Sudan University of Science and Technology

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M.Sc Program in Electronics Engineering

Analysis and Investigation of Interference Rejection Combining Technique inAdvancedLong Term Evolution (LTE)

فحص وتحليل تقنية الجمع للحد من التداخل في نظام التطور طويل الأمد المتقدم

A THESIS SUBMITTED AS PARTIAL FULFILLMENT OFTHE REQUIREMENTS FOR THE DEGREE OF M.Sc. (Honors) INELECTRONIC ENGINEERING (COMMUNICATIONS ENGINEERING).

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الآية

بسم الله الرحمن الرحيم

قال تعالى:

((فتعالى الله الملك الحق ولا تعجل بالقرآن من قبل أن يقضى إليك وحيه

وقل رب زدني علما))

صدق الله العظيم

سورة طه (114)

Dedication

•My parents: *Thank you for your unconditional support with my studies. I am honored to have you as my parents. Thank you for giving me a chance to prove and improve myself through all my walks of life. I love you*

.

•My family: *Thank you for believing in me; for allowing me to further my studies. Please do not ever doubt my dedication and love for you.*

•My brother: *Hoping that with this research I have proven to you that there is no mountain higher as long as Allah is on our side. Hoping that you will walk again and be able to fulfil your dreams.*

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I also take this opportunity to express a deep sense of gratitude to My friends, for his/ cordial support, valuable information and guidance, which helped me in completing this task through various stages.

A b s t r a c t

One of the main problems which is happened in long term evolution Advanced system (LTE-A) or 4G, is interference

In this thesis Interference Rejection Combining (IRC) technique have been applying to reduce interference, especially That is happenings between cell edge or inter cell interference , IRC is a method to increase the channel quality by using receiver antenna diversity and interference rejection.

IRC is able to suppress the interfering signal and thereby increase the quality of the received signal. This situation, is typical for high capacity areas (urban areas)or low capacity areas(suburban areas) where tighter frequency reuse is in place

(IRC) is comparing with other algorithms in reducing interference, through the results (by investigation and analyzes) it has been found that (IRC) is less (BER)Than other algorithms and this is lead to increase throughput and capacity of system

المستخلص

إحدى المشاكل الرئيسية التي تحدث في نظام إمداد القدرة الطويل الأمد المستمر أو الجيل الرابع هو مشكلة التداخل .

في هذه الأطروحة تم تطبيق تقنية رفض التداخل الجمع بين الإشارات للحد من التداخل خاصة ذلك الذي يحدث بين حافة الخلية أو تداخل خليه مع أخري.

تقنية الجمع للحد من التداخل هو وسيله لزيادة جوده القناة باستخدام جهاز استقبال هوائي التنوع ورفض التداخل.

وهي قادرة علي قمع إشارة التداخل وبالتالي زيادة جودة الإشارة ألمستقبله هذه الحالة بالنسبة للمناطق ذات القدرة العالية المناطق الحضرية أو المناطق ذات القدرة المنخفضة الضواحي حيث تشديد إعادة استخدام التردد في مكان ما.

بمقارنة خوارزمية الجمع للحد من التداخل مع خوارزميات أخرى وباستخدام لغة الماتلاب ومن خلال النتائج بالفحص والتحليل وجد أن خوارزمية الجمع للحد من التداخل بها أقل معدل خطأ وهذا يؤدي لزيادة الإنتاجية وسعة النظام ككل

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Abbreviations

$ABSF_S$	Almost Blank Sub frames
AIR	Active Interface Rejection
AWGN	Additive White Gaussian Noise
$P\ A_S$	Power Amplifiers
CB	Cooperative Beam forming
CDMA	Code Division Multiple Access
COMP	Coordinated Multipoint
CS	Cooperative scheduling
CSI	Channel State Information
DCT	Discrete Cosine Transform
EICIC	Enhanced Inter Cell Interference coordination
eNB_S	enhanced Node Base station
EVM	Error Vector Magnitude
Het Net	Heterogeneous Network
ICIC	Inter Cell Interference Coordination
IRC	Interference Rejection Combining
JP	Joint processing
LTE-A	Long Term Evolution – Advanced

MIMO	Multiple Input Multiple output
MMSE	Minimum Mean Square Error
MMSEC	Minimum Mean Square Error Combining
MN	Moving Network
MRC	Maximal Ratio Combining
MRN	Moving Relay Network
MUE	Multiple User Equipment
MU-MIMO	Multi- User Multiple input Multiple output
NOMA	None Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division multiplex
BER	Bit Error Rate
QoS	Quality of service
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference ratio
SU-MIMO	Single- User Multiple input Multiple output
UE	User Equipment
UMTS	Universal Mobile Telephone System
VPL	Vehicular Penetration Loss
VUE	Vehicle User Equipment
ZF	Zero Forcing

CHAPTER ONE

INTRODUCTION

Chapter one

Introduction

1-1 preface

The concept of interference rejection combining (IRC) is to regenerate the transmitted signal based on estimated data from the previous receptions, emulate distortion occurring from the multi – path channels and finally subtract all regenerated interfering signals from the uplink received signal to obtain more reliable estimation of original users data.

This feature utilizes the spatial separation and characteristics of inter- cell interference to determine the power of the interference UE which belongs to another cell. Once the pattern and power level is determined, the victim cell can then remove the interference from the received signal [1].

cellular systems such as 3GPP LTE, LTE-advanced, and wimax. Interference mitigation is one of the key issues currently under investigation in different standardization bodies and forums. Based on used methods, mitigation technique is generally categorized into three major classes. One is interference cancellation. Another is interference averaging and the third is interference avoidance technique. The basic principle of interference cancellation technique is the receiver signal processing to estimate interference and subtract it from the desired signal component. deploying the network with the same frequency have the following superiorities, such as high frequency efficiency, deployment flexibility, low requirement of supporting frequency range for the UE, low complexity of the RF terminal and low terminal price. So it has been extensive used in outdoor network deployment. Due to resource scheduling on the same frequency, the target cell and neighboring cells must take measures to suppress the co-channel interference to improve the system performance co-channel interference is a major impairment in current and future wireless systems Channel estimation and interference mitigation are essential to maintaining quality-of-service (QoS) for the users. Several papers discuss channel estimation for LTE Advanced. For example, the discrete cosine transform (DCT)is used in for channel estimation. Time-domain channel estimation and selection of the cyclic shifts of the training sequence are discussed in. As expected, cyclic shifts should be chosen to minimize the spectral leakage between users. In most of the works on LTE-Advanced channel estimation, co-channel interference from other cells is not considered. For co-channel interference mitigation, neighboring cells can coordinate schedulers to allocate resources with reduced interference. Such inter-cell interference coordination (ICIC) requires communication between cells and is supported in the LTE-Advanced standard. Another approach is estimation and cancellation (subtraction) of co-channel interfering signals [3].

1-2 Problem statement:

One of the main problems in long term evolution Advance system (LTE-Advance) is the interference which is reduce the system efficiency, on this thesis this problem have been discussed.

1-3 Proposed solutions:

Different techniques may be used to mitigate interference in LTE- advance for example maximal ratio combining (MRC) or Minimum mean square error (MMSE) or user equipment receiver (UE) and interference rejection combining (IRC) in this work last one was suggested to investigated.

Figure (1-1) illustrated the IRC technique: in antenna1 the transmitted signal (St) with blue colored and interferer signal (Sr) with red colored and also in antenna2 the transmitted signal(St) with red colored and interferer signal (Sr)with blue colored, the interference signals on the two antennas are rejected(subtracted) then the original signals are combined to give the desired signal which it is amplified

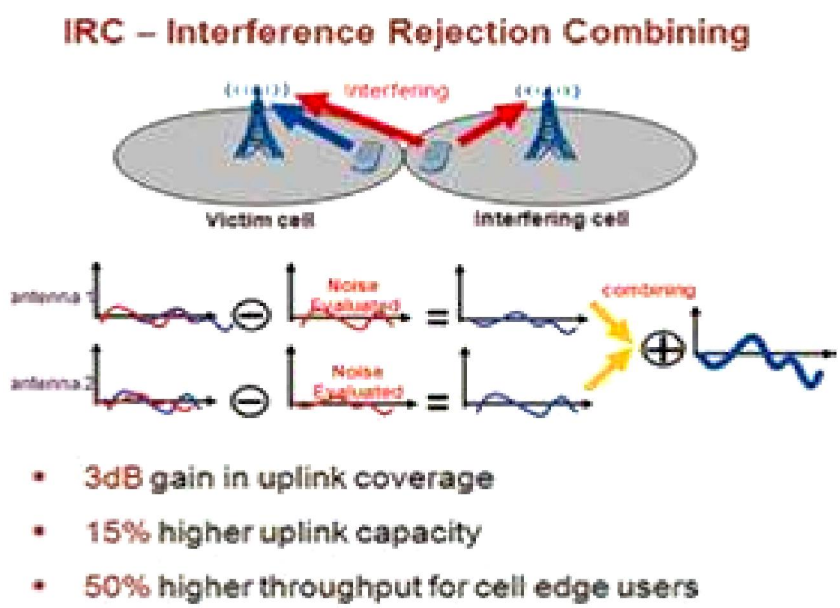


Figure (1-1) Interference rejection combining (IRC)Network

1-4 Objectives:

- reduce interference in LTE advanced
- increase system capacity and by reduce (BER) in LTE Advance
- Implement IRC techniques in different scenarios in heterogeneous LTE advanced

1-5 Methodology:

mat lab software have been applied for proposed technique in MIMO scenarios and also implemented in different networks simulation analyzes through the relationship between values of SINR and BER about throughput and system capacity

1-6 Thesis out lines:

The thesis is organized as follows chapter one provides an introduction. Chapter two theoretical literature overview chapter three present model of IRC techniques and simulation chapter foure the results and discussion chapter five conclusion and recommendations

CHAPTER TWO

THEORTICAL LITERATURE OVERVIEW

Chapter two

Theoretical Literature Overview

2-1 introduction

LTE-A builds on the LTE OFDM/MIMO architecture to further increase data rate. It is defined in 3GPP releases 10 and 11. There are five major features: carrier aggregation, increased MIMO, coordinated multipoint transmission, heterogeneous network (HetNet) support, and relays.

Carrier aggregation combines up to five 20-MHz channels into one to increase data speed. These channels can be contiguous or non-contiguous as defined by the carrier's spectrum assignments. With maximum MIMO assignments, 64QAM, and 100-MHz bandwidth, a peak downlink data rate of 1 Gbit/s is possible.

LTE defines MIMO configurations up to 4x4. LTE-A extends that to 8x8 with support for two transmit antennas in the handset. Most LTE handsets use two receive antennas and one transmit antenna. These MIMO additions provide future data speed increases if adopted.

Het Net support refers to support for small cells in a larger overall heterogeneous network. The HetNet is an amalgamation of standard macro cell base stations plus microcells, macro cells, Pico cells, femto cells, and even Wi-Fi hotspots. This network increases coverage in a given area to improve connection reliability and increased data rates.

Coordinated multipoint transmission, also known as cooperative MIMO, is a set of techniques using different forms of MIMO and beam forming to improve the performance at cell edges. It uses coordinated scheduling and transmitters and antennas that aren't collocated to provide greater spatial diversity that can improve link reliability and data rate.

