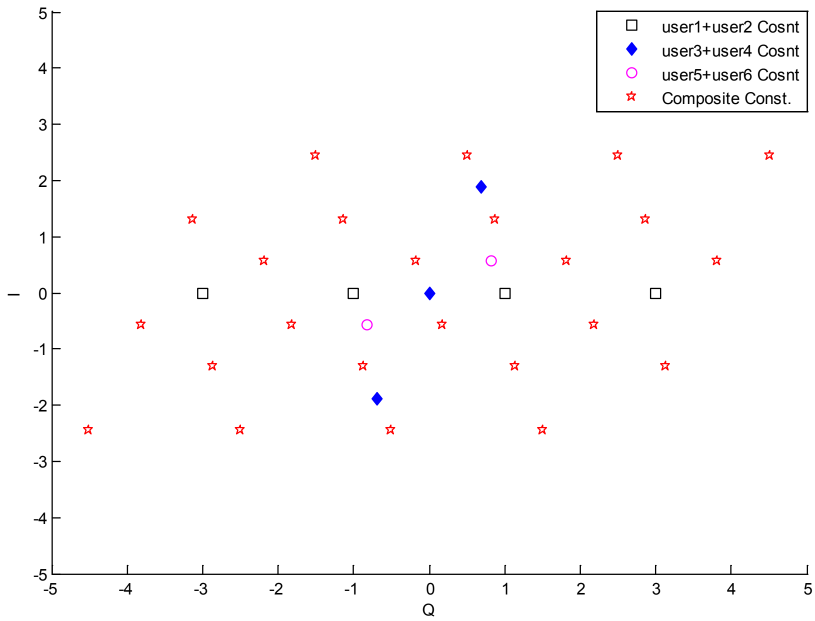


Figure 5- 15 Composite constellation for six equal power BPSK users with H-CMMA (T=3(3, 2, 1)) as configured by Table 5- 4

Figure 5- 15 shows the BER performance of various H-CMMA combinations obtained from Monte Carlo simulations using MATLAB. It can be seen that even with a small reduction in rate as in the case for H-CMMA with *T=4(2, 2, 1, 1)*, R_{sum}*=4.584,* the BER performance improves by 7 dB compared with CMMA. This is due both to the reduction in the number

of unique constellation points from 64 to 36 and the more regular mapping (more equal distribution of constellation points) which leads to increased minimum distance between constellation points. It can also be seen that with an H-CMMA *T=2(3, 3)*, the BER performance approaches that of a single user while achieving a threefold increase in rate compared with a single user case. It also achieves a gain of 5 dB in BER performance over a TDMA based approach with the same sum rate where the six users are divided into two time slots. This rate can be increased to 3.792 bits/channel use by adding another subgroup with configuration *T=3(3, 2, 1)* with only a modest 2.35 degradation in BER performance.

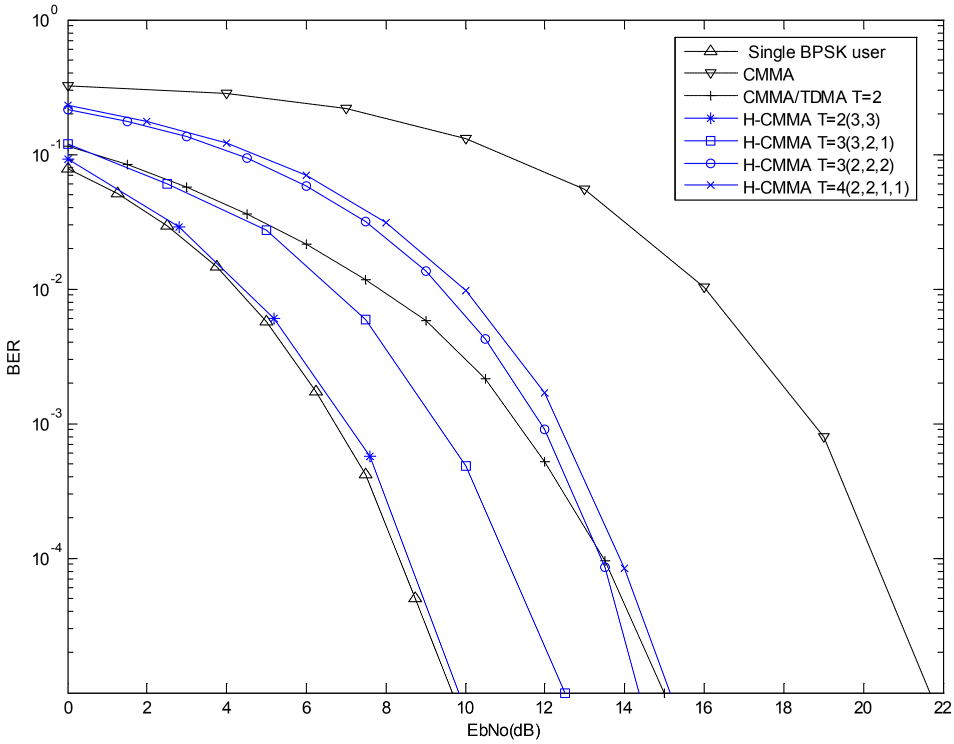


Figure 5- 16 BER Performance of six users with equal Power employing BPSK modulation under different H-CMMA formation as configured in Table 5.4

5.3.5 Conclusion

In this section, we introduced a hybrid approach combining both collaborative coding and modulation referred to as H-CMMA. H-CMMA can adjust the minimum distance of the received composite constellation by varying the number of unique constellation points for the same average total power. This hybrid approach enables CMMA to accommodate large number of users while flexibly managing the complexity and BER performance of the combined simultaneous transmissions of these users. H-CMMA can also simultaneously accommodate users with different QOS requirements (in terms of rate and BER performance). It was shown that for a fixed sum rate and same number of users, H-CMMA is superior to a more conventional approach to reduce complexity and increase minimum distance using time division with CMMA. H-CMMA can also be seen as a practical method of implementing CCMA in fading environments while achieving higher rates and user capacity than that possible with conventional CCMA.

6 Cooperative Modulation (CM)

6.1 Introduction

Conventionally, the advantages of cooperative diversity come at the expense of a reduction in spectral efficiency due to the half-duplex constraint and the orthogonal relaying transmissions since users must transmit on orthogonal channels in order to take full advantage of the multiple available paths. In this chapter, we introduce a new two user's low-overhead channel-aware cooperative diversity that uses scheduling and adaptive modulation to take advantage of the spatial diversity achieved through cooperation while maintaining the same bandwidth compared with direct transmission. To extend our adaptive scheme for more than two users, we propose a new set of high spectral efficiency cooperative diversity schemes referred to as cooperative modulation (CM). CM utilises the concepts of opportunistic scheduling and collaborative modulation to enable N active users to share the same bandwidth over two consecutive time slots and retain a diversity gain in the order of N.

6.2 Overview of Cooperative Communications

In cooperative communications, neighbouring mobile users with a single receive antenna can achieve spatial diversity by relaying each other data due to the broadcast nature of the wireless channel and the fact that these users experience independent fading channels. Due to practical restrictions, mobile devises cannot perform perfect echo-cancelation; hence most practical cooperation schemes consider half-duplex transmission where users transmit and receive at different times. Although users allocate some of their resources (i.e. time, power, etc.) to relay other users' data , the achieved spatial diversity gain is big enough to offset any costs enabling higher throughput, reliability, net power saving, and extended cell coverage. The origin of cooperative communication can be traced to the pioneering work by Van der Meulen [97] who introduced the relay channel and by Cover and El Gamal [98] who proposed a number of relaying schemes and analysed the capacity of the degraded relay channel. Despite the importance of their work, cooperative communication is different than relay networks in two aspects. Firstly, in its purpose to provide spatial diversity in a fading channel and secondly users in cooperative networks act both as sources and relays.

Sendonaris in [99] presented a Code-Division Multiple Access (CDMA) implementation of decode and forward cooperation scheme where two users (each with its own spreading code) cooperate with each other over three-bit-interval cycles. In the first and second intervals, each user transmits its own bits and tries to detect its partners' bits. In the third interval both users transmit a linear combination of their own second bit and the partners second bit, each multiplied by the appropriate spreading code using superposition coding. The powers for the three intervals are allocated such that an average power constraint is maintained and varied accordingly to the conditions of the uplink and interuser channels. Also the BS needs to know the interuser channel information for optimal decoding.

However, the first practical cooperation schemes based on time division among users was proposed by Laneman in [100][101]where nodes transmit their data using separate time slots each consisting of B channel uses in the non-cooperative case. When they cooperate, each user divides its time slot into two equal periods. In the first $B/2$ channel uses of a user designated time slot, it transmits its own data which will be received by both its partner and the BS. During the second $B/2$ channel uses, it relays the data received from its partner during the previous time slot. Laneman proposed three relaying approaches using amplify-and-forward and adaptive decode-and-forward, respectively in [100] [101]. In the amplify-and-forward scheme, users will not attempt to decode their partner signal and will just scale the power of the partner's received signal to satisfy a power constraint and relay it to the BS which will in turn combine it with the previously received signal from the original user. For the adaptive decode-and-forward scheme, users will try to decode their partner's signal, if successful, they will re-encode the partner's data and transmit it during the second half of their time slot, and otherwise the user will return to non-cooperative mode and re-transmit its own data. This scheme therefore takes into account the strength of inter-user channel and insures that cooperation is only performed when it is beneficiary.

However, both schemes don't make efficient use of the available degrees of freedom of the channel, users relay their partners' data, even when it has been successfully received by the BS during the original transmission from the source, therefore Lineman [101] in proposed an incremental relaying scheme that exploits limited feedback from the BS to indicate whether the direct transmission was successful, therefore decreasing unnecessary relaying and improve spectral efficiency. Due to the half-duplex constraint and the fact that users repeat each other data constituting a low-coding-gain repetition code, these schemes provided through spatial diversity enable increased reliability and lower transmit power on the expense of doubling the bandwidth compared with direct transmission for a given rate.

To avoid the use of repetition coding and maintain the same rate as in direct transmission, Hunter proposed in [102] [103] [104] [105] coded cooperation where cooperation is integrated with channel coding. In coded cooperation, each user will encode K information into B coded bits per block, so that $R = K/B$. Then the N bits codewords will be partitioned into two segments of lengths $B1$ and $B2$ transmitted over two successive time frames. In the first frame, a sub-codeword of rate $R1 = K/B1$ is broadcasted to both the BS and the partner. The partner will attempt to decode $B1$ and if successful will generate and transmit the $B2$ bits for the partner; Otherwise $B2$ additional parity bits for the user's own data will be transmitted instead. Since different segments of the codewords are transmitted by two independent fading channels, spatial diversity gain as well as coding gain can be achieved. Different channel codes can be used in coded cooperation, Hunter employed Rate-

Compatible Punctured Convolutional (RCPC) codes in [102] and space-time and turbo coding in [105] which are more suitable in fast fading scenarios.

Chen in [106] proposed a network coding approach to cooperation to enable more than two users to cooperate thus achieving a diversity gain in the order of the number of users while maintaining a fair distribution of resources between participating users and without employing extra resources compared with conventional cooperative schemes. Like other schemes mentioned earlier, each user divide its transmission into two time slots. During the first time slot, it transmits its own data to both the BS and its partners. However, during the second time slot it will combine the data received from its partners during previous time slots using linear network coding and transmits the result.

Xiao in [107] proposed another network coding approach to cooperative diversity featuring the algebraic superposition of convolutional channel codes over a finite field. Each user will pseudo-randomly interleave previously detected data from its partner before combining it with its own encoded data using linear network coding and then broadcasting the combined packet over its own time slot to both its partner and the BS. Its partner will use its *a priori* knowledge of its own data relayed within its partner packet to extract its partner data while the BS will detect users' data by iterative processing in a back-and-forth manner over a window of B consecutive codewords from both users. The extrinsic information from the codewords immediately before and after a given codeword is used in processing that codeword. After B iterations, the decoder makes a decision and the window is advanced by one codeword.

Larsson in [108] proposed a similar scheme to Xiao in which users simultaneously transmit their own data packet and the packet for which they act as relay by using superposition coding instead of network coding with appropriate power allocation between the two packets.

Another approach based on superposition coding to achieve full rate transmission called superposition coding assisted cooperative multiple access is proposed by Zhiguo in [109],where *N* users each transmitting over *N* orthogonal channels (frequency, time, or code) superimposes their own data along with previously received data from the *N-1* remaining users. The pre-coding and channel matrices used by each user should be known to all other users and the BS to achieve successful detection. This requires closed loop operation with feedback channels, leading to higher complexity and overheads compared with conventional cooperative systems. Nevertheless, this scheme achieves optimum diversity-multiplexing trade-off due to the fact that the data of each user is sent *N* times through *N* independent channels without adding any extra time slots compared with direct communication.

