BEHAVIORAL MODEL TO STUDY IMPACT OF POWER AMPLIFIER NON LINEARITY ON OPTIMAL RESOURCE ALLOCATION

By

Usman Mahmood Malik

Submitted to the Faculty of Department of Information Security,
Military College of Signals, National University of Sciences and Technology, Rawalpindi,
in partial fulfillment of the requirements for the degree of MS in System Engineering

January 2016

SUPERVISOR CERTIFICATE

It is certified that the Final Copy of Thesis has been evaluated by me, found as per specified format and error free.

Dated: ________________

____
(Col Dr. Imran Rashid)

ABSTRACT

Multiple Input Multiple Output (MIMO) offers significant increase in data throughput and link range without additional bandwidth or increased transmit power. It does so by deploying multiple antennas at both transmitter and receiver and by dividing the landscape into cells and cell sectors. Performance of MIMO system depends largely on resource allocation that is, how the time, power, frequency, and spatial resources are divided among users while balancing the fundamental tradeoff between maximizing aggregate system throughput and maintaining user fairness [1].

A variety of non-idealities effect the performance of MIMO system. Transceiver impairments have a minor impact on point-to-point system but this effect is severs in MIMO system because of large number of transmit and receive antennas and cannot be ignored. Transceiver impairments exist because of nonlinear power amplifiers, phase noise, and IQ-imbalance. This study has focused on non-linear power amplifiers as main source of transceiver impairments to develop a behavioral model to study impact of nonlinear power amplifiers on optimal resource allocation.

DEDICATION

In the name of ALLAH, the most merciful, the most beneficent.

Dedicated to ALLAH and his last Prophet Muhammad (S.A.W.).

ACKNOWLEDGEMENTS

With respect, I would like to thank and extend maximum gratitude to my supervisor Col Dr. Imran Rashid for all the guidance and help that he provided me in timely completion of thesis work. I would also like to thank my committee members, Lt Col Mohammad Haroon Siddiqui and Maj Dr. Muhammad Faisal Amjad for their help and support.

Special thanks to Maj Jamal Zafar, Maj Waqar-ul-Hassan and Maj Ubaid-ur-Rehman for their continuous support and encouragement throughout my thesis work.

I would also like to thank all colleagues of MSSE-1 who always offered helping hand whenever I needed them.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

Base Station	BS
Branch-Reduce and Bound Algorithm	BRB Algorithm
Error Vector Magnitude	EVM
High Amplitude Power Amplifier	HAPA
Multi-objective Optimization Problem	MOP
Multiple Input Multiple Output	MIMO
Virtual MIMO	VMIMO
Orthogonal Pairing Scheduling	OPS
Orthogonal Frequency Division Multiplexing	OFDM
Poly back Algorithm	PA Algorithm
Proportional Fairness Scheduling	PFS
Quality of Service	QoS
Radio Frequency	RF
Random Pairing Scheduling	RPS
Resource Block	RB
Round Robin Scheduling	RRS
User Equipment	UE

Chapter 1

INTRODUCTION

Wireless communication has seen an exceptional growth for the last two decades and cellular wireless communication augmented with internet access is by any measure, the fastest growing part of the communications industry, today. Wireless communication effects all aspects of human life and wireless devices have taken center stage in our daily lives. Smartphones, tablets, laptops and cameras connected online via wireless communication have changed our perception about communication. Users demand high speed wireless connectivity on the move for voice, video and data applications. WhatsApp, YouTube and other social networking sites have become most popular now a days. People want to convert their houses to smart homes by connecting every device of the house like television, air conditioners, security systems and cameras etc. to a single device and all this require wireless connectivity.

These changing user trends and extra demand of resources round the clock have forced service providers to step up and come up with new techniques and methods to manage the meager wireless resources in more efficient manner and make better tradeoffs between user fairness and system aggregate throughput. While at the same time they have to find technical solutions to use cheap, light weight and simple user equipment (UE) by overcoming the problems associated with limitations of radio frequency (RF) components and power amplifiers.

This chapter will present a brief overview and basic necessary concepts of different aspects of the presented thesis.

1.1. Introduction to Multiple Input Multiple Output (MIMO)

Ever increasing requirements of data rates has led us to the systems using Multiple Antennas at Transmitter and Receiver, known generally as Multiple Input Multiple Output (MIMO). By deploying multiple antennas at transmitter and receiver, MIMO offers significant increase in data throughput and link range without additional bandwidth or increased transmit power. This is achieved by dividing the landscape into cells and cell sectors. These multiple antennas provide an extra spatial dimension to be exploited along with conventionally used time and frequency dimension.