Relays use repeater stations to help coverage in selected areas, especially indoors where most calls are initiated. LTE-A defines another base station type called a relay station. It is not a complete base station but a type of small cell that will fit in the HetNet infrastructure and provide a way to boost data rates and improve the dependability of a wireless link.

Some deployment of LTE-A is expected in late 2013 with increasing adoption in 2014 and beyond. LTE-A is forward and backward compatible with basic LTE, meaning LTE handsets will work on LTE-A networks and LTE-A handsets will work on standard LTE networks.

The investigation of co-channel interference mitigation techniques which includes interference cancellation through receiver processing, interference randomization by frequency hopping, and interference avoidance through resource usage restrictions imposed by frequency and power planning, has become a key focus area in achieving dense spectrum reuse in the next generation cellular systems such as 3GPP LTE, LTE-advanced.

Interference mitigation is one of the key issues currently under investigation in different standardization bodies and forums. Based on used methods, mitigation technique is generally categorized into three major classes. One is interference cancellation. Another is interference averaging and the third is interference avoidance technique. The basic principle of interference cancellation technique is the receiver signal processing to estimate interference and subtract it from the desired signal component. Interference averaging technique such as frequency hoping ensures user equipments to access a range of channels rather than a narrow set in a specific pattern so that interference effect is averaged out for all At last, the interference avoidance technique lays emphasis on finding an optimal effective reuse factor often achieved through restrictions on frequency and

When co-channel interference exists in the channel environment, the statistical properties of interference will change. Effect of interference on transmitting signal will increase, which will make performance of traditional detection algorithm decrease. Facing co-channel interference environment that there must exist in the LTE communication system, in order to achieve downlink maximum data transmitting rate in the LTE standard, receiver detector must use detection algorithm with interference mitigation ability. For interference elimination algorithm in MIMO-OFDM systems, the research is mainly manifested on the two algorithms which are maximum ratio combining algorithm and interference suppression algorithm. Link model in interference environment is shown in Fig. (2-1).

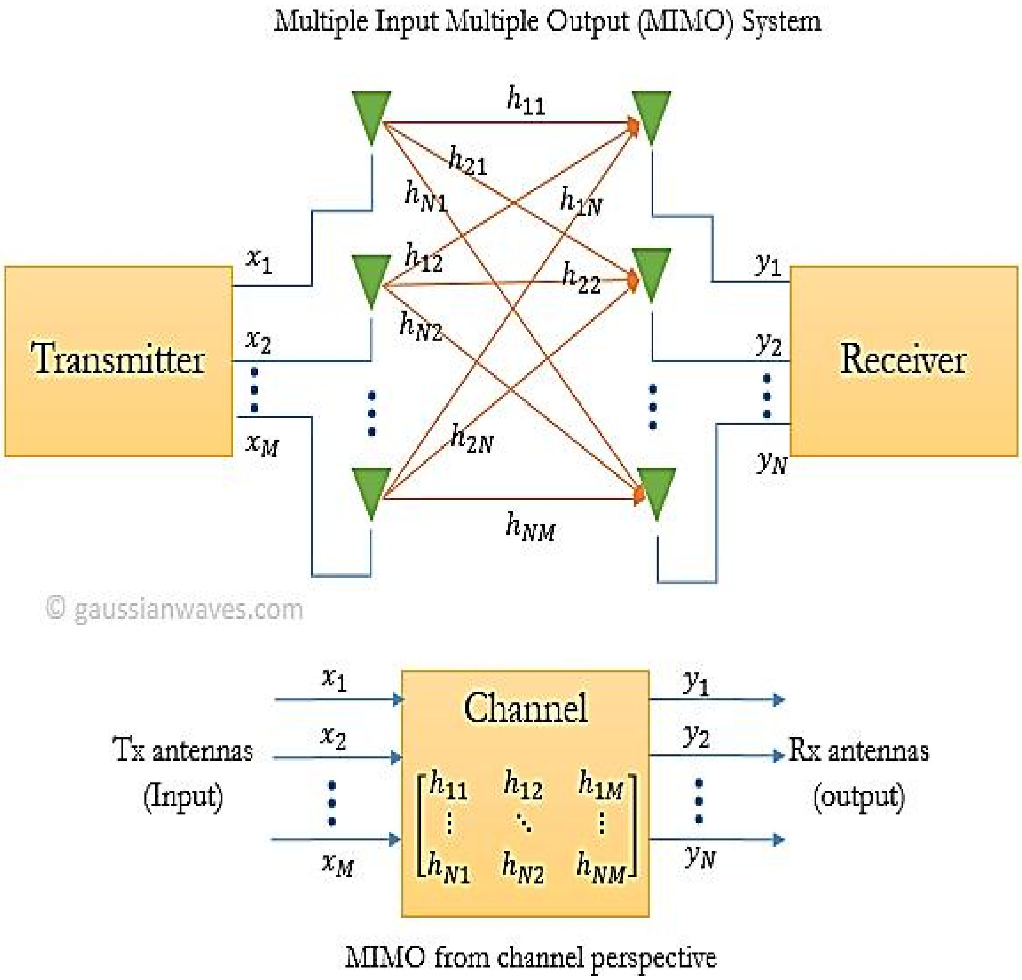


Figure (2-1) Link model in interference environment

2-2 Multiple Antenna Systems or MIMO:

Here, the system configuration typically contains M antennas at the transmitter and N antennas at the receiver front end as illustrated in the next figure. Here, each receiver antenna receives not only the direct signal intended for it, but also receives a fraction of signal from other propagation paths. Thus, the channel response is expressed as a transmission matrix H. The direct path formed between antenna 1 at the transmitter and the antenna 1 at the receiver is represented by the channel response h_{11} . The channel response of the path formed between antenna 1 in the transmitter and antenna 2 in the receiver is expressed as h_{21} and so on. Thus, the channel matrix is of dimension $N \times M$.

2-3 LTE-A Design Challenges

LTE solves many problems in providing high-speed wireless service. There is no better method, at least for now, but it does pose multiple serious design issues. The greatest problem is the necessity of having to use multiple bands that often are widely spaced from one another. As a result, multiple antennas, multiple power amplifiers, multiple filters, switching circuits, and, sometimes, complex impedance matching solutions are required. Each cellular operator specifies cell phones for its spectrum.

In addition, the power amplifiers (PAs) must be very linear if error vector magnitude (EVM) is to be within specifications for the various multi-level modulation methods used. Linear amplifiers are inefficient and consume the most power in the phone except for the touch screen. The need to cover multiple bands necessitates the use of multiple PAs. Battery life in an LTE phone is typically shorter as a result. The need to include MIMO also means additional antennas and PAs.

Solutions to these problems lie in fewer yet more efficient PAs. Also, wider-bandwidth antennas solve the multiband problem [13] .

Advanced antenna systems may take the following forms:

- Receiver diversity
- Transmit diversity
- Fixed multi-beam
- Multiple Input Multiple Output (MIMO) multi stream transmission
- Adaptive beam forming with linear array antenna

Receiver Diversity and Optimal Combining: Base station receiver diversity is widely used in all 2nd and 3rd generation cellular mobile systems including GSM, UMTS and CDMA using cross-polarized antennas. The combining solution can be Maximum Ratio Combining (MRC) or Interference Rejection Combining (IRC). MRC is the optimal solution when the interference is spatially white Gaussian, while IRC is optimal in case of dominant interferers.

Transmit diversity – open and closed loop: Base station transmit diversity can be utilized to enhance the downlink coverage and capacity. The transmit diversity can be based on an open loop or closed loop approach. The closed loop

Multiple Input Multiple Output (MIMO): MIMO uses at least two transmit antennas at the base station and two receive antennas at the terminals. It may use space time coding or diversity transmission or spatial multiplexing/dual stream transmission. Spatial multiplexing transmits two parallel data streams to double the data rate. Downlink MIMO can utilize the same cross-polarized antenna that is used for receive diversity. MIMO in the uplink faces the problem that two power amplifiers would be needed in the terminal, increasing the cost, size and power consumption of the devices.

2-4 Antennas for MIMO

MIMO is a multiple antenna technology that uses advanced signal processing techniques to increase capacity in a radio link; it employs multiple transmit and receive channels and antennas with different data streams sent over each antenna. MIMO antenna systems are a magic ingredient in the quest for broadband wireless systems with higher capacity, performance and reliability. MIMO technology exploits multi-path to provide higher data throughput, and simultaneous increase in range and reliability all without consuming extra radio frequency. MIMO technology achieves a multifold user throughput gain and multiple aggregated capacity increase compared to current 3G macro-cellular networks. Because of these properties, MIMO has become an important part of modern wireless communication standards such as HSPA+, IEEE 802.11n (WiFi), 4G, 3GPP LTE and WiMAX. With MIMO technologies and higher order modulation, In LTE Peak data rates of up to 300 Mbps (4x4 MIMO) and up to 150 Mbps (2x2 MIMO) in the downlink and up to 75 Mbps in the uplink are specified[14] .

The capacity enhancement approaches consist of three main technology components: spectrum efficiency, spectrum extension, and network density as shown in Fig.2-3. Spectrum efficiency solutions include beam-forming, Massive MIMO, Coordinated Multipoint Transmission and Reception

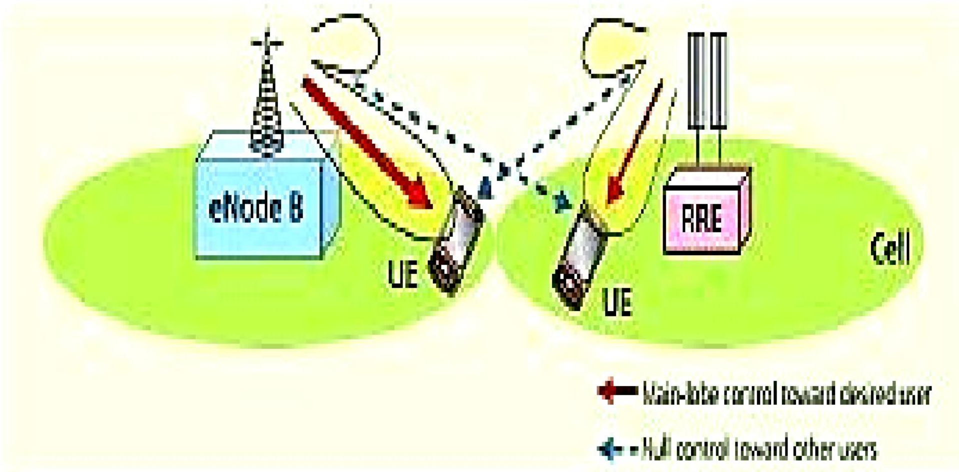
(CoMP), and advanced receiver techniques while spectrum extension includes Carrier Aggregation (CA). Significant capacity enhancement can be achieved using Heterogeneous Networks (HetNet) where various types of small cells are densely deployed in addition to conventional Macro cells. In the current discussions, there is also a strong emphasis for improving cell edge throughput including data rate fairness, a major issue in the current LTE networks. In fact LTE capacity decreases as more terminals are located near the cell edge. For network density enhancements, co-channel deployments of Macro cells and small cells were intensively discussed and studied in 3GPP Release 10/11. It includes small cell solutions such as Pico/femto nodes, remote radio heads and relay nodes sharing the same frequency with the