Reducing the effect of half duplex constraint can also be achieved with spatial multiplexing. This concept was introduced by Kannan in [110][101] which proposed a Space Division Relaying (SDR) that allows two users to exchange their data in first and second periods, and in the third period, space division multiplexing rather than time division is used for simultaneous relaying of users' data. It shows that improved rate of 2/3 compared with 1/2 in [101] while achieving full diversity order.

Full rate and second-order diversity can also be achieved using multiple alternating relays per source. For example, a scheme referred to as opportunistic multipath for bandwidth-efficient cooperative multiple access, is proposed in [111] for CDMA where each user is assigned two idle relays that forward its estimated data in turn over two consecutive time periods. It exploits the capability of CDMA pseudo noise spreading codes to resolve the multipath from the relays to meet the above objective, however at the cost of increased multiuser interference as the system loading increases.

6.3 Full-rate Cooperative Diversity with Adaptive Modulation

6.3.1 System Model

Our aim is to provide spatial diversity through cooperation for an uncoded system without compromising the rate and spectral efficiency due to the half-duplex constraint, compared with direct transmission with no cooperation and without the need to allocate multiple relays per user as in [111], or complex iterative detection at the receivers as in [108][109][110]We achieve this goal using channel-aware adaptive cooperative system with limited one bit feedback. Our scheme restricts the relaying to the user experiencing the stronger channel to the BS. Furthermore, users switch to higher modulation orders during the cooperative mode to compensate for the half-duplex constraint and maintain the same spectral efficiency as direct non-cooperative mode.

We assume slow flat fading and that channel remains constant during a specified time period (frame). The duration of each frame is fixed and corresponds with channel's coherent time. During a frame, each user will transmit a total of *B* bits regardless of whether cooperation takes place or not. Upholding the half duplex constraint, we will divide each frame into a number of time slots whereby only a single user is always to transmit at one time.

At the beginning of each frame, users will consecutively broadcast their training sequences to both the BS and their partners for channel estimation which will be used throughout the duration of the frame for both coherent detection of users' data at the relay and the destination as well as for users' scheduling, relay selection, and determining transmission mode (i.e. cooperative or direct transmission). It is worth noting that by rearranging the position of the training sequences in that way, we can employ them to facilitate scheduling and adaptive cooperation without adding any overhead compared with direct transmission.

The BS uses these sequences to estimate the channels between it and the users, while the users will estimate inter-user channel between them. The BS will use its knowledge of users' channels to send a single bit feedback indicating which user is allowed to transmit at the first time slot. The BS always chooses the user with the weaker channel to the BS to transmit first to insure that the limited time and power available for cooperation is used efficiently. On the other hand, users utilise CSI about their inter-user channel to determine if they will cooperate or not based on a predefined threshold for cooperation. Since the inter-user channel is reciprocal, users can make this decision locally without the need to inform their partner.

Non-cooperative mode: In the non-cooperative transmission mode shown in figure 6.1.a, users divide the reminder of the frame into two equal time slot and consecutively transmit their data encoded in a basic modulation set 2^{M_1}-QAM and using the same average power (*2P*). To preserve power, the user experiencing the strong channel to the BS is turned off during the first time slot and no listening will take place.

Cooperative mode: In the cooperative mode shown in figure 6.1.b, users will transmit using a modulation set 2^{M_2}-QAM, $M_2 = 1.5M_1$. The reminder of the frame will be divided into three equal time slots. In the first time slot the user with the weaker channel to the BS will transmit first with an average power of *1.5P*, in the second time slot the user with the stronger channel to the BS will relay its partner data with an average power *1.5P,* while it will use the third time slot to transmit its own data with an average power of *3P.* The BS will combine the signals from the first two time slots using maximum ratio combining to detect the data from the weaker user.

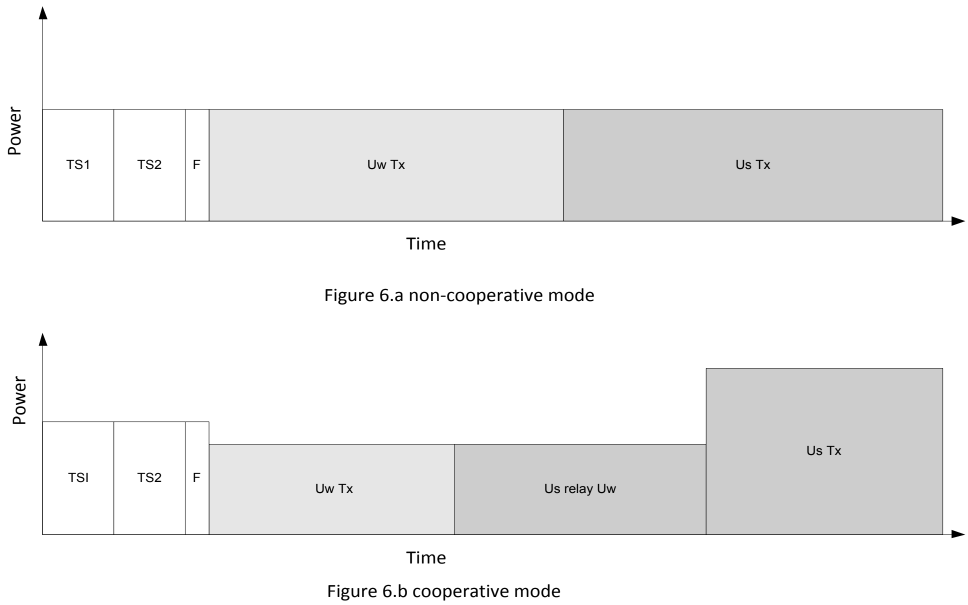


Figure 6- 1 Frame structure for direct and cooperative modes

Power allocation: It is worth noting that the average power per frame is the same for both non-cooperative and cooperative modes. However, in the cooperative case, three quarters of the available power will be emitted from the user experiencing the stronger channel to the BS. In both modes, power is equally distributed between the two transmitted packets of both users, hence the data packet of the strong user is assigned double the power of that of the weak user because it is only transmitted once while that of the weak user is also relayed by the strong user.

Adaptive modulation: In the cooperative mode, users transmit with higher-order modulation than that used for direct transmission. The new modulation level is chosen to increase the spectral efficiency to compensate for the extra time slot required to relay the weak user's data by the user with the stronger channel. This will ensure that the total number of bits per frame remain unchanged compared with direct transmission. Even though increasing the modulation order leads to a reduction in the constellation minimum distance for the same energy per bit. This new higher modulation is accompanied by full diversity order which offsets this degradation leading to a net improvement in BER performance over direct transmission with lower order modulation. This is validated through MATALB simulation (Table 6.1) by comparing the SNR required to achieve a fixed BER between direct transmission where regular 2^M-QAM is used and a cooperative system using our proposed protocol where $2^{1.5M}$-QAM is used in the cooperative mode. It was shown from these results than the cooperative gain is reduced when high order modulation is used which usually corresponds to users close to the centre of the cell with good overall channels. However even in this scenario; a significant improvement in BER performance can be achieved without compromising bandwidth efficiency.

Table 6- 1: Net diversity gain (DG) at fixed BER for adaptive modulation cooperation where (D) refers to direct transmission and (C) refers to cooperative case. DG is defined as the reduction in SNR required for achieving the same BER in cooperative mode with higher order modulation as compared with that of direct transmission with lower MQAM modulation.

BER/DG	**4-QAM(D)**	**16- QAM (D)**	**64- QAM (D)**	**256- QAM (D)**	**2^{10}- QAM (D)**
	8-QAM (C)	**64- QAM (C)**	**512-QAM (C)**	**4096-QAM(C)**	**2^{15}- QAM (C)**
10^{-4}	15 dB	13 dB	9 dB	7 dB	2.7 dB
10^{-5}	20 dB	18 dB	14 dB	12 dB	8 dB
10^{-6}	25 dB	23 dB	19 dB	17 dB	13 dB

6.3.2 Numerical example

We present a numerical example to illustrate the potential of the new scheme. For our simulations, the channels are Rayleigh fading with unit variance. We consider the case where two users employing QPSK modulation with an average transmit power of unity transmit in (a) direct non-cooperative way, (b) classical decode and forward cooperative transmission employing QPSK modulation, (c) adaptive decode and forward cooperative transmission employing QPSK modulation, (d) our proposed scheme employing QPSK for direct transmission and 8-QAM for cooperative mode. In all cooperative cases, we consider the inter-user channel between the two users (a) to have the mean channel gain equal to that of the channels between users and the BS (b) 10 dB higher.

Figure 6-2 shows the BER performance of various cooperative schemes, it can be seen that while preserving the spectral efficiency of uncoded direct transmission, COOP-AM still manages to deliver a significant improvement in BER performance even when the inter-user channel has the same average channel gain as users due to its inherent adaptive nature. Furthermore the loss in performance due to the use of higher level modulation in the cooperative mode compared with adaptive decode and forward is relatively small accounting to 0.5 dB considering that COOP-AM have double the spectral efficiency of conventional adaptive decode and forward.

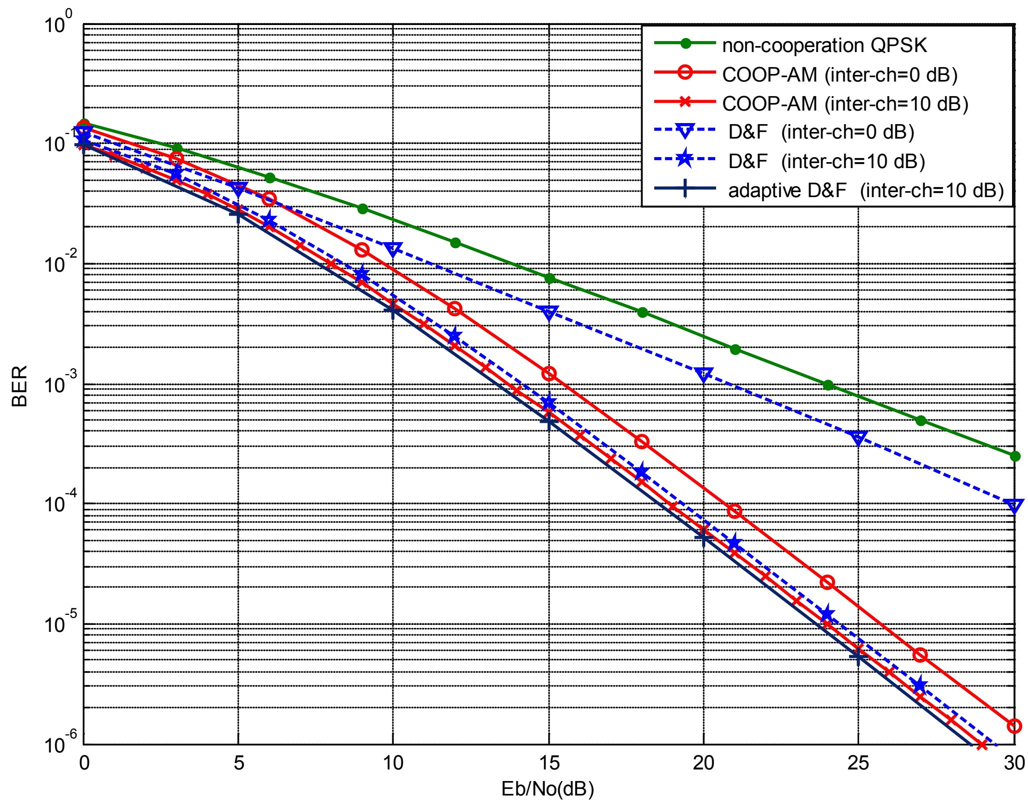


Figure 6- 2 BER Performance of cooperation with adaptive Modulation for two QPSK users

6.4 Cooperative Modulation for Multiuser Communications

In this section, a high spectral efficiency communication scheme, called Cooperative Modulation (CM) is proposed for cooperative multiuser systems. CM combines both the reliability and QOS resulting from the spatial diversity due to cooperation with the high spectral efficiency and user capacity due to the instantaneous superposition of multiuser signals resulting from collaborative modulation. CM can be seen as a direct expansion of Coop-AM introduced earlier when more than two users are involved. Both schemes maintain low feedback and high spectral efficiency by restricting relaying to the user with the strongest channel to the BS. Signals from multiple users are simultaneously transmitted to the relay without subdivision in time, frequency, or code. Instead, it relies on expansion in signalling space accompanied by a cooperative diversity with an order equal to the number of users.

6.4.1 System Model

Each communication session will be divided into frames, we assume that the channels remain constant during a frame and change independently between frames. Users transmit over uncorrelated flat-fading Rayleigh channels modelled as a complex Gaussian-distributed with zero-mean and unit variance. Channels change at a rate much slower than the data rate. Therefore, they remain constant over hundreds of symbols.

Each frame will be divided into three time slots or periods, the first time slot referred to as scheduling period (SP) will be used for relay selection and providing CSI required for pre-coding or detection. The second time slot referred to as the feeding period (FP) during which users will simultaneously transmit their data using collaborative modulation to the selected relay. And the final time slot referred to as the cooperative period (CP), the selected relay will add its own data and transmit a combined signal representing the data of all users in the group to the BS employing a high-level QAM constellation with a sum rate equal to the sum rate of all users in the group.

We will introduce two possible variations of CM depending on whether CSI are utilised at the BS and the selected relay or if CSI are utilised at the users.

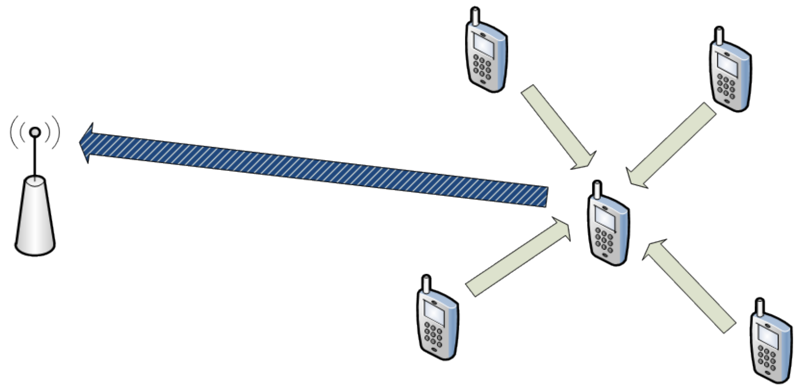


Figure 6- 3 Illustration of CM cooperative communication protocol

6.5 Precode, Amplify, and Forward (P&A&F)

In this section, we will consider how CMMA can be used to implement cooperative modulation in a system where CSI are only utilised at users. We will refer to this form of cooperative modulation as Precode, Amplify, and Forward (PAF), below is a basic description of PAF according to the CM's system model explained earlier.

6.5.1 Scheduling Period for PAF

Before the scheduling-period (SP) and at the start of every frame, the BS broadcasts a common pilot to all users, so users can utilise it to locally synchronize their transmission and estimate their channel gain (due to reciprocity property of a wireless channel). The probability density function (pdf) of the channel-gain is initially divided into regions with identical probability measure defined by a set of thresholds λ_i , *i* = *1, N* such that $\lambda_1 \geq \lambda_2 \geq . . . \lambda_N$, where *N* is the number of users. These regions and their associated thresholds can be computed locally at the users in a distributed manner using CSI obtained from the common pilot. If the channel gain $|h_i|$ of user *i* satisfies $\lambda_i \leqslant |h_i| < \lambda_{i-1}$, then the user will quantize its channel gain into one of the *N* possible mini-time slots and broadcast a training sequence of B_p during its mini-time slot while licensing to other users during other mini-slots. At the end of each mini-slot the BS will transmit a flag indicating whether no user transmitted (transmit second mini slot), exactly one user transmitted (end scheduling period and start feeding period), or a collision occurred (start collision resolution). In the case of collision, the collided users will modify their threshold according to a binary search like algorithm and users whose channel gain is between the new thresholds transmit in the next mini slot until collision is eliminated.

For PAF, We assume that the distance between users is much smaller than that between users and the BS. Therefore, The average gain of interuser channels are much higher than that between users and the BS, while instantaneous interuser channel gain is kept constant by precoding at the users. Therefore the relay selection process is reduced to selecting the user with the best channel to the BS.

6.5.2 Feeding and cooperative period for PAF

CMMA will be used in the feeding period (FP) in order to simultaneously transmit data from the *N-1* remaining users to the selected relay by assigning each user within a cooperative group with a unique modulation set centrally designed at the BS to ensure that the received signal formed from the superposition of users' signals belongs to a composite constellation with higher modulation level and a data rate equivalent to the sum of rates of all the individual streams. Due to the local collaborative precoding at the users, the mapping of this composite constellation is fixed throughout the session and already known to the BS which predesigned the constellation.

The baseband representation of the received signal at the selected relay i formed from the super position of precoded signals from the remaining *N-1* users is

$$y_{sr} = \sum_{k=1}^{N,k\neq i} \sqrt{P_k}\, e^{j\theta_k} c_k h_{ki} + n_r \tag{6.1}$$

Where P_k and $\theta_k$are respectively the power weight and phase rotation of user k at time instant t to insure that its' received signal at relay i corresponds to its unique modulation set S_k. c_k is a complex signal representing data symbol of user k where the average symbol power is unity. h_{ki} represents the complex channel gain of the interuser cannel between users k and i *and,* n_r represent white Gaussian noise vector at the relay and is modelled as complex Gaussian-distributed signal with zero mean and variance σ_r^2.

The relay i will then add its own data modulated according to its assigned unique modulation set $S_i = \{s_1, s_2, \dots . s_{m\}}$ before adjusting the combined signal using channel inversion.

The baseband representation of received signal at the BS from relay i is:

$$y_d = \sqrt{P_i} h_{id} \left(\sum_{k=1}^{N,k \neq i} \sqrt{P_k}\, e^{j\theta_k} c_k h_{ki} + s_i \right) + n_r \sqrt{P_i} h_{id} + n_d \tag{6.2}$$

Where h_{id} represent the complex channel gain of channel between relay i and the BS , n_d represent white Gaussian noise vector at the BS and is modelled as complex Gaussian-distributed signal with zero mean and variance σ_d^2, and P_i is the transmit power of relay i at time t .

Channel inversion is done by varying the relay transmit power P_i according to its channel h_{id} to insure that:

$$y_d = r_j + n_r \sqrt{P_i} h_{id} + n_d \tag{6.3}$$

Where $r_j \in R$ is a complex vector representing a unique point at the composite constellation R predesigned and known at the BS. The BS can then perform a simple joint ML detection identical to that of CMMA to recover users' data.

6.5.3 Simulation Results

In this section we will validate through simulation the BER performance of PAF. We assume that all users and the BS are each equipped with a single antenna. Users transmit over uncorrelated flat-fading Rayleigh channels modelled as a complex Gaussian-distributed with zero-mean and unit variance. Channels change at a rate much slower than the data rate; therefore they remain constant over the duration of one frame and change independently between frames. Also perfect CSI at the transmitters was assumed. ρ is defined as the ratio of average channel gain of interuser channel over that of average channel gain between users and the BS.

Figure 6.4 shows the BER performance of a PAF involving four users employing BPSK digital modulation. The BER performance of PAF is worse than that of conventional CMMA when $\rho = 0\ dB$. This is expected due to the added noise at the relay. However a significant improvement of BER performance can be realized due to cooperative diversity as ρ increase. At $\rho = 10\ dB$ the BER performance of PAF shows an improvement over conventional CMMA equal to 5 dB at BER of 10^{-5}. The cooperative diversity gain in this case offsets the BER degradation caused by modulation space expansion due to CMMA and the BER performance per user shows 1.5 dB improvement over a scenario where users transmit to the BS using channel inversion and over four orthogonal channels.

Figure 6.5 shows the BER performance of a PAF involving six users employing BPSK digital modulation. The BER performance of PAF improves remarkably by as much at 8.5 dB at a BER of 10^{-5} and $\rho = 20\ dB$ compared with direct CMMA transmission from users to the BS. However due the exponential increase in composite constellation size at the relay, the BER performance of PAF in this case is slightly worse than that of conventional orthogonal MAS where users transmit to the BS using channel inversion over six orthogonal channels.

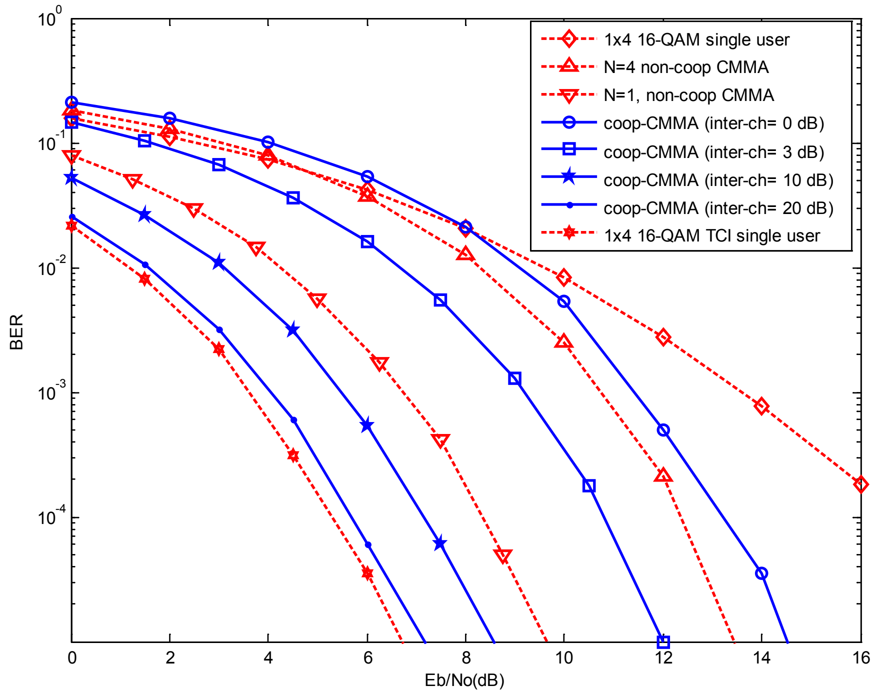


Figure 6- 4 BER Performance of Precode & Amplify & forward (coop-CMMA) for four users employing BPSK modulation

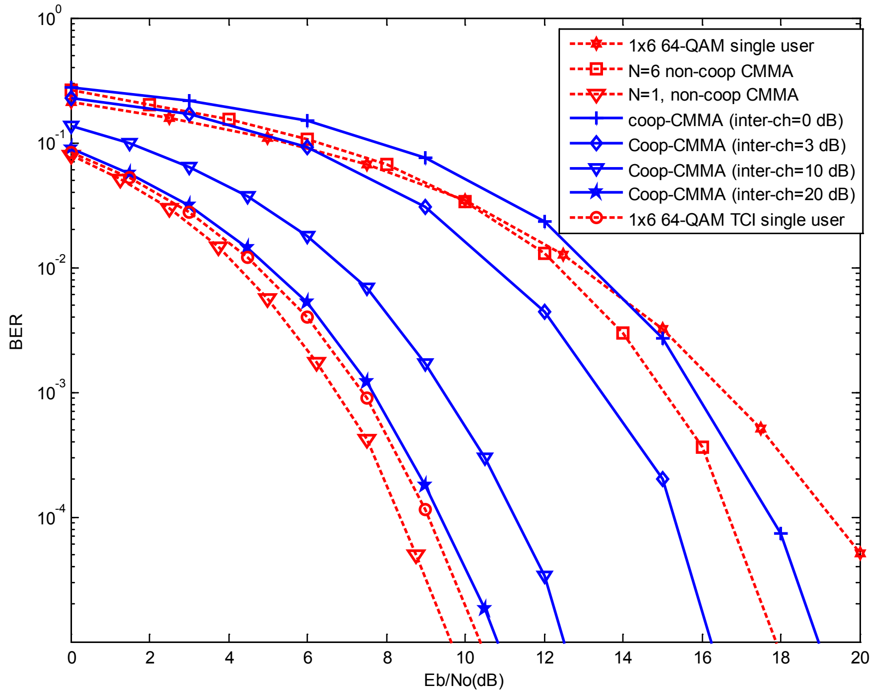


Figure 6- 5 BER Performance of Precode & Amplify & forward (coop-CMMA) for six users employing BPSK modulation

6.6 Decode, Remap, and Forward (DMF)

6.6.1 Introduction

The aim of this section is to design a new cooperative scheme that provides both a spatial diversity gain of the order of the number of cooperating users and spatial multiplexing gain where all users share the same orthogonal channel and achieve a combined sum rate that increases with the number of users. This is achieved through a new concept referred to as cooperative modulation which allows users to simultaneously superimpose their signals using the same bandwidth and signal signature while offsetting their mutual interference by the use of cooperative diversity. Furthermore, the benefits of CM are realized without the need to allocate dedicated relays to users or the need for complex iterative detection at the receivers.