Macro cells. However dense deployment of small cells in co channel deployments can result to interference between Macro cells and small cells. As the Macro cells provide the underlying network coverage, operators will hesitate to deploy small cell solutions that would impact the Macro cell layer's key performance indicators. A more straight-forward solution for enhancing network density in cellular networks is introducing additional layers at different frequencies (previously known as Hierarchical Cell Structure). For LTE this means deploying smaller cell

Applying non orthogonal multiple access (NOMA)and multiple input multiple output (MIMO) Scheme with IRC-SIC receivers .NOMA is a multiplexing scheme that utilizes an additional new domain, i.e., the power domain, which is not sufficiently utilized in previous systems. Non- orthogonality is intentionally introduced via power-domain user multiplexing; however, interestingly, quasi orthogonality still can be achieved. In fact, user demultiplexing is ensured via the allocation of large power difference between paired UEs and the application of SIC

One approach to diminish the performance-limiting interference is by reducing the inter-cell interference with the assist of joint transmission. Cooperative Multipoint (CoMP) transmission and reception is a structure that refers to a system where a number of geographically scattered antenna nodes work together with the mean of improving the execution of the users processed in the common collaboration area It covers all required system architectures to accomplish tight coordination for transmission and reception. Cooperation among base stations (denoted as eNBs in Long Term Evolution and Long Term Evolution-Advanced) is categorized by the need of an interconnection among the different access points via dedicated backhaul links. These backhaul links should be a very high speed and low-latency link. The criteria are crucial for the accomplishment of the cooperative communication, even though its design will be very challenging due to the huge amount of information that have to be interchanged between the nodes. Long Term Evolution Advanced (LTE-A) will utilize the standard interface X2 for these roles. There are several possible coordinating schemes available in the circumstance of LTE-Advanced. Coordinated beam forming/scheduling is a less complicated approach where only a single cell transmits user data to the user equipment (UE). Joint processing scheme, on the other hand, involves multiple nodes to transmit user data to the UE. There are two approaches are being considered in joint processing scheme: joint transmission, which needs multi-user linear precoding, and dynamic cell selection, where data are transmitted from only one cell that is dynamically selected. The transmission schemes can be implemented on any types of network configurations that will be presented in the following section. CoMP is considered for LTE-A as a tool to improve the coverage of high data rates, the cell-edge throughput as well as to increase the system throughput. In a cellular deployment and specifically if frequencies are reused in each cell, other-cell interference traditionally degrades the system capacity. The aim in CoMP is to turn the other cell interference into a useful signal specifically at the cell border.

the possible CoMP categories in LTE-Advanced for both the uplink and the downlink. In the downlink, two main CoMP transmission methods are discussed: figure(2-2) cooperative scheduling/beam forming (CS/CB) and joint processing (JP). Their main difference lies in the fact that in the coordinated scheduling/beam forming scheme it is only one eNB that transmits data to the UE, although different eNBs may share control information. In the joint processing scheme, many eNBs transmit data simultaneously In general, the cost of the CoMP mode is found only beneficial to the cell edge users where the perceived Signal-to-Interference-and Noise Ratio (SINR) is low. This is because more system resources are allocated to a single user during its operation. However, simulation results suggest that CoMP can be used to increase both the average cell throughput and the cell-edge user throughput as compared with conventional non cooperative system category of joint intended for a particular UE are jointly transmitted from multiple eNBs to improve the received signal quality and cancel interference. processing, data In the uplink the CoMP scheme, aimed at increasing the cell-edge user throughput, implies the reception of the signal transmitted by UEs at multiple and geographically separated points



Figure(2-2)Coordinated scheduling/ beam forming scheme

There are different schemes that can be used at multiple reception points to combine the received signals. Maximum Ratio Combining (MRC), Minimum Mean Square Error Combining (MMSEC), and Interference Rejection Combining (IRC) are examples of techniques that extract the transmitted information from the received signal. Despite the above-mentioned considerations, it has been noticed that there are some issues which may impact the system performance and should be further investigated.[16]

2-5 Interference Mitigation Techniques

Interference mitigation in a terminal receiver can be achieved using the following possible approaches:

Non-linear approach: In this case, the interfering signal is first estimated and then subtracted from the received signal in an iterative fashion. It demands an explicit modeling of the interfering signal. The approach provides excellent performance but is very sensitive to errors, since signal interference is based on estimate.

Linear approach: This approach utilizes multiple antennas at the receive-end to perform spatial suppression of the interfering signal. The receiver forms a receive antenna beam with a spatial null in the direction of the interferer The approach is best suited with a large number of receive antennas as it has the capacity to handle a number of interferers. Receivers of such are termed as Interference Rejection Combiner (IRC) receivers.

Sequans Active Interference Rejection (AIR): This is a compact LTE receiver designed by Sequans Communications with the capability of mitigating interference. The design was based on the specific requirements of interference mitigation in LTE, and is suited to the various transmission modes of LTE. Sequans AIR adopts the linear approach to interference mitigation, and has been co-developed with technology partner –Array Comm, which is a pioneer in antenna processing and interference management techniques. Sequans has leveraged its own expertise in OFDMA and MIMO receivers to create innovative and interference mitigation algorithm and optimized implementation that is capable of mitigating interference not only from data channels but also from control channels. Though control channels are designed to be more robust than data channels, it can still suffer from strong interference such that the terminal faces problem of demodulation and consequently loses connection from the network.

2-6 The Enhanced Inter- Cell Interference Coordination (EICIC) The Inter-Cell Interference Coordination ICIC methods specified in Release 8 and Release 9 do not specifically consider HetNet settings and may not be effective for dominant HetNet interference scenarios. To address this challenge, therefore, enhanced Inter-Cell Interference Coordination (eICIC) techniques were developed for Release 10 and 11. The solution techniques have been grouped according to the following categories:

2-7 Time Domain Techniques

(Sub-frame Alignment):When there is Multiple User Equipment (MUE) in the vicinity of a femto cell, they can be scheduled within the sub frames overlapping with the Almost Blank Sub frames (ABSFs) of the femto cells, which significantly mitigates cross-tier interference . Where there is no interference coordination for range-expanded picocell users, it results in a large DL interference from the macro cell. Such interference problem can be mitigated through using ABSFs at the macrocell.

2-8 Frequency Domain Technique:

In frequency-domain eICIC solutions, control channels and physical signals of different cells are scheduled in reduced band widths in order to have totally orthogonal transmission of these signals at different cells.

2-9 Power Control Techniques:

According to this very technique is heavily discussed in 3GPP for handling dominant interference scenarios, by applying different power control techniques at femtocells. The single most effective

method for reducing the potential for harmful interference is to reduce the RF power being generated. Incidentally, reducing the radiated power at a femtocell may also reduce the total throughput of femto cells users, but significantly improves the performance of victim MUEs. Then, four different DL power control approaches at femto cells can be listed as follows (all values are in dBm)[17].

the deployment of moving base stations on public transportation vehicles is considered as one of the most promising solutions. for system capacity Each public transportation vehicle forms a moving network (MN) inside the vehicle to serve the users on board, one of the key challenges is the inter-cell interference In order to reduce this problem, we employ and compare various solutions to enhance the performance of MNs. We show that by using MNs that have advanced multi-antenna systems, Several studies raise the issue of how to service these VUE sufficiently One of the most promising solutions is to deploy moving relay nodes (MRNs) on the vehicles, which circumvent the vehicular penetration loss (VPL) and improve the quality-of-service (QoS) at the VUEs improve the QoS at the VUEs. Furthermore, as a vehicle is less constrained by power and transceiver complexity, sophisticated multi-antenna solutions and more advanced signal processing techniques can be integrated to MRNs to further improve their performance. For example it was showed that by using predicting antennas on top of high-speed vehicles ,reliable channel state information (CSI) could be obtained at the MRNs to support advanced multi-antenna applications .Moreover, from a system point of view, the use of MRNs can significantly reduce the number of handover failures for high speed VUEs, and lower the signaling overhead for mobility management. However, to the best knowledge of the authors, the current study of using MRNs is either about system architectures or in very simplified scenarios. There is no detailed study about deploying MRNs in typical urban scenarios.

New implementation challenges arise when we introduce a new type of node, i.e., the MRN, to the system, especially in a densely deployed urban scenario where the inter-cell interference becomes more complicated

to understand the practical challenges of deploying MNRs in an ultra-dense urban scenario, in this work, we extend our earlier work in by considering a practical densely deployed heterogeneous and small cell networks (HetSNets) framework introduced by the EU 5G project METIS. We assume each of the public transportation vehicles forms a moving network (MN) to serve the VUEs on board. Depending on the availabilities of CSI at the receivers, we consider either the use of maximum ratio combining (MRC) or interference rejection combining (IRC) to enhance the reception of the backhaul links of MNs, and the use of almost blank sub frames (ABSs) is explored to protect the access links of MNs. We show that by deploying MNs to the system, the throughput at the VUEs can be significantly improved, while the performance of regular outdoor users have no obvious degradation. Hence, the use of MNs constitutes a promising approach in future mobile communication systems to improve the experience of VUEs.

2-10 Enhancement of backhaul links of MNs

We consider using multi-antennas at the MN receivers to combat the inter-cell interference at the backhaul links. MNs on public transportation vehicles are less constrained by power and size compared to regular UEs. Hence, more antenna elements can be deployed and more advanced signal processing algorithms can be used at the receivers. A single transmit antenna is considered at each macro cell, and multiple antennas are assumed for the backhaul links receivers. Depending on the availability levels of CSI, various schemes can be used to improve the SINR at the receivers. We consider two cases, i.e., (MRC), and (IRC).

2-11 Maximum ratio combining

MRC is a common way to coherently combine the desired signal from the receiver antennas to improve the received desired signal power. To use MRC, the receiver only needs to estimate the CSI of the desired signal at each of the antennas. An MRC receiver is optimal in terms of SNR, as it maximizes the output power of the desired signal .

2-12 Interference rejection combining

If the CSI from the interferer can also be observed at each receiving antennas, we can use the multiple antennas at the receiver to suppress the interference, and maximize the output SINR. This scheme is usually referred to as IRC in the literature. when assuming some arbitrary weight vector

The use of MNs can improve the performance of the VUEs in ultra-dense urban scenarios, if advanced receivers are used. This is one of the biggest advantages of using MNs as they are less constrained by antenna space, power and transceiver complexities. Moreover, the impact of using MNs on regular outdoor users are very limited. However, the backhaul links are still the bottle necks to further improve the performance of MNs. The performance of backhaul links can be further improved in several ways, especially in a densely deployed scenario. For example, only up to 64-QAM is supported in the current LTE-A system as the modulation methods. In a densely deployed scenario, the SINR can support the use of 256-QAM. Moreover, as demonstrated in by using advanced antenna systems on public transportation systems, reliable CSI can be obtained at the transmitter side which enables the use of more advanced multi-antenna schemes. Certainly modifications of the current mobile communication systems are required to support MNs. This issue has been discussed in. However, most of the components at the network side can be reused, and only new protocols need to be introduced to support the mobility of the MNs. The cost of deploying MNs on the public transportation vehicles can be recouped by bringing in more business opportunities for operators and service providers. Nevertheless, the use of MNs is very promising for the next generations of mobile communication systems to improve the experiences of VUEs[18].

Multiple-input multiple-output (MIMO) systems are being considered as one of the key enabling technologies for future wireless networks. However, the decrease in capacity due to the presence of interferers in MIMO networks is not well understood. the developing an analytical framework to characterize the capacity of MIMO communication systems in the presence of multiple MIMO co-channel interferers and noise. We consider the situation in which transmitters have no channel state information, and all links undergo Rayleigh fading. We first generalize the determinant representation of hyper geometric functions with matrix arguments to the case when the argument matrices have Eigen values of arbitrary multiplicity. This enables the derivation of the distribution of the Eigen values of Gaussian quadratic forms and Wishart matrices with arbitrary correlation, with application to both single-user and multiuser MIMO systems. In particular, we derive the ergodic mutual information for MIMO systems in the presence of multiple MIMO interferers. Our analysis is valid for any number of interferers, each with arbitrary number of antennas having possibly unequal power levels. This framework, therefore ,accommodates the study of distributed MIMO systems and accounts for different spatial positions of the MIMO interferers. Index Terms—Eigen values distribution, Gaussian quadratic forms, hyper geometric functions of matrix arguments, interference, multiple-input multiple-output (MIMO), Wish art matrices.

THE use of multiple transmitting and receiving antennas can provide high spectral efficiency and link reliability for point-to-point communication in fading environments. The analysis of capacity for multiple-input multiple-output(MIMO) channels in suggested practical receiver structures to obtain such spectral efficiency. Since then, many studies have been devoted to the analysis of MIMO systems.

Only a few papers, by using simulation or approximations, have studied the capacity of MIMO systems in the presence of co-channel interference. In particular, a simulation study is presented in for cellular systems, assuming up to three transmit and three receive antennas. The simulations sho ed that co-channel interference can seriously degrade the over all capacity when MIMO links are used in cellular networks. In and it is studied whether, in a MIMO multiuser scenario, it is always convenient to use all transmitting antennas. It was found that for some values of signal-to-noise ratio (SNR)and signal-to-interference ratio (SIR), allocating all power into a single transmitting antenna, rather than dividing the power equally among independent streams from the different antennas, would lead to a higher overall system mutual information. The study in adopts simulation to evaluate the capacity of MIMO systems in the presence of co-channel interference, and the difficulties[19]

2-13 Related work

Different contributions and studies have already been done about the use of interference rejection combining(IRC) the Authors In[4] propose and analyze a frequency domain interference rejection combining (FD-IRC) algorithm for uplink CP-CDMA systems to suppress the ISI and MAI Investigated of Interference Rejection Suppression in MIMO Systems In[6] methods using minimum mean square error, and could obtain better results by applying algorithms.

Authors In[7] Introduces the IRC interference covariance matrix estimation procedure is emulated with techniques based on random matrix theory

In[8] the author used two techniques Maximum Ratio Combining (MRC)and (IRC)Interference Rejection Combining for Interference aware MIMO linear receiver.

Also In[11] Building a virtual zero latency gigabit experience, to overcome the interference problem, Maximum Ratio Combining Inter-cell interference unaware MIMO linear receiver, Interference Rejection Combining (IRC) Interference aware MIMO linear receiver.

CHAPTER THREE

MODEL OF IRC TECHNIQUES AND SIMULATION

CHAPTER THREE

The Modeling OF IRC Technique and Simulation

3-1 Mathematical model

There are N1independent co-channel interference signal in the channel environment. The number of transmitting antenna is M and the number of receiving antenna is N The receiving signal vector can be expressed as

$$y=\sqrt{p_d}H_d\omega_T S_d + H_I P_I^{1/2} S_I + n \qquad (3\text{-}1)$$

S_T=(S_1,S_2,⋯,S_{NT})$T$is co-channel interference signal vector

$S_d$is transmitted objective signal. nis additive Gaussian white noise of

N× 1 dimension.$H_I$is matrixof N× $N_I$dimension$H_I(i,j)$is channel frequency domain feature value corresponding to the j-th co-channel interference signal of the i-th antenna.$H_d$is channel frequency domain matrix of N× Mdimension from transmitter to receiver. $p_d$is average receiving power of objective signal.$p_{I=}$diag{P_1 ,P_2 ⋯,P_{NI}}is average

receiving power of co-channel interference signal. vector of transmitter isω_T

=U_{max}. $U_{max}$is eigenvector corresponding to the maximum eigenvalue

λ_{max} of matrix $H_d^H H_d$. The maximum ratio combining of output signal

of receiver is

$$x_{MRC}=\omega_R^H y$$

$$=\sqrt{p_d}u_{max}^H H_d^H H_d U_{max} S_d + u_{max}^H H_d^H H_I P_I^{1/2} S_I + u_{max}^H H_d^H n \qquad (3\text{-}2)$$

$$u_{max}^{H} H_d^{H} H_d U_{max} = \lambda_{max} \quad (3\text{-}3)$$

(3) is substituted into (2) and (4) is obtained.

$$x_{MRC} = \sqrt{p_d}\lambda_{max} S_d + \mathrm{w} \quad (3\text{-}4)$$

w is sum of co-channel interference and noise of receiver

$$\mathrm{w} = u_{max}^{H} H_d^{H} H_I P_I^{1/2} S_I + u_{max}^{H} H_d^{H} \mathrm{n} \quad (3\text{-}5)$$

The output signal-to-noise ratio of MRC receiver is (3-6).

$$\gamma_{SINR} = \frac{p_d \lambda_{max}^{2}}{u_{max}^{H} H_d^{H} \left(H_I P_I H_I^{H} + \sigma_n^2 I\right) H_d U_{max}} \quad (3\text{-}6)$$

When there is not co-channel interference in the channel, (3-6) can be expressed as

$$\gamma_{\mathrm{SINR}} = \frac{\mathrm{p_d}\lambda_{\mathrm{max}}}{\sigma_{\mathrm{n}}^{2}} \quad (3\text{-}6)$$

IRC algorithm can be regarded as extension of MMSE algorithm based on minimum mean square error criterion. The difference is interference of IRC algorithm not only consider the effect of noise, but also consider the effect of co-channel interference.. Interference rejection combining (IRC) on the other hand, not only estimate each channel independently, but also calculates the Covariance matrix. After knowing the coherence between each channel, interference from other channels can be removed

Principle of interference rejection combining algorithm is as follows.

$E\{\|X - CY\|^2\}$=tr{E[(X-CY)(X-CY)]^H}

$$=\mathrm{tr}\{E[XX^H - XY^HC^H - CYX^H + CYY^HC^H]\} \qquad (3\text{-}7)$$

$$=\mathrm{tr}\{E(XX^H)\} - tr\{E(XY^HC^H)\} - tr\{E(CYX^H)\} + tr\{E(CYY^HC^H)\}$$

Total transmitting power of transmitter is P, autocorrelation matrix of transmitting signal can be expressed as (3-8).

$$R_{XX} = E(XX^H)$$

$$= \frac{P}{n_T} I \qquad (3\text{-}8)$$

$$P = \sum_{i=1}^{n_t} p_i = \sum_{i=1}^{n_t} \left(\mu - \frac{\sigma_n^2}{\partial_i}\right) \qquad (3\text{-}9)$$

P is accumulated value of n_t number of transmitting antenna power

μ is a constant and is equal to 1/ L ln 2 . L is Lagrange multiplier.∂_i is the i-th singular value of channel matrix H σ_n^2 is variance of noise. In order to facilitate analysis, assumptions on the transmitting antenna transmission power is the same, and equal to 1 (3-8) can be expressed as (3-10).

$$E(XX^H)=1 \qquad (3\text{-}10)$$

$$E\{\|X-CY\|^2\}=tr\{E(xx^H)\} -tr\{E(XY^HC^H)\}$$
$$-tr\{E(CYX^H)\}+tr\{E(CYY^HC^H)\}$$

$$=tr(I_{nt})-tr(H^HC^H)-tr(CH)+tr\{C(HH^H+R_{ww})C^H\} \qquad (3\text{-}11)$$

Do partial derivative to Con both sides of (3-11). The left side is set to 0 and IRC filter matrix (3-15) is obtained. IRC algorithm can be expressed as (3-16) and

R_{yy}can be calculated by (3-12)

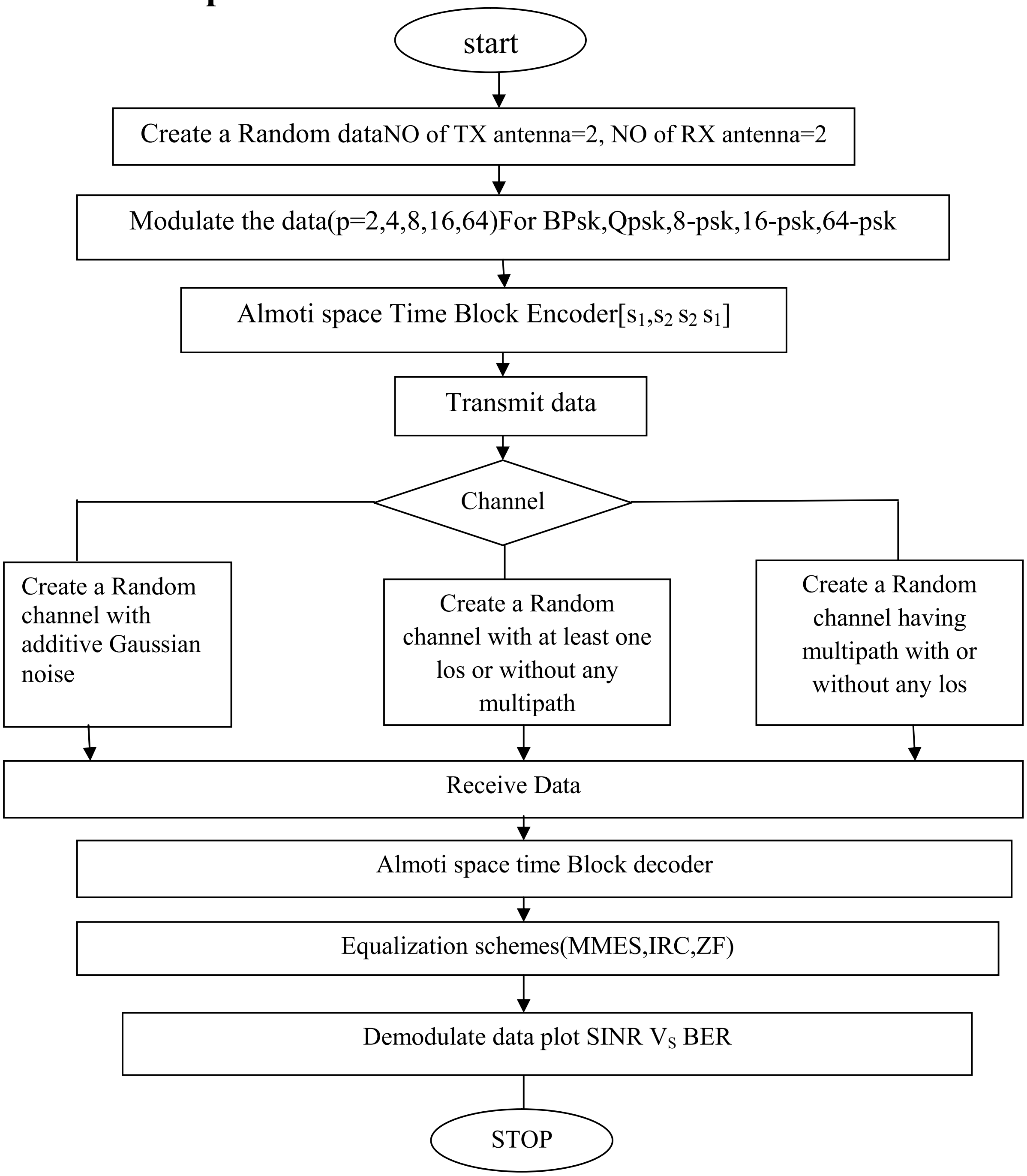
$$\boldsymbol{C_{IRC}}=\boldsymbol{H^H}(\boldsymbol{HH^H}+\boldsymbol{R_{ww}})^{-1}$$
$$=H^H(\boldsymbol{HH^H}+\boldsymbol{R_{ww}})^{-1}$$
$$=\boldsymbol{H^H}(\boldsymbol{HH^H}+E[(\textstyle\sum_i G_i S_i+n)(\sum_i G_i S_i+n)^{\mathrm{H}}])^{-1} \qquad (3\text{-}13)$$
$$=\boldsymbol{H^H}(\boldsymbol{HH^H}+\textstyle\sum_i G_i E(ZZ^H)G_i^H+E(nn^H))^{-1}$$
$$=\boldsymbol{H^H}(\boldsymbol{HH^H}+\textstyle\sum_i G_i G_i^H+\sigma_n^2\mathrm{I})^{-1}$$