The main contribution of this section can be summarized as follows:

- A novel cooperative communication protocol named decodes re-modulate and forward (DMF) is proposed to implement CM by restricting the relaying to the user with the best overall route to the BS. All constituent users of a CM system are active users, furthermore all participating users benefit from cooperation unlike other schemes.
- In addition to the spatial diversity gain provided by cooperation, CM enables spatial multiplexing of many users signals even when the BS is equipped with a single receive antenna.
- A new relay selection scheme based on maximising the minimum distance of the composite constellation formed from the superposition of N users at the relay is proposed to obtain an optimum performance for CM.
- A novel sphere-based algorithm based on the geometric properties of the composite constellation is proposed for measuring the minimum distance of these

constellations for relay selection and joint detection. This algorithm greatly reduces the number of calculation required for selection and detection compared with exhaustive search and conventional ML detection.

6.6.2 Overview of DMF

Figure 6.6 illustrates the basic concept of CM where up to *N* active users each equipped with a single antenna cooperate with each other to deliver their data to a base station (BS) with a single receive antenna. At any time instant *t*, one of these users is selected as a relay and the remaining *N-1* users will simultaneously transmit their data to the selected relay using the same transmit power and without any subdivision in time, frequency, or code. The combined signal at the relay belongs to a composite constellation formed from all the possible summation of users' signals. The relay utilise channel state information (CSI) of inter-user channels between the relay and the remaining users to construct this composite constellation and perform a joint ML detection to extract users' data. The relay then add its own data and forward the combined data from all users to the BS utilising a regular M-QAM constellation with a rate equal to sum rate of all users. This process is repeated over fixed time periods referred to as frames where each frame interval corresponds to the coherent time of the fading channel.

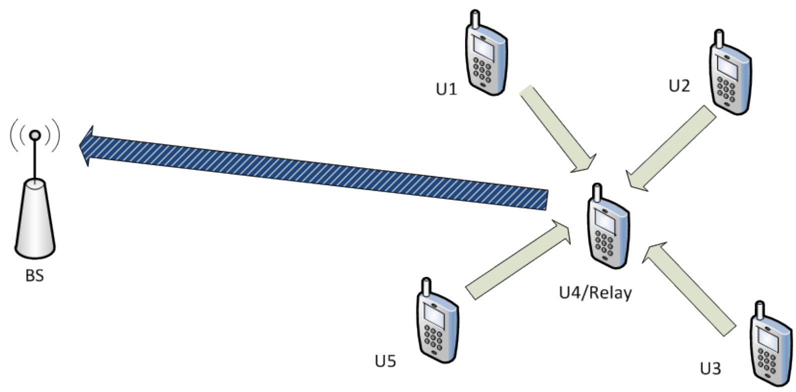


Figure 6- 6 : Illustration of CM cooperative communication system where the solid arrows refers to the feeding stage from users to the selected relay at time slot 1 while the shadowed arrows refer to the cooperative stage from the relay to the BS.

To implement CM, Decode, reModulate, and Forward (DMF) cooperation protocol is introduced. DMF is two-hop cooperative communication protocol where N users utilise the independence of their inter-user channels and the channels between them and the BS to perform both superposition coding (to achieve high spectral efficiency) and cooperative diversity (to achieve good QoS and reliable communication). The main idea is, as the number of users increase, the modulation order of the composite QAM constellation formed from the superposition of users' data will also increase leading to degradation in BER performance. However, this degradation will be offset by full diversity order due to cooperation. The number of consecutive transmissions required to deliver data from users to the BS is always two, therefore the cost of the half duplex constraint does not increase with the number of users.

In DMF, each communication session is divided into frames, we assume that the channels remain constant during a frame and change independently between frames. Users transmit over uncorrelated flat-fading Rayleigh channels. Channels change at a rate much slower than the data rate. Therefore, they remain constant over hundreds of symbols.

As shown in Figure 6.7, each frame is divided into three time slots or periods, the first time slot referred to as Scheduling Period (SP) is used for relay selection and exchanging of pilots between users and the BS to obtain channel state information (CSI) required for coherent detection in later periods. The second time slot referred to as the Feeding Period (FP) during which users simultaneously transmit their data to the selected relay with an average power per user equal toE_{av}. And the final time slot referred to as the Cooperative Period (CP), the selected relay will add its own data and transmit a combined signal representing the data of all users in the group to the BS employing a high-order QAM constellation with a sum rate equal to the sum rate of all users and using a transmit power equal to (N+1) E_{av}. Since all channels are assumed independent and uncorrelated, all users will have an equal chance of being selected as a relay which translated into a probability of 1/N and an average transmit power per user per time slot equal to E_{av}. Since no precoding is used at the FP in order to form the composite QAM constellation at the relay, the structure of the resulting composite QAM constellation is highly random. Therefore, it is very important to understand how these composite QAM constellations are formed and detected and how their structure will affect the relay selection process before proceeding to explaining the three periods of a DMF scheme.

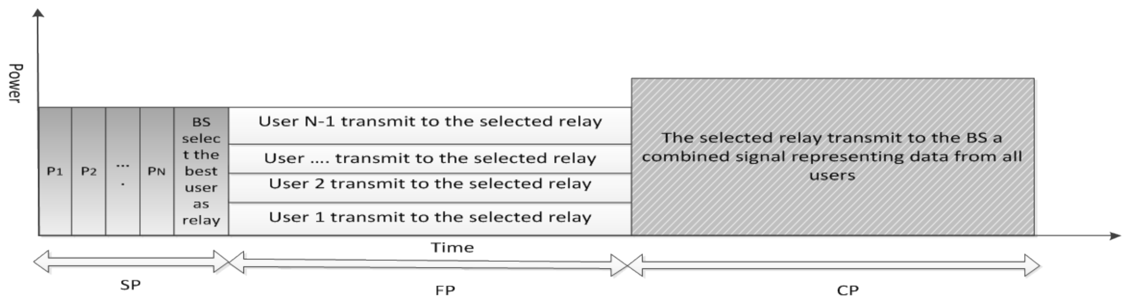


Figure 6- 7 Frame structure for DMF

6.6.3 Composite QAM constellations at the Relay

During the FP and assuming full synchronization between users, *N-1* users will simultaneously transmit to the selected relay which in turn utilizes CSI about users' channel obtained during the scheduling period to perform joint ML detection to decode individual users' data.

Let's assume that user *i* is selected as a relay at time *t,* this user can calculate the mapping π_i of the composite constellation R_i formed from the superposition of the *N-1* signals from the remaining users, $i \in \{1,2,..,N\}$ as follows,

$$[R_i] = [Ge] \times [H_i] \tag{6.4}$$

Where $[R_i]$ is a $1 \times 2^{N-1}$ matrix representing 2^{N-1} complex constellation points formed from superposition of *N-1* users transmitting using BPSK modulation.

$[Ge]$ is a $2^{N-1} \times (N-1)$ matrix representing all the possible combinations of *N-1* transmitted signals. When users employ BPSK digital modulation and assume the average symbol power is unity, the entries on Ge will be either +1 or -1.

$[H_i]$ is a $1 \times (N-1)$ matrix representing complex inter-user channel coefficients between user i and *N-1* remaining users within its group.

Due to the physical separation of users and the multipath fading nature of the wireless channel, the amplitude and phase of the received signal of each user is highly likely to be independent leading to the formation of non-ambiguous (fully decodable) composite constellations formed the superposition of all signals. However due to the random nature of this superposition it is also highly likely that the mapping of this received composite constellation is irregular and has lower minimum distance between constellation points compared with that of a regular QAM constellation with the same modulation order and the same average symbol power transmitted from a single user.

The BER performance of this composite QAM constellation is linearly related to the square of the minimum distance between any two constellation points (d_{min}). d_{min} fluctuates in value over time in a rate equivalent to the channel's coherent time which is what usually happen in a conventional single user transmitting over Rayleigh fading channel. However for a single user point to point transmission, the mapping of M-QAM constellation is fixed and usually chosen to maximize d_{min} for any given average symbol power, unlike in our case where not only the intensity of the composite QAM signal will vary due to fading but also the mapping (structure) of the constellation due to the gain and phase correlation between fading channels.

The performance of the composite QAM constellation will therefore be a degraded version of that of a single user with equivalent rate transmitting at the same average power over

Rayleigh fading channel. The rate of degradation will be directly related to the drop in average d_{min} compared with conventional single user point to point case.

For a group of *N* users, the number of inter-user channels between any two users is equal to $\sum_{i=1}^{N-1} i$. These inter-user channels between any one user *i* and all the remaining users in the group are independent not only in their individual channel coefficients but also in the correlation between channels at each potential relay. The channel matrix $[H_i]$ representing complex inter-user channel coefficients between user i and *N-1* remaining users within its group is different by *N-2* rows that any other channel matrix $[H_j]$ formed at any other user *j* where $j \neq i$. Therefore the *N* possible constellations sets $[R_i], i = \{1, \dots, N\}$ will all have different and independent mapping and it is highly likely that at least one of these constellations will have sufficient d_{min} enabling successful detection.

To illustrate this point, Figures 6.8 and 6.9 respectively show the probability density function (pdf) of the minimum distance between any two composite constellation points formed from the superposition of four and six users, simultaneously transmitting over fully uncorrelated Rayleigh fading channels modelled as complex variable with Gaussian distribution with zero mean and unity variance. We assume that all users employ BPSK modulation with an average energy per bit equal to unity. PDFs were obtained through simulations from a random sample of 10^6 channel realizations. As can be seen from these figures, the degradation in average d_{min} between a composite constellation and that of a QAM constellation with the same modulation order transmitted from a single user over fading channel increases with the number of users. However since each user can be used as a potential relay and the composite constellation formed at each user is independent due to the independent nature of the inter-user channel, selecting the user with the best d_{min} out of *N* users not only offsets the effect of random structures of QAM constellation but leads to a significant increase in d_{min} compared with a single point to point transmission as shown in figure 6.9. Therefore, the combination of multiuser superposition and cooperation leads to a new form of cooperative diversity referred to as Constellation Diversity (CD).

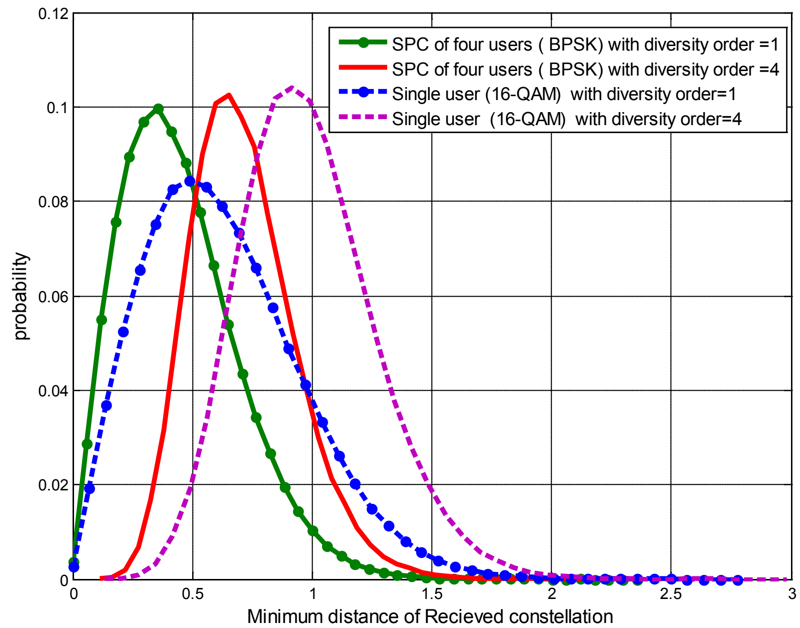


Figure 6- 8 Probability density function of minimum distance of received composite constellation for four users employing BPSK with uncorrelated Rayleigh fading channels