$$E(yy^H)=E[H_X+\textstyle\sum_i G_i S_i+n)(H_X+\sum_i G_i S_i+n)^{\mathrm{H}}] \qquad (3\text{-}14)$$
$$=\boldsymbol{HH^H}+R_{nn}+\textstyle\sum_{i=1} G_i G_i^H$$

$$C_{IRC}=\boldsymbol{H^H}\boldsymbol{R_{yy}}^{-1} \qquad (3\text{-}15)$$

$$\boldsymbol{R_{yy}}=\frac{1}{LB}\sum_{i=1}^{L}\sum_{K=1}^{B} y_{K.i}\, y_{k.j}^H \qquad (3\text{-}16)$$

3.2 Computer model



Figure(3-2) Flow chart of (IRC) technique

3.3 Simulation description

In this thesis matlab software is used to proposed technique in MIMO scenarios and also implemented in different networks, urban area, suburban area ,simulation analyzes through the relationship between values of SINR and BER about throughput and system capacity the parameters used in simulation shown in the table(3- 4) blew

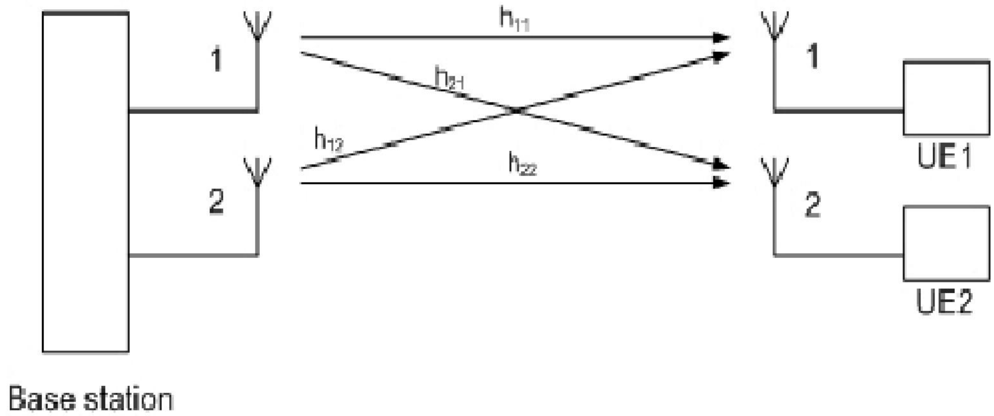
Parameters	Value
Channel type	AWGN, Rayleigh fading
Modulation type	PSK, QAM,16QAM
Transmitted signal	Tx=3GHZ
Receive signal	Rx=2.5GHZ
Modulation order	M=8,16
Channel coding	Turbo code
SINR ranges	0:2:8 dB

Table(3- 1) simulation parameters

3-4 First scenario in urban area:

Multi User MIMO (MU-MIMO):

When the individual streams are assigned to various users, this is called Multi User MIMO (MU-MIMO) This mode is particulary usful in the uplink becaus complexity on the UE side can be kept at a minimum by using only one smit antenna. As shown in figure (3-3)

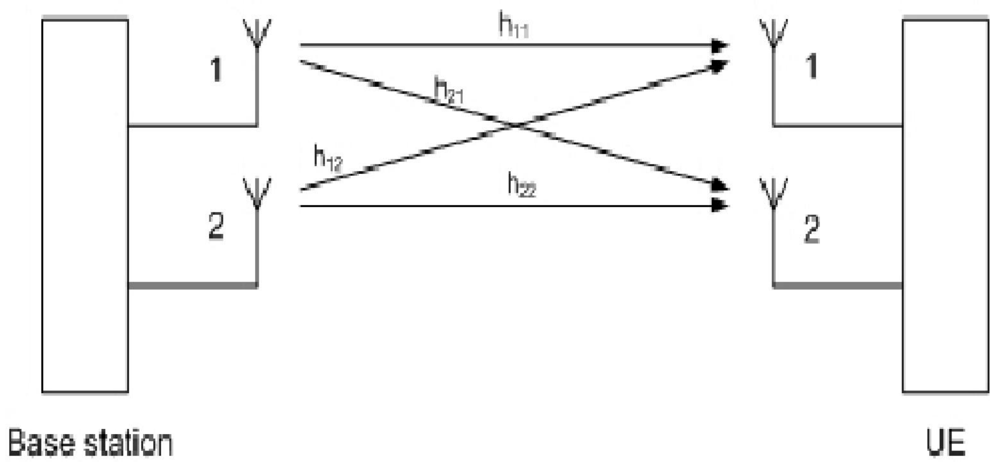


Figure(3-3)

3-5 Second scenario in suburban area:

Single User MIMO (SU-MIMO):

When the data rate is to be increased for a single UE this is called Single user MIMO(SU-MIMO) as shown in figure (3-4)



Figure(3-4) (SU-MIMO)

3-6 Maximal Ratio Combining (MRC)

Maximum ratio combining (MRC) assigns weight according to each Rx signal's SINR, i.e. the signals are equalized based on each channel before being summed up. The output SNR is, therefore, the sum of the SNR at each element.

The MRC technique assumed that the fading signal at each element is independent of the signal at other elements.

On the i^{th}receive antenna, the received signal is,$y_i = h_i^x + n$ (3-17)
where

$y_i$is the received symbol on thei^{th} receive antenna,
$h_i$is the channel on thei^{th} receive antenna,
$x$is the transmitted symbol and
nis the noise oni^{th} receive antenna.

Expressing it in matrix form, the received signal is y=$h_x +$ n (3-18)

where

y= $[y_1 y_2 \cdots y_N]^T$ 3-20

is the received symbol from all the receive antenna

h=$[h_1 h_2 \cdots h_N]^T$ (3-19)

is the channel on all the receive antenna$X$is the transmitted symbol and

$n = [n_1 n_2 \cdots n_N]^T$ (3-20)

is the noise on all the receive antenna. The equalized symbol is, It is intuitive to note that the term,

$$h^H \text{h}= \sum_{T=1}^{N} |h_i|^{2} \qquad (3\text{-}21)$$

i.e sum of the channel powers across all the receive antennas.

3-7 Linear MMSE estimator

In many cases, it is not possible to determine a closed form expression for the conditional expectation$\boldsymbol{E}\{{}^{\boldsymbol{x}}/_{\boldsymbol{y}}\}$required to obtain the MMSE estimator. Direct numerical evaluation of the conditional expectation is computationally expensive, since they often require multidimensional integration usually done using Monte Carlo methods. In such cases, one possibility is to abandon the full optimality requirements and seek a technique minimizing the MSE within a particular class of estimators, such as the class of linear estimators. Thus we postulate that the conditional expectation of$x$ given $y$is a simple linear function of$\boldsymbol{y}$,$\boldsymbol{E}\{{}^{\boldsymbol{x}}/_{\boldsymbol{y}}\}$=$\boldsymbol{W}_{\boldsymbol{y}} + \boldsymbol{b}$ (3-22)

where the measurement $y$is a random vector is a matrix and$b$is a vector. The linear MMSE estimator is the estimator achieving minimum MSE among all estimators of such form. One advantage of such linear MMSE estimator is that it is not necessary to explicitly calculate the posterior probability density function of x. Such linear estimator only depends on the first two moments of the probability density function. So although it may be convenient to assume that $x$and $y$are jointly Gaussian, it is not necessary to make this assumption, so long as the assumed distribution has well defined first and second moments. The form of the linear estimator does not depend on the type of the assumed underlying distribution.

The expression for optimal $b$and W is given by

$$\boldsymbol{b} = \bar{\boldsymbol{x}} + \boldsymbol{W}\bar{\boldsymbol{y}} \qquad (3\text{-}23)$$

W=$\boldsymbol{C}_{XY} + \boldsymbol{C}_{Y}^{-1}$3-26

Thus the expression for linear MMSE estimator, its mean, and its auto-covariance is given by

$$\boldsymbol{x} = \boldsymbol{W}(\boldsymbol{y} - \overline{\boldsymbol{y}}) + \bar{\boldsymbol{x}} \qquad (3\text{-}24)$$

$\boldsymbol{E}\{\hat{\boldsymbol{x}}\} = \hat{\boldsymbol{x}}$3-28

$$\boldsymbol{C}_{x} = \boldsymbol{C}_{XY}\boldsymbol{C}_{Y}^{-1}\boldsymbol{C}_{XY} \qquad (3\text{-}25)$$

where$\bar{x} = E\{x\}$,$\bar{y} = E\{y\}$ the$\boldsymbol{C}_{XY}$is cross-covariance matrix between$\boldsymbol{x}$and **y**, the $\boldsymbol{C}_{Y}$is auto-covariance matrix of **y**, and the$\boldsymbol{C}_{XY}$is cross-covariance matrix between**y**and $\boldsymbol{x}$. Lastly, the error covariance and minimum mean square error achievable by such estimator is

$$\boldsymbol{C}_{e} = \boldsymbol{C}_{X} - \boldsymbol{C}_{X^{`}} = \boldsymbol{C}_{X} - \boldsymbol{C}_{XY}\boldsymbol{C}_{Y}^{-1}\boldsymbol{C}_{YX}1 \qquad (3\text{-}26)$$

LMMSE=$tr\{C_{e}\}$

For the special case when both x and y are scalars, the above relations simplify to

$$\hat{\boldsymbol{x}} = \frac{\sigma_{XY}}{\sigma_{Y}^{2}}(\boldsymbol{y} - \overline{\boldsymbol{y}}) + \overline{\boldsymbol{x}} \qquad (3\text{-}27)$$

$$\boldsymbol{\sigma}_{e=}^{2}\boldsymbol{\sigma}_{X}^{2} - \frac{\sigma_{XY}^{2}}{\sigma_{Y}^{2}} \qquad (3\text{-}28)$$

3-8 Zero Forcing Equalizer

Zero Forcing Equalizer refers to a form of linear equalization algorithm used in communication systems which applies the inverse of the frequency response of the channel. This form of equalizer was first proposed by Robert Lucky. The Zero-Forcing Equalizer applies the inverse of the channel frequency response to the received signal, to restore the signal after the channel. It has many useful applications. For example, it is studied heavily for IEEE 802.11n (MIMO) where knowing the channel allows recovery of the two or more streams which will be received on top of each other on each antenna. The name Zero Forcing corresponds to bringing down the inter symbol interference (ISI) to zero in a noise free case. This will be useful when ISI is significant compared to noise.