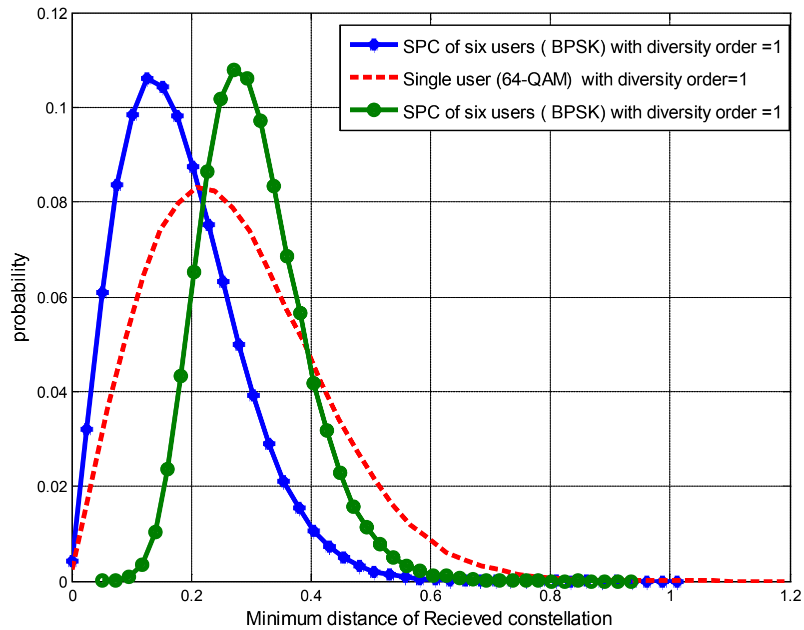
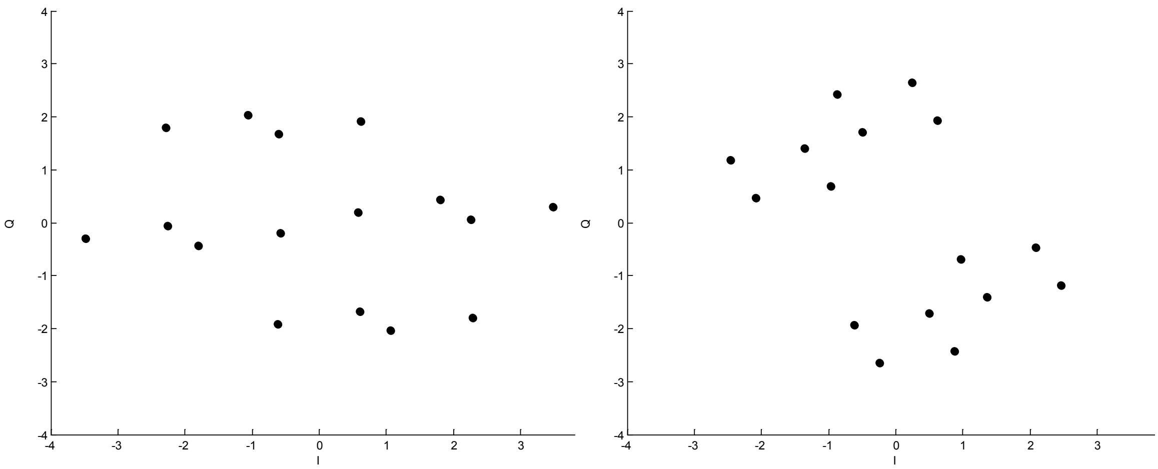


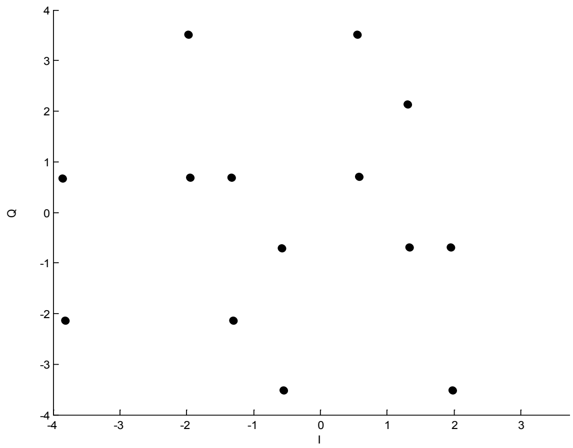
Figure 6- 9 Probability density function of minimum distance of received composite constellation for six users employing BPSK with uncorrelated Rayleigh fading channels

An example of constellation diversity is shown in Figure 6.9 where various 16-QAM composite constellations formed at different users in a DMF system consisting of four users employing BPSK transmitting over uncorrelated channels. The mapping and d_{min} of composite constellations formed at each of the four potential relays differ greatly ranging from 0.16 to 0.95. Constellation diversity creates a virtual multiuser MIMO system while spatial multiplexing of various independent signals from N users can be achieved even when the BS are only equipped with a single receive antenna and even when only a single relay equipped with a single antenna is utilised.

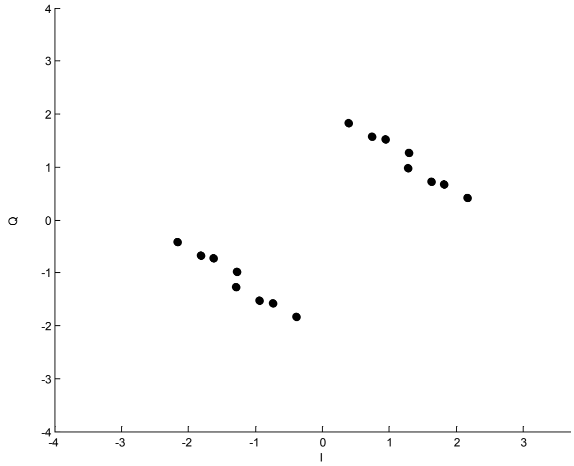
As in the case of MIMO systems high channel correlation will lead to a significant degradation in capacity and performance as it results in a significant reduction in d_{min}. However, the high channel correlation experienced in some potential relays (for example Figure 6.9d) will be offset by constellation diversity since the composite constellation at other users are formed from different channels and its highly unlikely that all groups of interuser channels are correlated.



(a) composite constellation formed at user 1 (b) composite constellation formed at user 2



(c) composite constellation formed at user 3



(d) composite constellation formed at user 3

Figure 6- 8 Examples of composite constellation formed from the superposition of four users employing BPSK modulation and transmitting over uncorrelated fading channels.

6.6.4 Route (Relay) selection algorithms for DMF

At any time, any one of the *N* active users can act both as a source transmitting its own data as well as a relay between the remaining *N-1* users and the BS. Hence there are *N* possible routes between the users and the BS each consisting of two hops. The first being the link between the users and the relay and the latter one is that between the relay and the BS. As is the case for multi-hop communication, the performance of each possible route is limited by that of the weakest hop at each route. Let's assume that $\lambda_{i1}, \lambda_{i2}$ respectively, represent the equivalent *SNR* of the first and second hop in route Ψ_i, *i={1,2,....N},* then the quality of route Ψ_i is limited by the *SNR* of the weakest hop. Therefore the *SNR* of route λ_i can be defined as:

$$\lambda_i = argmin\{\lambda_{i1}, \lambda_{i2}\} \tag{6.5}$$

Therefore the best possible route between users and the BS (optimum relay selection) is

$$\lambda_{op} = argmax\{\lambda_1, \lambda_2, \dots \dots, \lambda_N\} \tag{6.6}$$

The first hop of each route is Multiple-Input-Single-Output (MISO) connection where *N-1* users transmit simultaneously over uncorrelated channels to a single relay. Hence, it is essential for relay selection to convert this MISO connection into an equivalent Single-

Input-Single-Output (SISO) system and calculate the equivalent *SNR* for the first hop in order to compare it to that of the second SISO hop and to that of other possible routes (relays). Two different approaches for calculating the equivalent *SNR* of the first MISO hop are proposed. The first is based on low-complexity norm-based conversion while the more computationally-complex optimum-performance second approach is based on d_{min} based-conversion.

a) Norm-based conversion: Let's assume that $\lambda_{eq,1,i}$ represents the equivalent *SNR* of the first hop at route i then $\lambda_{eq,1,i}$ is proportional to the Frobenius norm of the channel matrix$[H_i]$ representing complex inter-user channel coefficients between user *i* and *N-1* remaining users given by:

$$\lambda_{eq,1,i} = \frac{E_s\sqrt{\sum_{j=1}^{N,j\neq i}\left|h_{ij}\right|^2}}{\sigma_n^2} \tag{6.7}$$

Where E_s is the average symbol power per user, $\left|h_{ij}\right|$ represents the gain of the channel between users *i* and j, and σ_n^2 is the mean noise power.

b) Minimum distance-based conversion: The *SNR* of the first hop at route *i* is equivalent to that of a SISO transmission where a single user employing a rectangular QAM constellation of size 2^{N-1} and unity d_{min} transmit over a fading channel h_{eq} whose instantaneous channel gain at time *t* is equal to the minimum distance of the composite constellation formed at relay *i* at time *t* ($d_{min,i}$).

$$\lambda_{eq,1,i} = \begin{cases} \sum_{j=1}^{j=(N-1)/2} 4^{j-1} d_{min,i}^2 \Big/ 2\sigma_n^2 & odd\ N \\ (1 + \sum_{j=1}^{j=(N-2)/2} 4^{j}) d_{min,i}^2 \Big/ 4\sigma_n^2 & even\ N \end{cases} \tag{6.8}$$

Eq. (6.8) is obtained by calculating the average symbol power derived in relation to minimum distance of a regular rectangular QAM constellation with size of 2^{N-1} and a minimum distance equal to $d_{com,i}$.

The SNR of the second hop of route i representing the link between user i and the BS is defined as:

$$\lambda_{i2} = \frac{(N+1)E_s|h_{id}|^2}{\sigma_{n,id}^2} \tag{6.9}$$

Where $|h_{id}|$ represents the gain of the channel between users *i* and the destination (BS).

6.6.5 Norm based vs. minimum distance based conversion

In a point (source) to multi-point (*N-1* relays) transmission, the received signal at each relay belongs to a QAM constellation with a fixed mapping (structure). This QAM constellation is rotated in phase and scaled in amplitude due to multipath fading between the user and any specific relay. Therefore, it is sufficient to measure the *SNR* of the received signal at the relays and choose the highest. However, in multi-point to multi-point transmission, the received signal formed from the superposition of *N-1* users at the *N-1* potential relay form random constellations with variable mapping hence measuring the *SNR* as a relation to the norm of users' channels does not give the real picture about the quality of link between that relay and the remaining users.

To illustrate this point, Figure 6.11 shows the mapping of two composite constellations formed from the superposition of two users employing BPSK modulation at two relays R_1, R_2. Since the channels between users and the relays are assumed to be independent, the phase and gain correlation between channels at each relay leads to two constellations with different mapping. The average symbol power for the constellation at R_1 is more than double of R_2. However, due to the mapping of the constellations, the minimum distance between any two points in R_2 is 33% more than that of R_1. Hence, although R_2 has lower

SNR that of R_1; it is superior to R_1 in terms of BER performance by 2.5 dB . Therefore, optimum relay selection should be based on choosing the relay with highest minimum distance between any two composite constellation points rather than the *SNR* of the received constellation.

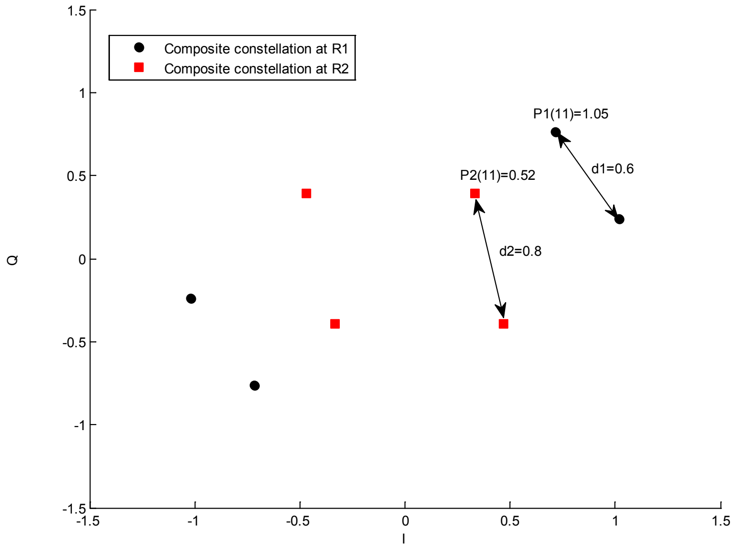


Figure 6- 9 Example of Two composite constellations formed form the superposition of two users employing BPSK modulation at two relays R_1, R2

6.6.6 Sphere-based search minimum distance algorithm

Although the optimum criteria for relay selection is based on d_{min}, the computational complexity of finding d_{min} is prohibitively large. For a group of *N* users employing BPSK modulation, there are *N* potential relay and the number of calculations required to obtain the d_{min} per relay is equal to$\sum_{i=1}^{2^{N-1}-1} i$. Therefore it becomes essential to reduce this complexity to a manageable level.

While the mapping of the composite constellation varies according to the gain and phase correlations between constituent users' channels, all composite constellations regardless of their mapping have the following common characteristics:

1. The d_{min} of the composite constellation formed from the superposition of *N* individual constellations each with a minimum distance d_i , $i = \{1, \dots . N\}$ is equal to or less than

the smallest received minimum distance of any constituent constellation. In other words, $d_{min} \leq argmin\ \{d_i|h_i|\}$

2. d_{min} is equal to or less than that of any composite constellation formed from any subgroup of $(N_1 \leq N)$ constituent users.
3. The two sub-constellations $[R_i^U]$, $[R_i^l]$ formed respectively from the upper and lower halves of $[R_i]$ (Eq.6.4) have identical mapping because the constituent constellations forming $[R_i]$ are symmetrical.
4. For every point $r_i \in [R_i^U]$, there exists another point $-r_i \in [R_i^l]$. Therefore, if $r_i, r_j \in [R^U]$ and $\emptyset_{r_i - r_j} \leq 90°$ then $|r_i - r_j| \leq |-r_i - r_j|$. Therefore in order to find the d_{min}, it is sufficient to calculate the distances between points in $[R_i^U]$ where the distance between any two points in $[R_i^U]$ is equal to $|r_i - r_j|$ if $\emptyset_{r_i - r_j} \leq 90°$ and to $|r_i + r_j|$ otherwise.
5. For two equal-power users employing BPSK modulation, the minimum distance of the composite constellation d_{min} formed from the superposition of these two users over fading channels is:

$$d_{min} = \begin{cases} argmin\ \{d|h_i|\} & 0.5 \geq |h_1|/|h_2| \geq 2 \\ argmin\ \{d|h_i|\} & 45° \leq \emptyset_{12} \leq 135° \\ d|h_1 - h_2| & 0° \leq \emptyset_{12} \leq 45° \\ d|h_1 + h_2| & 90° \geq \emptyset_{12} \geq 135° \end{cases} \quad (6.10)$$

By utilising these properties of the composite constellation, we propose a sphere-based search (SBS) algorithm in order to find d_{min} accurately and with minimal complexity compared with the basic exhaustive search algorithm. Below is a step by step description of how sphere-based search works:

- Channel ordering is performed using the rows of the channel matrix $[H_i]$. Channel rows are ordered in a descending way according to the magnitude of each column.

- Using Eq (6.10) we obtain the vector $\overrightarrow{v_1}$ whose magnitude represents the minimum distance of the composite constellation formed from the superposition of the first two users with the strongest channel. We replace the first two elements in $[H_i]$ with $\overrightarrow{v_1}$ maintaining the ascending order and reducing the size of $[H_i]$ by 1.
- We repeat the process described in the previous step *N-2* times until $[H_i]$ is reduced to a single element $\overrightarrow{v_{min}}$ whose magnitude $|v_{min}| \geq d_{min}$. v_{min} represents an upper bound on the minimum distance of the composite constellation.
- Sort the rows of $[R_i^U]$ in a descending order according to the magnitude of each column.
- Calculate the distance between the first row of $[R_i^U]$ and all consecutive rows whose magnitudes are equal to or less than $|v_{min}|$ before repeating the same process for the second row and so on.
- If the distance between any two points is less than $|v_{min}|$, this new distance will replace the initial value of $|v_{min}|$ obtained in step 3.
- The runtime measured by the required operations to find d_{min} is highly dependent on mapping of the composite constellation.

To validate the accuracy of SBS , we performed a simulation in MATLAB using up to 10 users (1024-QAM) transmitting over uncorrelated fading channels. Results show that SBS is 100% accurate and offers a significant reduction in the number of calculations compared with exhaustive search (ES) as shown in Table 6.2. In order to put things into prospective, the number of calculation with SBS required to find the d_{min} of 64-QAM formed from six users is 125 which is equivalent to the same number required for ML detection of two symbols while that of ES is 2080 which is equivalent to the same number required for ML detection of 33 symbols.

Table 6- 2 Number of calculations required to obtain the minimum distance of a composite QAM constellation using both sphere-based search and conventional exhaustive search

No. of users	Size of Composite QAM constellation	Minimum number of calculations for sphere-based search (SPS)	Average number of cal. for SPS	maximum number of cal. for SPS	Number of cal. for conventional search
4	16	7	21	31	136
6	64	21	125	381	2080
8	256	91	681	1787	32896
10	1024	541	3447	9457	524800

6.6.7 Scheduling Period for DMF

At the start of every frame, the SP will be divided into N equal mini time slots each associated with a single user out of N users. During its designated mini time slot, each user will broadcast a training sequence to the BS and other users within its group. Since our assumption that the channels remain constant during the whole duration of the frame, it is worth noting that by rearranging the position of the training sequences in that way, we can employ them to facilitate both relay selection and coherent detection (at the Relay and BS during FP and CP, respectively) without adding any overhead compared with direct transmission since CSI at the receiver is necessary for detection even in direct communication. The BS will utilise CSI about the channels between it and other N users in order to estimate the *SNR* of the second hop at each potential relay while the users will utilise the extracted CSI about their inter-user channels to calculate the equivalent *SNR* of the first hop associated with this user either by using norm-based conversation or minimum distance based conversion.

To simplify the relay selection process and to avoid having to feed the quantized values of the equivalent *SNR* from users to BS making the scheduling period prohibitively long, a minimum equivalent *SNR* referred to as λ_1^{min} is chosen to guarantee a successful detection at the feeding stage.

After the end of last mini-slot, the BS will send a flag identifying the user with the strongest channel to the BS. Upon receiving the flag, this user will transmit an acknowledgment to the BS indicating whether its equivalent *SNR* is higher than λ_1^{min} (end scheduling period and start feeding period), or its equivalent *SNR* is lower than λ_1^{min} (the BS will then transmit another flag identifying the user with the second strongest channel).

6.6.8 Feeding and cooperative periods for DMF

Once a user has been selected as a relay, the remaining *N-1* users within its group will simultaneously transmit their signals to the selected relay without any subdivision in time, frequency or code.

Let's assume that user i was selected as a relay then the baseband representation of the composite received signal at the relay y_{1i} can be written as:

$$y_{1i} = \sum_{i=1}^{N,j\neq i} x_j h_{ij} + n_1 \tag{6.13}$$

Where, $x_j \forall\, j \in \{1, \dots, N\}\, j \neq i$,is independent modulated data for the j^{th} user, h_{ij} is complex-valued Rayleigh fading channel from user j to the relay i, and n_i is a complex-valued AWGN at relay *i* modelled as a Gaussian variable with zero mean and $\sigma_{n_i}^2$ variance.

The composite constellation formed at the relay has a modulation order of 2^{N-1} assuming individual users employing BPSK modulation. Due to the irregular and suboptimum structure of the composite constellation, joint ML detection is required for detection at the relay. Joint Maximum likelihood (ML) Joint detection method calculates the maximum a posteriori probabilities (MAP) for all the 2^{N-1} possible received data vectors[R_i].

Estimation of users' data will be provided by selecting a vector which maximizes this probability.

The distance squared between the received signal and the i^{th} possible combination signals $r_i \in [R_i]$ can be calculated as

$$d_i^2 = |y_{1i} - r_i|^2, \qquad 1 \le i \le 2^{N-1} \tag{6.14}$$

Using the set of 2^{N-1} calculated distances, the receiver makes its decision based on minimum distance criterion. The possible transmitted signals are selected as a symbol r_i which produces the minimum distance as

$$\{\hat{r}_1, \dots, \hat{r}_{2^{N-1}}\} = \arg \min_{r_i \in [R_i]} d_i^2 \tag{6.15}$$

Finally user's data are found by remapping these symbols as used at the transmitters.

However, the complexity of joint ML detection grows exponentially with the number of users making it prohibitive for a large number of users especially considering that relays are mobile nodes with limited power and processing capabilities. Therefore, in order to maintain the optimum performance of joint ML while reducing its complexity to a manageable level, we propose extending our sphere-based search algorithm for finding the minimum distance to enable a low-complexity ML-based detection for the composite constellation at the relay. Below is a step by step summary of how this composite constellation sphere-decoding works.

1. Sort the rows of $[R^U]$ in a descending order according to the magnitude of each column then insert y_{1i} into $[R^U]$ in the right order.
2. Calculate all distances between y_{1i} and all consecutive rows whose magnitudes are equal to or less than d_{min} before repeating the same process for the proceeding rows.
3. If $r_i \in [R^U]$ $|r_i| - |y_{1i}| \le d_{min}$ *and* $\emptyset_{y_{1i}-r_i} \ge 90°$ then ignore r_i and calculate the distance between y_{1i} and $r_j = -r_i \in [R^L]$.

4. If more than one point is found within a sphere of radius d_{min} choose the closest point to y_{1i}. Otherwise double the radius of the sphere and repeat the earlier search process until a point is found.

The estimated data from *N-1* users obtained from the output of the detector will then be added to that of the relay and transmitted it to the BS during the CP after it has been re-modulated using a regular rectangular QAM constellation of size 2^N. In other words, while the mapping of the composite constellation received at the relay is variable and random, the remapping of detected users' data at the relay ensures that the received constellation at the BS has a fixed rectangular mapping. Remapping at the relay is necessary for a number of reasons:

- ***Remapping Gain:*** The relay is usually located much closer to the rest of the users compared with the BS, hence the path loss between the relay and users are relatively small and high *SNR* is expected compared with direct communication from users to the BS. This combined with the constellation diversity embedded in the selection process should enable it to successfully decode the composite constellation despite the suboptimum d_{min} due to the irregular composite constellation. However, due to the larger distance between users and the BS, optimising d_{min} for a given power constraint becomes very important for successful detection at the BS. Remapping therefore leads to a remapping gain G_{π} which is defined as the reduction in total transmit power which results from using a rectangular QAM constellation compared to a composite QAM constellation with random mapping when both have equal BER, average symbol power, and size. Simulation results show that this remapping gain grows with the size of the constellation varying from 1.6 dB for QPSK to 2.6 and 3.4 respectively for 16-QAM and 64-QAM.

- ***User identification***: since both the relay and the BS use the same mapping table to encode and decode data from users, the BS can perform user identification without requiring any additional overhead. A different relaying strategy like amplify and forwards would require the relay to forward its inter-channel matrix $[H_i]$ to the BS to enable detection and user identification.
- ***Gray coding gain:*** The BER performance of QAM constellation is not only affected by d_{min} but also by the Hamming distance (d_H) between neighbouring constellation points which is defined as the difference in bits between successive symbols. The composite nature of QAM constellation formed at FP leads to suboptimal bit mapping where the d_H is higher than one. Figure 6-11a shows the bit mapping for 16-QAM composite constellation formed from the superposition of two QPSK users with a power ratio of four. The maximum d_H is two, making it more prone to errors. Remapping this constellation at the relay using Gray mapping as in Figure 6-12 reduces the d_H to one. The BER performance due to bit mapping can be significant. For example [112] shows that the performance difference between binary and Gray mapped 16-QAM in Rayleigh fading is around 10 dB.

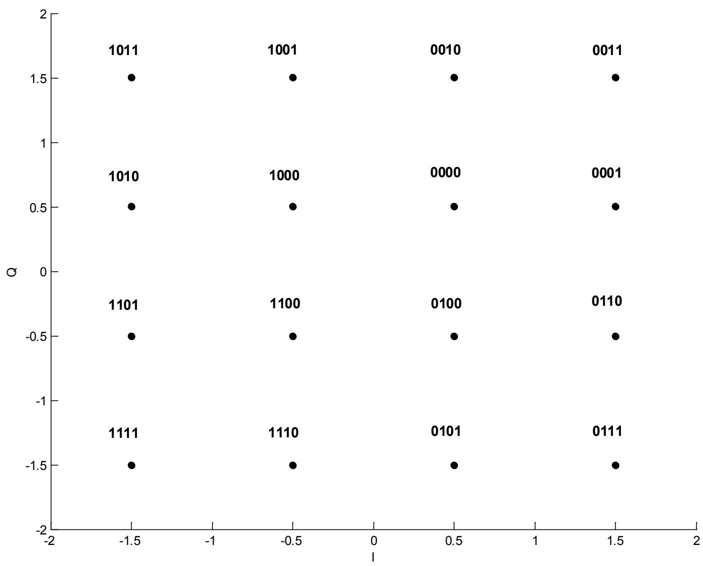


Figure 6- 10 Bit mapping for 16-QAM composite constellation formed from the superposition of two QPSK constellations with a power ratio of four

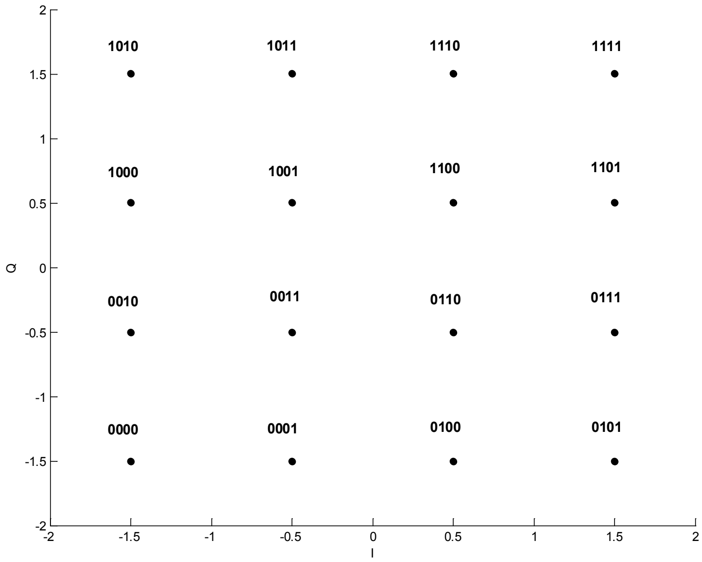


Figure 6- 11 Gray Bit Mapping for 16-QAM constellation

6.6.9 Simulation Results

In this section, the BER performance of DMF is validated through simulation. All users and the BS are each equipped with a single antenna. Users transmit over uncorrelated flat-fading Rayleigh channels modelled as a complex Gaussian-distributed with zero-mean and unit variance. Channels change at a rate much slower than the data rate; therefore they remain constant over the duration of one frame and change independently between frames. Also perfect CSI at the relay and the BS were assumed. Figures 6.13 and 6.14 shows the BER performance of a group of four and six users, respectively. DMF were implemented using both basic norm-based selection (DMF-NBS) and optimum d_{min}-based selection (DMF-dmBS). Simulation results were obtained by varying the ratio ρ which represents the average channel gain of inter-user channel over that of average channel gain between users and the BS. ρ is assumed to be high when the distances between users are much smaller than that between users and the BS.