For a channel with frequency response$F(f)$the zero forcing equalizer $C(f)$is constructed by$C(f) = \frac{1}{F(f)}$. Thus the combination of channel and equalizer gives a flat frequency response and linear phase .$F(f)C(f) = 1$

In reality, zero-forcing equalization does not work in most applications, for the following reasons:

1. Even though the channel impulse response has finite length, the impulse response of the equalizer needs to be infinitely long
2. At some frequencies the received signal may be weak. To compensate, the magnitude of the zero-forcing filter ("gain") grows very large. As a consequence, any noise added after the channel gets boosted by a large factor and destroys the overall signal-to-noise ratio. Furthermore, the

channel may have zeroes in its frequency response that cannot be inverted at all. (Gain * 0 still equals 0).

This second item is often the more limiting condition. These problems are addressed in the linear MMSE equalizer by making a small modification to the denominator of : $C(f)$

: $C(f) = {}^{1}/_{F(f)}+\mathrm{k}$ 3-16, where k is related to the channel response and the signal SNR.

CHAPTER FOUR

RESULTS AND DISCUSSION

Chapter four

The results and discussion

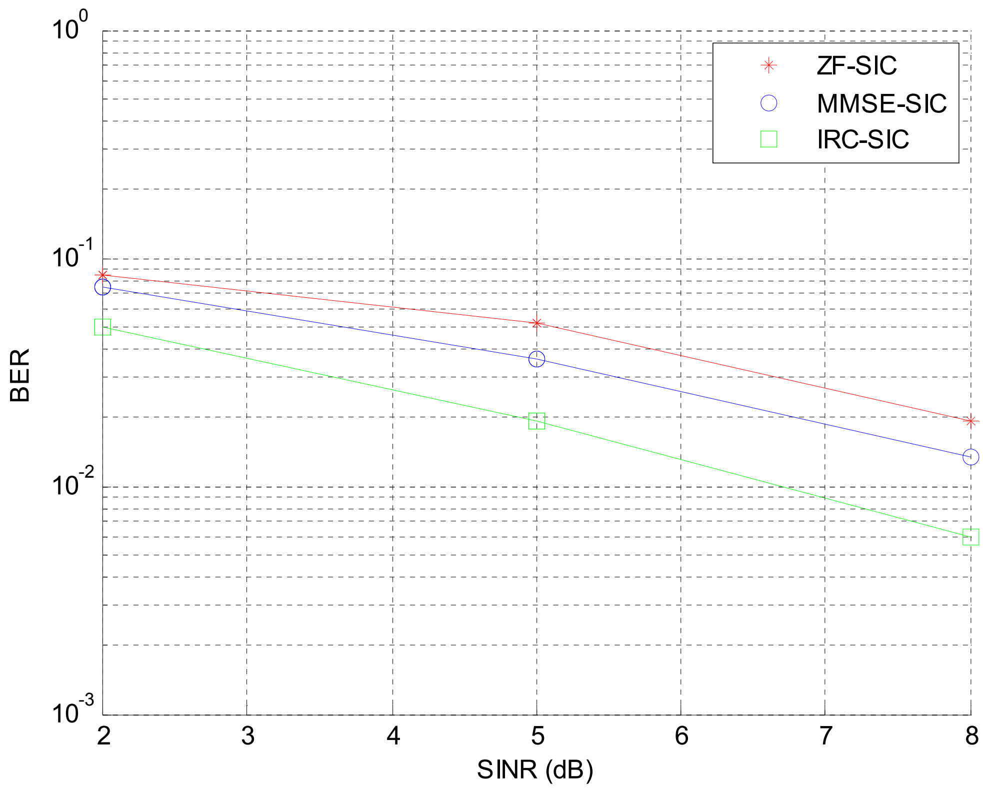
4-1First scenario: In urban area

Multi user Multiple Input Multiple output(Mu-MIMO)

Interference Rejection Combining (IRC)is a linear combining technique that relies on multiple receive antennas and the estimate of the interfering channels to project the received signals on a subspace in which the Minimum Mean Square Error (MMSE) is minimized the disturbance from an interferer by combining the signal received on diverse antennas and suppressing the interfering signal

This method are used in urban area of various users figures (4-1) (4-2) (4-3) shows MIMO Technique with different algorithms zero forcing(zf),minimum mean square error(MMSE)and interference rejection combining (IRC) in figure(4-1) 2×2 means that N=2 number of transmit antenna and M=2 number of received antenna through figure (IRC) algorithm is the best one as compare with zf and MMSE,(IRC) is less bit error rate(BER) so higher throughput can be achieved, throughput increases with decrease of (BER) and this improve channel capacity of system because it reduced interference also (BER) decreased by increasing the values of (SINR), at(8 dB) (BER) is less than at (5dB).

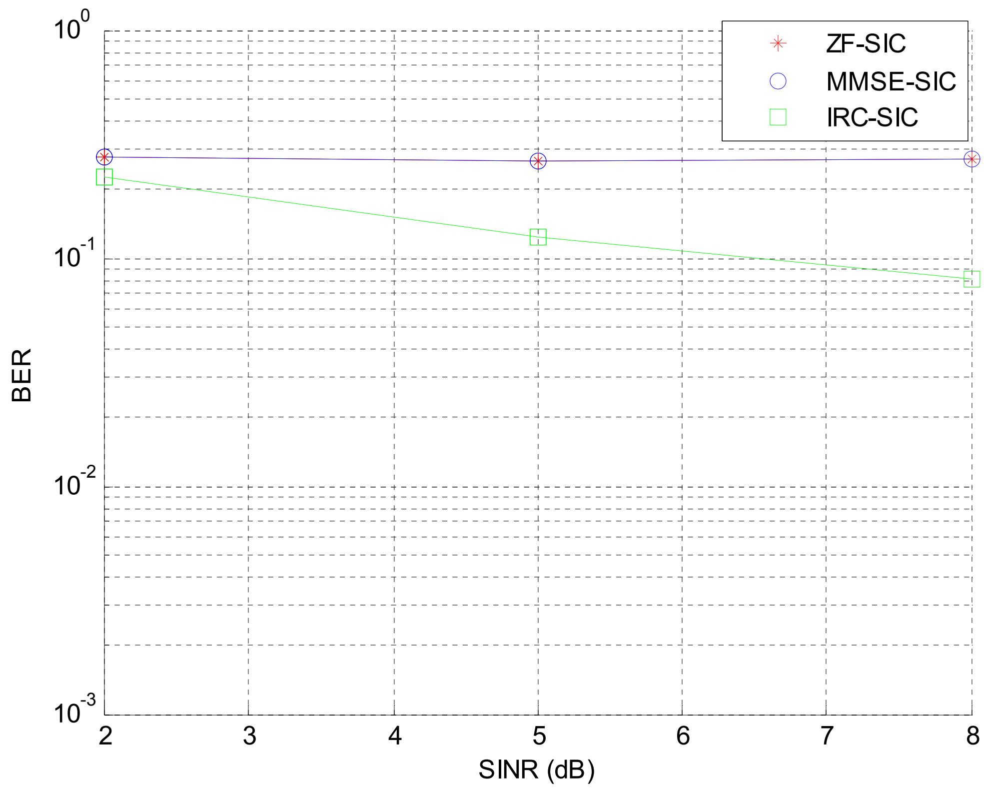
Also from figure (4-1) (MMSE) is better than zf in reducing interference when applying two antenna at the transmitter and two at the receiver



2× 2 Mu- MIMO system urban area

Figure(4-1)

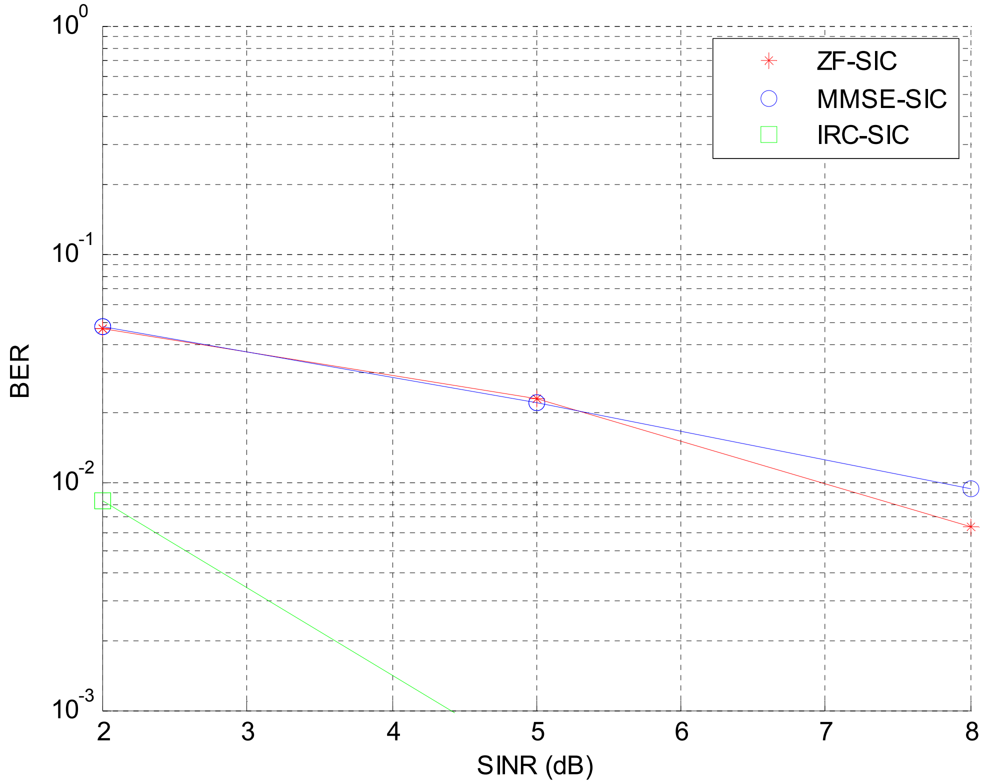
Figure(4-2) shows that zf and MMSE at the same in reducing interference by applying transmit diversity method (BER) is not decreases by increasing (SINR) values ,(IRC) decreases (BER) gradually that means one antenna at the receive side causes interferences