DMF is compared with direct multiuser non-cooperative transmission based on superposition coding and joint ML detection and with that of a single user transmitting using the same total average power as the DMF group to a BS equipped with *N* receive antennas.

Both DMF relay selection schemes provide BER performance improvement even when $\rho = 0\ dB$ over direct transmission using SPC and joint ML detection (non-coop SPC). However DMF-dmBS greatly outperforms basic DMF-NBS especially for low value of ρ. For example at $\rho = 0\ dB$ and BER=10^{-4}, NBS only attains 1 dB BER improvement over non-coop SPC in both four and six users grouping while d_{min}-based selection attains a BER improvement over non-coop SPC of 17 dB and 20 dB for four and six users grouping, respectively. As the value of ρ increases, the difference in performance between the two relay selection schemes gradually narrows down but remain significant at around 7 dB at BER of $10^{-5}$and $\rho = 20\ dB$ for the four users grouping.

The expansion of constellation size at the relay which leads to BER degradation compared with that of individual users' BPSK modulation is greatly offset by the cooperative diversity gain of DMF. For four users grouping as can be seen in Figure 6.13, the BER of DMF with d_{min}-based selection shows a 17 dB improvement at BER of 10^{-4} and $\rho = 0\ dB$ compared to single user employing BPSK. For six users grouping the BER improvement is still excellent at 12 dB as can be seen in Figure 6.14. This shows that a BER improvement over a single-user orthogonal transmission can be achieved while increasing the rate and achieving spatial multiplexing at the same time. Finally as $\rho \to \infty$, the BER of DMF with both relay selection schemes becomes identical to that of $1 \times N$ scheme with selective diversity combining at the BS and where a single user transmit using a regular QAM constellation with size 2^N. This is expected as when the users are very close together, they can be remodelled as a single user with *N* transmit antennas with uncorrelated channels.

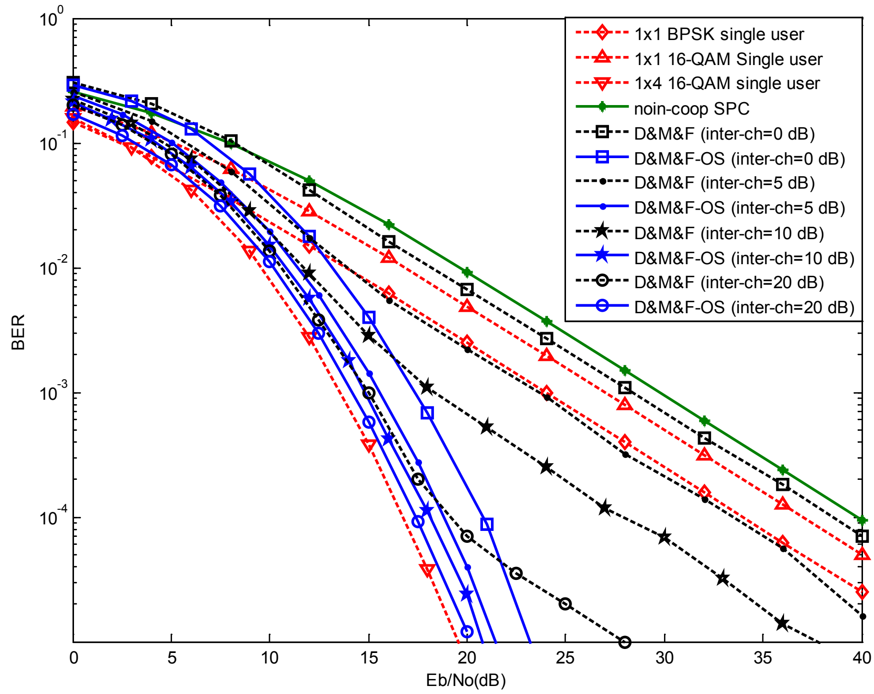


Figure 6- 12 BER Performance of Decode & Remap & Forward (D&M&F) using basic relay selection and optimum selection (OS) for four users employing BPSK modulation.

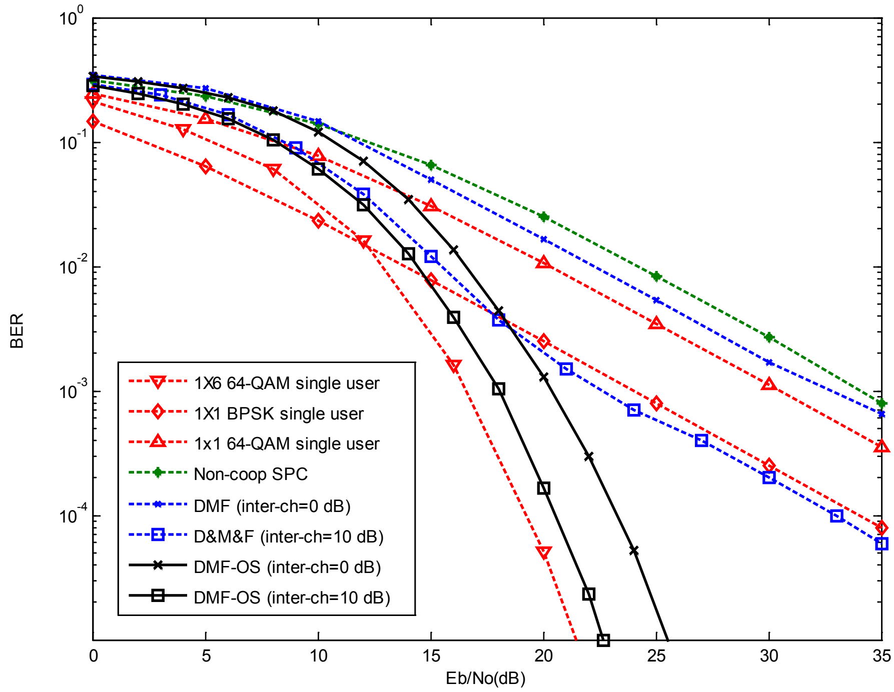


Figure 6- 13 BER Performance of Decode & Remap & Forward (D&M&F) using basic relay selection and optimum selection (OS) for six users employing BPSK modulation

6.7 Data Rate Analysis for CM

In cooperative communication schemes, exchange of data is required among the users where time, frequency or code is used to maintain orthogonality among the exchanged data. The most popular method for this purpose is time sharing, where the users transmit only in the allocated time slot using TDMA [113]. Assuming that each symbol is transmitted in a single time slot, the number of time slots required for the time sharing cooperative communication method with a single BS is equal to $N + N(N-1)$. Another more efficient way to exchange data is by using superposition coding [107-109] where users transmit a linear combination of their own data and that of other users during their designated time slot, hence the number of times slots required for superposition based cooperative methods in a N-user system with a single BS is equal to N.

In CM, the number of time slots required for cooperative communications using CM for a N-user system is always equal to 2. Therefore CM requires significantly smaller number of time slots in comparison to time sharing cooperation or superposition based cooperation. Reducing number of time slots, improves the users' data rate. Assuming that users have equal transmission rates, the data rate per user is defined as the total number of transmitted bits over the total number of time slots required for transmission

In Table 6.3, the data rate per user for CM, time sharing and SPC-based schemes are provided for the case where each user transmits a single bit. It is shown that the data rate per user is higher in the CM as a result of fewer required time slots for cooperation. Furthermore, in CM method, the rate improves as the number of users increase achieving a higher then unity rate for more than two users.

Table 6- 3 Comparison of data rate per user in CM, time sharing, and SPC sharing methods.

Number of users	2	3	4	5	6
Total transmitted	2	3	4	5	6

bits						
Data rate per user ($\mathcal{R}$) bits/time slot	**CM**	$\frac{2}{2}=1$	$\frac{3}{4}=1.5$	$\frac{4}{2}=2$	$\frac{5}{2}=2.5$	$\frac{6}{2}=3$
	Time Sharing	$\frac{2}{4}=0.5$	$\frac{3}{9}=0.33$	$\frac{4}{16}=0.25$	$\frac{5}{25}=0.2$	$\frac{6}{36}=0.16$
	SPC Sharing	$\frac{2}{2}=1$	$\frac{3}{3}=1$	$\frac{4}{4}=1$	$\frac{5}{5}=1$	$\frac{6}{6}=1$

6.8 Conclusion

This chapter introduced a simple two-user cooperative diversity scheme that utilises adaptive modulation and relaying to achieve a full-rate full-diversity communication with only a modest reduction in BER performance compared with conventional adaptive decode and forward. Next a novel high-rate multiuser cooperative scheme referred to as cooperative modulation (CM) has been proposed. The data rate analysis has demonstrated that CM provides a rate per user that actually increase with *N* contrary to time sharing cooperative communications and superposition based sharing. Two relaying schemes based on CM were proposed: PAF and DMF. PAF assumes that CSI at available only at the users. In PAF, a simple relay selection based on choosing the user with the best channel to the BS is employed to minimise feedback. After selection, users simultaneously transmit using CMMA to the selected relay which adds its own date using its own unique modulation set then amplifies the composite signal and retransmit it to the BS using simple channel inversion. PAF achieves high spectral efficiency and cooperative diversity using only a small overhead for relay selection and without the complexity of detecting the composite QAM constellation at the relay. Simulation results show that PAF offers a significant improvement in BER performance compared with direct CMMA when > 0 .

A second system based on CM called DMF which only utilise CSI at the relay and the BS has been proposed. Two DMF relay selection algorithms has been proposed, the first is based on simple norm-based selection, while the second one incorporate the d_{min} of the composite QAM constellation formed at each potential relay into the selection process. To minimise the computational complexity required to calculate the d_{min} at the relay, a new sphere-based search algorithm was proposed that exploits the geometric common properties of the composite constellation. Simulations result demonstrates that DMF using d_{min}-based selection provide a remarkable improvement in BER performance; compared with single user employing BSPK modulation Even when $\rho = 0\ dB$. d_{min}-based selection outperforms that using norm-based selection by huge margin especially at lower value of ρ where the latter only attains a modest improvement in performance.

7 Conclusions and Future work

7.1 Conclusions

In this thesis, we have created a framework for designing and evaluating a new set of wireless non-orthogonal multiple access schemes that take advantage of physical-layer collaboration among users. Specifically, in these collaborative modulation schemes, as we have referred to them throughout this thesis, A group of users pull their transmit power together in a collaborative manner to create a virtual user with power and rate equal to those of all users combined. By doing so, users trade off costs in BER performance, rate, and complexity for a net gain in group spectral efficiency and efficient utilisation of available network bandwidth. We showed that these gains in multiple access and spectral efficiency can be achieved with small feedback, regardless of channel correlation, and independent of the number of receive antennas.

In order to fulfil these design objectives ***in chapter 3,*** a new non-orthogonal multiple access scheme called collaborative modulation multiple access (CMMA) was proposed. The main design philosophy for CMMA is the notion that users can be allowed to share a common channel as long as any combination of data from these users combined over the common channel produces a unique interference pattern or constellation point (remove ambiguity) that is known at the receiver and the separation between these unique interference patterns (the minimum distance between constellation points) is sufficient to mitigate noise and enable successful detection.