2× 1Mu-MIMO system urban area transmit diversity

Figure(4-2)

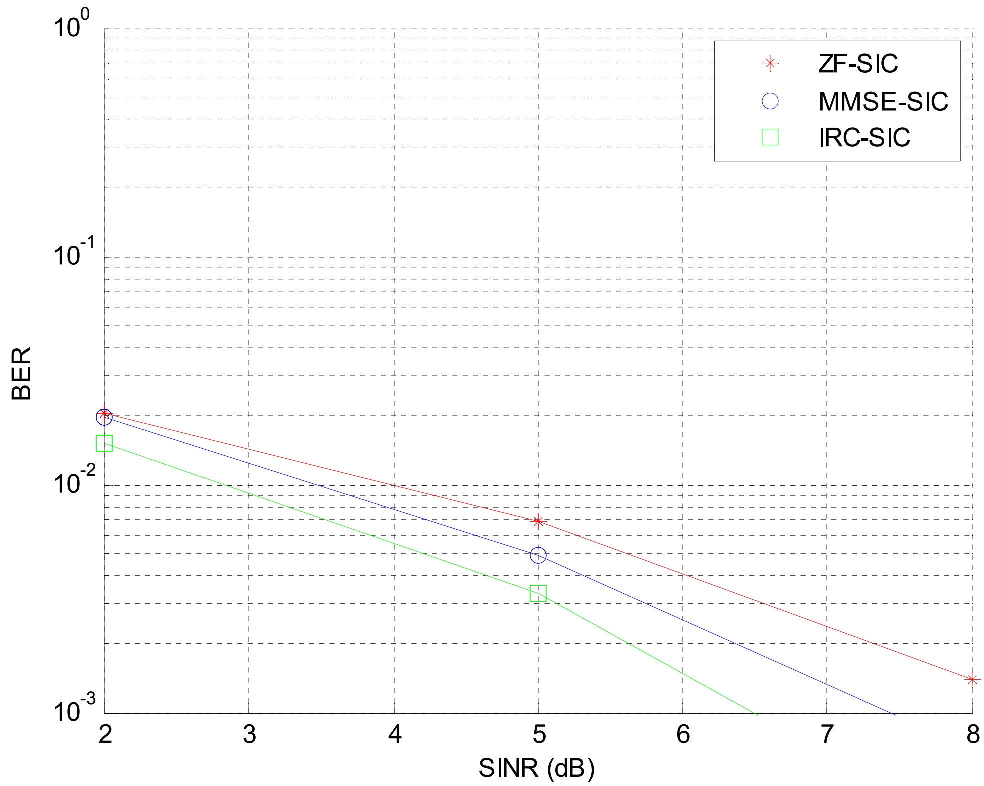
In figure (4-3) interference reduced by reducing (BER) because the use of four antenna at the transmitter and four at the receiver at values SINR equal to or greater than (5dB) (BER) of IRC algorithm is constant and zf is better than (MMSE).



4× 4Mu- MIMO system urban area

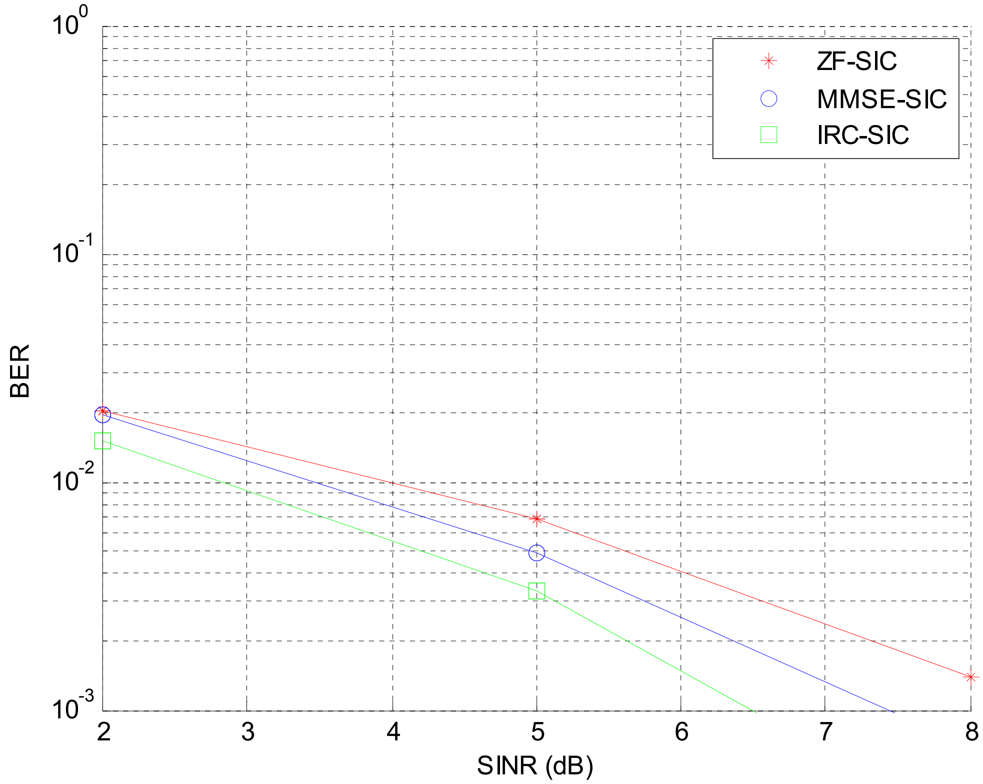
Figure(4-3)

Figures(4-4) and (4-5) shows 2× 3 and (3× 3) respectively the effect of two ways to (BER) and interference see figures



2× 3 Mu MIMO system urban area

figure(4-4)



3× 3 Mu MIMO system urban area

figure(4-5)

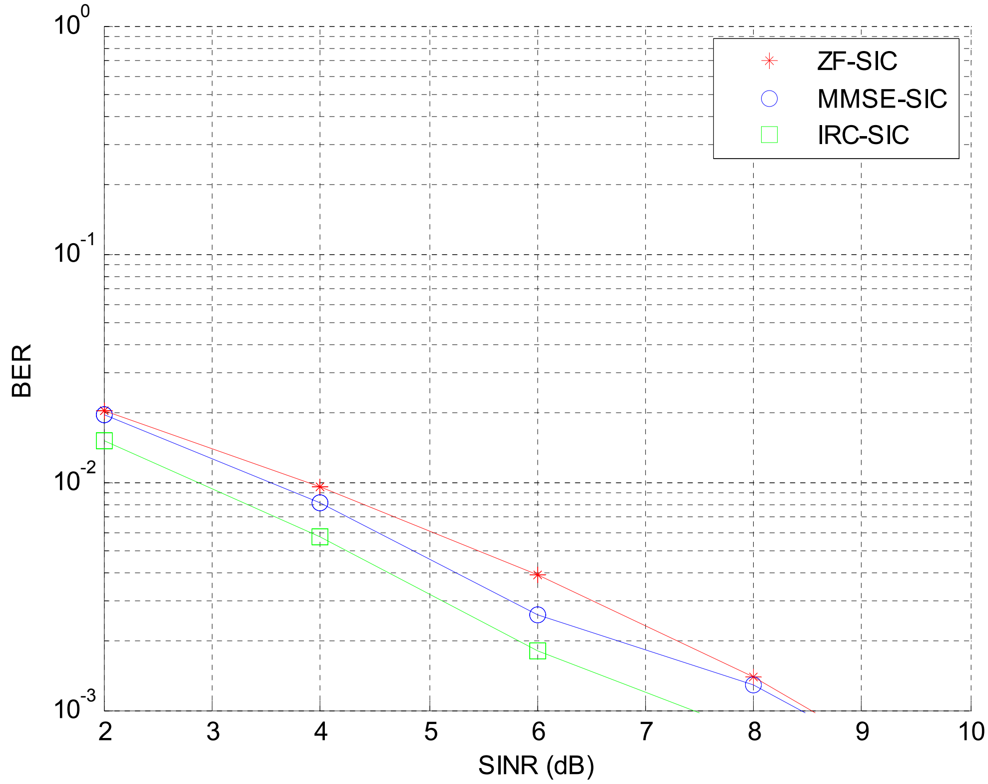
4-2Second scenario: In suburban area

single user Multiple Input Multiple output(SU-MIMO)

Multiple-Input-Multiple-Output (MIMO) systems, which use multiple antennas at the transmitter and receiver ends of a wireless communication system. MIMO systems are increasingly being adopted in communication systems for the potential gains in capacity they realize when using multiple antennas. Multiple antennas use the spatial dimension in addition to the time and frequency ones, without changing the bandwidth requirements of the system.

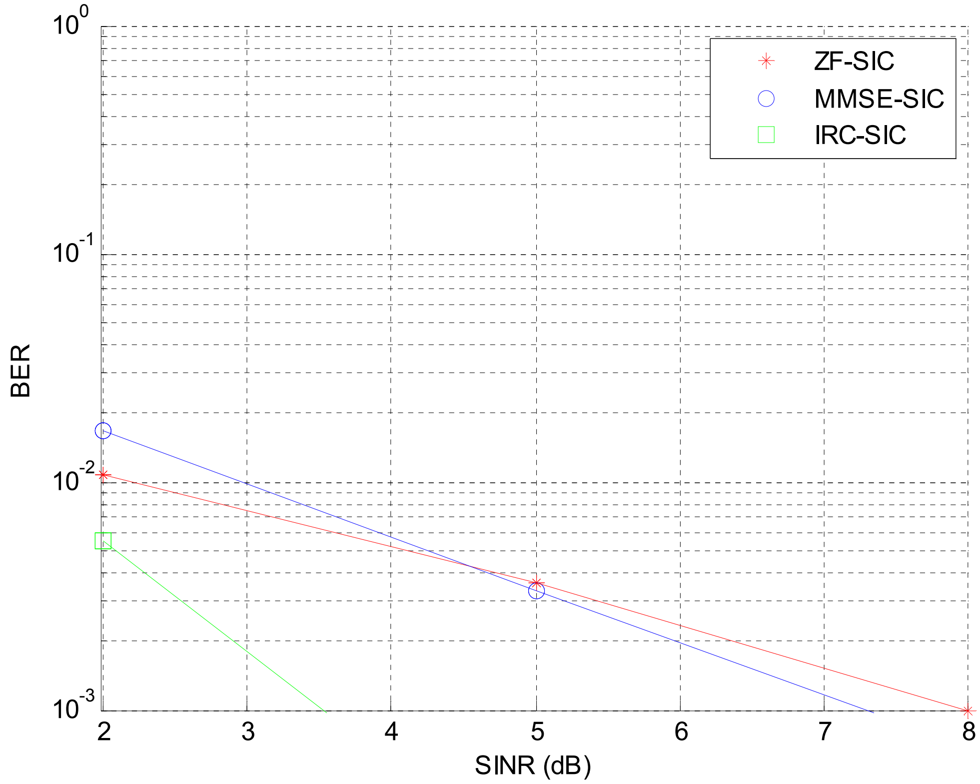
The simulation covers an end-to-end system showing the encoded and/or transmitted signal, channel model, and reception and demodulation of the received signal. It also provides the no-diversity link (single transmit- receive antenna case) and theoretical performance of second-order diversity link for comparison. It is assumed here that the channel is known perfectly at the receiver for all systems. We run the simulation over a range of SINR points to generate BER results that allow us to compare the different systems. figure

(4-6) and(4-7) show that



2x3 SU – MIMO system suburban area

figure(4-6)



3x4 SU-MIMO system suburban area

Figure(4-7)

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5-1 conclusion

In this thesis, have been proposed a method of reduced interference in Long Term evolution Advanced system (LTE-A) by using interference rejection combining technique(IRC) .