CMMA assigns users with unique modulation sets centrally designed to fulfil these two design objectives. Users on the other hand, perform collaborative precoding which involves a simple truncated channel inversion and phase rotation of user's transmitted signal according to CSI obtained through a common pilot. This pilot is also used to independently maintain synchronization between users. Collaborative precoding insures that users' signals arrive at the BS according to their unique modulation sets and combine coherently to form a complex vector which belongs to the predesigned composite constellation hence CSI is not required for detection. Finally a simple joint ML detection is used at the BS.

A centralized multi-stage composite constellation design algorithm was proposed for CMMA. It optimises the power, phase, and modulation mapping of individual users in order to produce a composite QAM constellation that maximises the number of users while maintaining a minimum BER performance. It was shown that non-ambiguous composite constellations can still be formed from users with equal power by optimising phase rotation between their individual constellations; however the resulting composite constellation in this case has an irregular mapping with d_{min} between constellation points smaller than that of a rectangular constellation with the same average power and size formed from users with unequal power. It was also demonstrated that replacing individual user's constellation with regular mapping like QPSK by irregular sub-optimal mapping with the same constellation size, can result in composite constellations with regular mapping and higher d_{min} even when users have the same power. CMMA multi-stage composite constellation design is flexible and can accommodate users with different rates and BER requirement. It also allows the BS to add or remove users with little or no effect on other active users.

Through simulation and analysis, it was shown that CMMA can achieve a linear increase in link spectral efficiency at the expense of graceful degradation in BER performance, since increasing the number of users leads to an exponential increase in constellation size while the increase in power is only linear. For example while maintaining a rate of 4 bits/sec, a 4-user CMMA scheme endures a 2.6 dB drop in BER performance compared with a single user transmission with a rate of only 1 bit/sec. Hence like other non-orthogonal MAS, CMMA has a soft user capacity but is interference limited. Therefore it is envisaged that CMMA can be easily integrated with orthogonal multiple access techniques (such as TDMA, OFDMA) to extend user capacity and improve link utilization. Due to the channel adaptation which is an integral part of CMMA, the BER performance of CMMA shows a significant BER performance compared with non-adaptive transmission. For example 4-user CMMA system achieves 14 dB improvement at BER of 10^{-4} compared with non-adaptive TDMA system where users employ 16-QAM modulation.

To improve the BER performance of CMMA, a new selection combining receive diversity scheme called SC-CMMA is proposed. SC-CMMA preserves the simple precoding, feedback, and detection structure of CMMA. The selection process chooses the antenna s which minimises the total transmit power required by users in a CMMA group to transmit their composite signal. By reducing the instantaneous transmit power, the average received power increases enabling composite constellations with higher $d_{\min}$. SC-CMMA updates the selection process periodically by using the detected data from the output of the selected antenna s as a training sequence to estimate channel gains at other antennas. With much reduced complexity, it was shown that the performance of 2×3 SC-CMMA outperforms that of a linear MMSE precoders used in 3×2 MIMO by up to 10.5 dB at BER 10^{-5} where users in both cases employ QPSK. However at a fixed number of receive antennae, the diversity gain obtained from SC-CMMA tend to decrease as the number of users increase. In the case of two receive antennae, the diversity gain drops from 4 dB for 2-user CMMA to 2.6 dB for 6-user CMMA. Contrary to MIMO, SC-CMMA benefit from high transmit correlation between users as all users in this case tend to experience their strongest channel at the same receive antenna maximising the attainable diversity gain at any number of users.

In chapter 4, closed form expressions of CMMA and SC-CMMA spectral efficiency (capacity per unit of bandwidth) as a function of average received SNR were derived. It was shown that the capacity of CMMA increases with the number of users but so does the multiuser interference between them which leads to only non-linear logarithmic increase in capacity. The capacity of CMMA is not affected by channel correlation since users precode their signals independently. The capacity of CMMA was compared with that of MUD. It was shown that MUD offers a higher capacity than CMMA on the expense of latency and scheduling overheads. The performance gap between the two schemes tends to decrease as the number of users increase because the power gain in CMMA increases linearly while additional improvement in diversity gain in MUD tends to diminish.

Next a new scheme combining both opportunistic scheduling using only partial CSI at the receiver and CMMA referred to as CMMA-OS was proposed in ***Chapter 5*** to combine both the power gain of CMMA and the multiuser diversity gain that arises from users' channel independence. To avoid the complexity and excessive two-way feedback associated with dynamic real-time update of the composite constellation, the BS takes into account the independence of users' channels in the design of the composite constellation and its constituent modulation sets which remains fixed thereafter. However these constituent sets are no longer associated with specific users but assigned dynamically to users depending on their instantaneous channel gain. Users utilise their CSI to estimate which modulation set to use and then feedback their estimation concurrently using their previous modulation set. The BS then corrects the choice of modulation set when more than one user experiences an instantaneous channel gain in the same region and thus chose the same unique modulation set causing ambiguity. Capacity analysis of CMMA-OS shows significant improvement over conventional CMMA. For example, the capacity of 4-user CMMA-OS increases from 8 to 10 bits/sec/Hz at SNR of 25 dB compared with conventional CMMA. A BER improvement of 7dB can also be realised in this case due to both better constellation mapping and multiuser diversity gain. CMMA-OS also offers higher capacity than MUD schemes at a comparable level of overhead and complexity and without excessive delays making it an attractive choice in high-capacity delay-sensitive applications.

The second part of ***Chapter 5*** introduced a hybrid approach combining both collaborative coding and modulation referred to as H-CMMA. H-CMMA can vary the d_{min} of the received composite constellation by changing the number of unique constellation points for the same average total power. This hybrid approach enables CMMA to accommodate large number of users while flexibly managing the complexity and BER performance of the combined simultaneous transmissions of these users. H-CMMA can also simultaneously accommodate users with different QoS requirements (in terms of rate and BER performance). For example a 6-user H-CMMA can improve the BER performance by almost 7 dB with a small reduction in rate from 6 to 4.584 bits/sec compared with CMMA. This is due both to the reduction in the number of unique constellation points from 64 to 36 and the more regular mapping (more equal distribution of constellation points) which in turn improves d_{min}. It was also demonstrated that for a fixed sum rate and same number of users, H-CMMA is superior to a more conventional approach to reduce complexity and increase minimum distance using time division with CMMA. H-CMMA can also be seen as a practical method of implementing CCMA in fading environments while achieving higher rates and user capacity than that possible with conventional CCMA.

Chapter 6 introduced a simple two-user cooperative diversity scheme that utilises adaptive modulation and relaying to achieve a full-rate full-diversity communication with only a modest reduction in BER performance compared with conventional adaptive decode and forward. Our scheme restricts relaying to the user experiencing the stronger channel to the BS. Furthermore, users switch to a higher modulation order during the cooperative mode to compensate for the half-duplex constraint and maintain the same spectral efficiency as direct non-cooperative mode.

Next a novel high-rate multiuser cooperative scheme referred to as cooperative modulation (CM) has been proposed. CM allows N active users to share the network simultaneously while retaining a cooperative diversity gain in order of N. CM does not require any code, time or frequency sharing for providing multiple access, instead it relies on expansion in signalling space. The number of time slots required for cooperation is always kept to two by restricting relaying of users' data to the user with best overall connection. The data rate analysis has demonstrated that CM provides a rate per user that actually increases with N contrary to time sharing cooperative communications and superposition based sharing. For a 6-user system, CM provides 3 bits/channel use in comparison to time sharing cooperation and SPC-based sharing which respectively only obtains rates of 0.16 and 1 bits/channel use.

Two relaying schemes based on CM have been proposed: PAF and DMF. PAF assumes that CSI is available only at the users. In PAF, a simple relay selection based on choosing the user with the best channel to the BS is employed to minimise feedback. After selection, users simultaneously transmit their data using collaborative precoding identical to that of CMMA to the selected relay which adds its own date using its own unique modulation set then amplifies the composite signal and retransmits it to the BS using simple channel inversion. PAF achieves high spectral efficiency and cooperative diversity using only a small overhead for relay selection and without the complexity of detecting the composite QAM constellation at the relay. Simulation results show that PAF offers a significant improvement in BER performance compared with direct CMMA transmission from users to the BS. For example a 6-user PAF scheme attains a 8.5 dB improvement at a BER of 10^{-5} and $\rho = 20\ dB$ compared with conventional CMMA.

A second system based on CM called DMF which only utilise CSI at the relay and the BS has been proposed. DMF allows users to transmit their data simultaneously to the selected relay over a common channel. Since no precoding is used at the users in order to form the composite QAM constellation at the relay, the structure of the resulting composite QAM constellation is highly random and unknown to the BS. Hence DMF requires the detection and remapping of users' data at the relay to maximise the d_{min} of QAM constellation and enable user identification at the BS. Moreover it requires more sophisticated relay selection algorithms that consider the two-hop nature of each potential route. Two DMF relay selection algorithms have been proposed, the first is based on simple norm-based selection utilising only information about the channel gain at the relays, while the second one incorporates the d_{min} of the composite QAM constellation formed at each potential relay into the selection process. To minimise the computational complexity required to calculate the d_{min} at the relay, a new sphere-based search algorithm was proposed that exploits the geometric common properties of the composite constellation. For example, the number of calculations with sphere-based search required to find the d_{min} of 64-QAM formed is 125 while that of conventional exhaustive search is 2080. Simulation result demonstrates that DMF using d_{min}-based selection provides an remarkable improvement in BER performance; even when $\rho = 0\ dB$, the performance of 4-user DMF with d_{min}-based selection shows a 17dB improvement at BER of 10^{-4} compared with single user employing BSPK modulation. d_{min}-based selection outperforms norm-based selection by huge margin especially at lower value of ρ where the latter only attains a modest improvement in performance. However the performance gap between the two DMF based selection schemes gradually reduces with increasing value of ρ therefore DMF can switch to lower-complexity NB-selection at high ρ.

7.2 Future work

- **CMMA with blind precoding:** throughout this thesis we assumed that CSI and collaborative precoding is used to optimise the d_{min} of composite QAM constellation formed from the superposition of multiple users. It is worth investigating if d_{min} can still be maximised even when CSI are not available at the transmitters by utilising the block fading nature of users' channels to perform blind precoding. To give a general idea of how such a system will work. Let's assume that two users transmit their data over independent Rayleigh fading channels to a single receive antenna simultaneously using the same frequency and orthogonal signature. Each cycle, one of the users transmits two symbols with a predefined phase rotation between them, while the other sends the same symbol twice. This phase rotation is chosen so that at least one of the two consecutive composite signals belongs to a constellation with a high d_{min}. The optimum signal will be jointly decoded first using ML detection and then the repeated symbol is subtracted from the signal with the suboptimal constellation to decode the last symbol. The new scheme increases the spectrum efficiency of two users' link by 50% compared with a single user case while maintaining a BER performance of a single user with the same sum rate over uncorrelated channels and significantly reducing the performance degradation caused by high channel correlation.

- **Grouping for CMMA:** despite the optimality of joint ML detection at the BS, its complexity grows exponentially with the number of users. A possible solution will be to divide users into a number of high and lower power groups where inter group detection is done by using a simple SIC receiver while users within each group are detected using joint ML detection. A grouping design algorithm must insure that the all composite constellation points formed from the lower power group must be at least 50% lower than the square minimum distance of the high-power composite constellation. This will insure that the overall composite constellation formed form the superposition of the two groups is non-ambiguous. Grouping should allow CMMA to accommodate a large number of users with greatly reduced complexity at the receiver and without suffering from an error floor in BER performance which usually occurs in conventional SIC receivers.

- **Iterative decoding for SC-CMMA:** In this thesis, detection in SC-CMMA is performed only at the selected antenna; however since blind channel estimation can extract full CSI for the channels in the remaining antennas, a joint multi-antenna ML detection similar to that used in MIMO can be performed across all antennas to improve the performance of initial detection. This should enable a comparable BER performance and capacity to that of MU-MIMO without the need to allocate any power or time for training sequences at the uplink.
- **Overloaded MIMO using multi-group cooperative modulation:** one attractive application of CM is to provide low-overhead low-latency technique to extend the number of users that can be served simultaneously in MU-MIMO beyond the number of antennas at the BS. This can be achieved by allowing more than one group to perform scheduling and feeding periods simultaneously then the selected relays at each group will use spatial multiplexing to transmit their group data. Inter-group interference during the scheduling and feeding periods can be suppressed by sufficient geographic separation between groups combined with power control.

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