In this method has introduced many algorithms to carry out the solution of storm problem applying those method in different scenarios first in urban area and second in suburban area with multiple input multiple output (MIMO).the MATLAB simulation is used as tool of proposed solution.

The proposed technique(IRC) is reduced interference so it decreased (BER) and this increases throughput witch increase system capacity. Also from the results (BER) was decreased by increasing SINR values. By comparing with others algorithms used in simulation (IRC) is decrease (BER) by 62% rate of the other algorithms.

5-2 recommendation

The results of BER improvements due to IRC receivers are shown in Figures . The graphs have BER on the vertical axis, and average received SINR on the horizontal axis, and show the results for mobile terminals the applications introduced are improvement BER and increased capacity of system It has recommending future research to do:

- In this thesis the interference is reduced by proposed technique
- Find new technique to improve channel capacity of system

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Appendices

Appendix A first scenario

```
N = 4;              M = 4;

SINRVec = 2:3:8;

modOrd = 2;

numSym = N;

hStr = RandStream('mt19937ar');

bits = de2bi(0:2^(modOrd*N)-1, 'left-msb')';

b = zeros(N, modOrd, length(bits));

for i = 1:length(bits)

   b(:, :, i) = reshape(bits(:,i), modOrd, N)';

end

dist = zeros(length(bits), 1);

[BER_ZF, BER_MMSE, BER_IRC] = deal(zeros(1, length(SINRVec)));

hMod = modem.pskmod('M', 2^modOrd, 'SymbolOrder', 'gray', 'InputType', 'bit');

hDemod = modem.pskdemod(hMod);

h = gcf; grid on; hold on;

set(gca,'yscale','log','xlim',[SINRVec(1)-0.01, SINRVec(end)],'ylim',[1e-3 1]);

xlabel('SINR (dB)'); ylabel('BER'); set(h,'NumberTitle','off');

set(h, 'renderer', 'zbuffer'); set(h,'Name','Spatial Multiplexing');

for idx = 1:length(SINRVec)

nErrs_zf = 0; nErrs_mmse = 0; nErrs_IRC= 0;

nBits = 0;

   while ( ((nErrs_zf< 100) || (nErrs_mmse< 100) || (nErrs_IRC< 100)) ...

&& (nBits< 1e4))
```

```
    % Create array of bits to modulate
msg = randi(hStr, [0 1], modOrd, numSym);
    source = modulate(hMod, msg);
Tx = reshape(source, N, numel(source)/N); clear source;
RayleighMat = (randn(hStr, M, N) +  1i*randn(hStr, M, N))/sqrt(2);
snr = SINRVec(idx) + 10*log10(modOrd);
    r = awgn(RayleighMat*Tx, snr, 0, hStr); clear Tx;
r_store = r;
    H = RayleighMat;
E_zf = zeros(modOrd, numSym); k = zeros(N, 1);
    G = pinv(H);
    [val, k0] = min(sum(abs(G).^2,2));
    for n = 1:N
            k(n) = k0;
      w = G(k(n),:);
      y = w * r;
E_zf(:, k(n):N:end) = reshape(demodulate(hDemod, y), modOrd, numSym/N);
      z = modulate(hMod, demodulate(hDemod, y));
      r = r - H(:, k(n))*z;
      H(:, k(n)) = zeros(M, 1);
      G = pinv(H);
      for aa = 1:n
        G(k(aa), :) = inf;
      end
      [val, k0] = min(sum(abs(G).^2,2));
```

```
        end
        H = RayleighMat; r = r_store;
E_mmse = zeros(modOrd, numSym); k = zeros(N, 1);
        G = (H'*H + N/(10^(0.1*snr))*eye(N)) \ H';
        [val, k0] = min(sum(abs(G).^2,2));
        for n = 1:N
            k(n) = k0;
            w = G(k(n),:);
                y = w * r;
E_mmse(:, k(n):N:end) = reshape(demodulate(hDemod, y), modOrd, numSym/N);
            z = modulate(hMod, demodulate(hDemod, y));
            r = r - H(:, k(n))*z;
            H(:, k(n)) = zeros(M, 1);
            G = (H'*H + N/(10^(0.1*snr))*eye(N)) \ H';
            for aa = 1:n
                G(k(aa), :) = inf;
            end
            [val, k0] = min(sum(abs(G).^2,2));
        end
        H = RayleighMat; r = r_store;
        for i = 1:2^(modOrd*N)
            sig = modulate(hMod, b(:, :, i)').';
dist(i) = sum(abs(r - H*sig).^2);
        end
            [notUsed, val] = min(dist);
```

```
        E_IRC = b(:,:,val)'; % detected bits
nErrs_zf = nErrs_zf + biterr(msg, E_zf);
nErrs_mmse = nErrs_mmse + biterr(msg, E_mmse);
nErrs_IRC = nErrs_IRC + biterr(msg, E_IRC);
nBits = nBits + length(msg(:));
    end
    BER_ZF(idx) = nErrs_zf./nBits;
    BER_MMSE(idx) = nErrs_mmse./nBits;
    BER_IRC(idx) = nErrs_IRC./nBits;
semilogy(SINRVec(1:idx), BER_ZF(1:idx), 'r*', ...
SINRVec(1:idx), BER_MMSE(1:idx), 'bo', ...
SINRVec(1:idx), BER_IRC(1:idx), 'gs');
    legend('ZF-SIC', 'MMSE-SIC', 'IRC-SIC');
drawnow;
end
semilogy(SINRVec, BER_ZF, 'r-', SINRVec, BER_MMSE, 'b-', ...
SINRVec, BER_IRC, 'g-');
hold off;
```

Appendix B second scenario

```
N = 3;               M = 4;
SINRVec = 2:3:8;
modOrd = 2;
numSym = N;
hStr = RandStream('mt19937ar');
bits = de2bi(0:2^(modOrd*N)-1, 'left-msb')';
b = zeros(N, modOrd, length(bits));
for i = 1:length(bits)
   b(:, :, i) = reshape(bits(:,i), modOrd, N)';
end
dist = zeros(length(bits), 1);
[BER_ZF, BER_MMSE, BER_IRC] = deal(zeros(1, length(SINRVec)));
hMod = modem.pskmod('M', 2^modOrd, 'SymbolOrder', 'gray', 'InputType', 'bit');
hDemod = modem.pskdemod(hMod);
h = gcf; grid on; hold on;
set(gca,'yscale','log','xlim',[SINRVec(1)-0.001, SINRVec(end)],'ylim',[1e-3 1]);
xlabel('SINR (dB)'); ylabel('BER'); set(h,'NumberTitle','off');
set(h, 'renderer', 'zbuffer'); set(h,'Name','Spatial Multiplexing');
for idx = 1:length(SINRVec)
   nErrs_zf = 0; nErrs_mmse = 0; nErrs_IRC= 0;
   nBits = 0;
   while ( ((nErrs_zf < 100) || (nErrs_mmse < 100) || (nErrs_IRC < 100)) ...
         && (nBits < 1e4))
     % Create array of bits to modulate
```

```
msg = randi(hStr, [0 1], modOrd, numSym);

source = modulate(hMod, msg);

Tx = reshape(source, N, numel(source)/N); clear source;

RayleighMat = (randn(hStr, M, N) +  1i*randn(hStr, M, N))/sqrt(2);

snr = SINRVec(idx) + 10*log10(modOrd);

r = awgn(RayleighMat*Tx, snr, 0, hStr); clear Tx;

r_store = r;

H = RayleighMat;

E_zf = zeros(modOrd, numSym); k = zeros(N, 1);

G = pinv(H);

[val, k0] = min(sum(abs(G).^2,2));

for n = 1:N

        k(n) = k0;

  w = G(k(n),:);

  y = w * r;

  E_zf(:, k(n):N:end) = reshape(demodulate(hDemod, y), modOrd, numSym/N);

  z = modulate(hMod, demodulate(hDemod, y));

  r = r - H(:, k(n))*z;

  H(:, k(n)) = zeros(M, 1);

  G = pinv(H);

  for aa = 1:n

    G(k(aa), :) = inf;

  end

  [val, k0] = min(sum(abs(G).^2,2));

end
```

```
H = RayleighMat; r = r_store;

E_mmse = zeros(modOrd, numSym); k = zeros(N, 1);

G = (H'*H + N/(10^(0.1*snr))*eye(N)) \ H';

[val, k0] = min(sum(abs(G).^2,2));

for n = 1:N

  k(n) = k0;

  w = G(k(n),:);

        y = w * r;

  E_mmse(:, k(n):N:end) = reshape(demodulate(hDemod, y), modOrd, numSym/N);

  z = modulate(hMod, demodulate(hDemod, y));

  r = r - H(:, k(n))*z;

  H(:, k(n)) = zeros(M, 1);

  G = (H'*H + N/(10^(0.1*snr))*eye(N)) \ H';

  for aa = 1:n

    G(k(aa), :) = inf;

  end

  [val, k0] = min(sum(abs(G).^2,2));

end

H = RayleighMat; r = r_store;

for i = 1:2^(modOrd*N)

  sig = modulate(hMod, b(:, :, i)').';

  dist(i) = sum(abs(r - H*sig).^2);

end

    [notUsed, val] = min(dist);

E_IRC = b(:,:,val)'; % detected bits
```

```
            nErrs_zf = nErrs_zf + biterr(msg, E_zf);
        nErrs_mmse = nErrs_mmse + biterr(msg, E_mmse);
        nErrs_IRC = nErrs_IRC + biterr(msg, E_IRC);
        nBits = nBits + length(msg(:));
    end
    BER_ZF(idx) = nErrs_zf./nBits;
    BER_MMSE(idx) = nErrs_mmse./nBits;
    BER_IRC(idx) = nErrs_IRC./nBits;
    semilogy(SINRVec(1:idx), BER_ZF(1:idx), 'r*', ...
          SINRVec(1:idx), BER_MMSE(1:idx), 'bo', ...
          SINRVec(1:idx), BER_IRC(1:idx), 'gs');
    legend('ZF-SIC', 'MMSE-SIC', 'IRC-SIC');
    drawnow;
end
semilogy(SINRVec, BER_ZF, 'r-', SINRVec, BER_MMSE, 'b-', ...
SINRVec, BER_IRC, 'g-');
hold off;
```