MIMO provides advantage of Diversity gain and has disadvantage of high cost of deploying multiple antennas, more space and circuit power requirements and added complexity for signal processing.

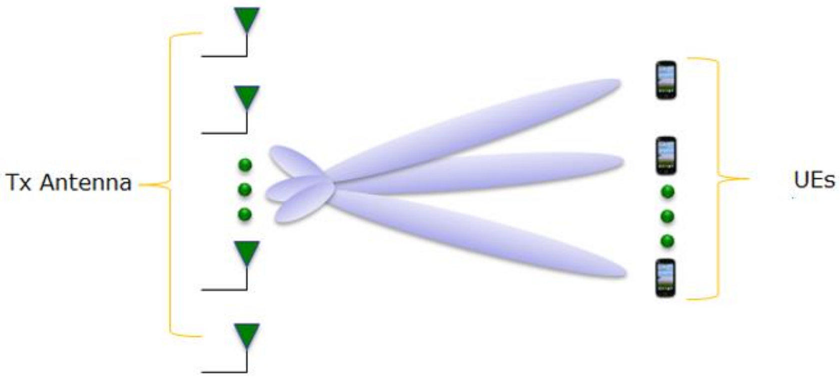

Figure 1.1. MIMO Channel [17]

1.2. Introduction of Virtual MIMO (VMIMO)

MIMO uses multiple antennas at both transmitter and receiver side. Performance of MIMO is greatly dependent on the independence of spatial paths between antenna pairs which imply that antenna elements on both transmitter and receiver to be significantly spaced so that the correlation between their signals is reduced. But employing multiple antennas at receiver is not always practical as it increases the size and weight of the device.

This problem can cause adverse effects on practicality of MIMO in mobile communication systems.

The solution for this problem is VMIMO which couples two User Equipment (UE) nodes with single antennas to virtually appear as multiple antennas on same receiver. This allows UE to communicate simultaneously with the Base Station (BS) using the same Resource Block (RB) independently. Transmitter sends signals to multiple users together and each user separates its intended signal by using certain algorithms while different users can send almost completely independent signals as uplink to the BS.

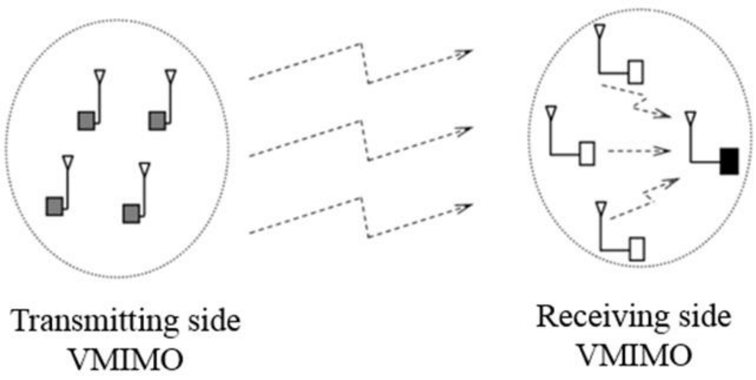

Figure 1.2. VMIMO [16}

1.2.1. Multi-User Diversity

BS handles cooperation between multiple users through scheduling which provides an extra dimension of multi-user diversity or selection diversity to the system. Multi-user diversity is based on the fact that BS can schedule the best channel user to further improve throughput performance of the system. This diversity gain is exploited by tracking the channel of each user independently and scheduling users when their channels are in better condition. VMIMO therefore exploits best channel conditions for the users and allows reduced complexity of user equipment by eliminating the requirement of installing multiple antennas at the receiver side. However, this multi-user diversity gain comes at cost of increase in complexity of scheduling algorithm.

1.3. Introduction to Resource Allocation

The changing user trends and high bandwidth requirements have made resource allocation a crucial challenge in modern wireless communication systems. Cellular operators have to manage limited system resources such as power, bandwidth and transmit time in most optimal and at the same time they have to draw a balance between system throughput and user fairness while allocating fluctuating resources to users. This tradeoff is directly linked with service provider’s revenue and user’s satisfaction. If cellular operator tries to maximize revenue then he will focus on aggregate system throughput which may starve users with poor channels. On the other hand if system is designed for absolute fairness, it may lead to low bandwidth efficiency. Resource allocation therefore, requires an efficient tradeoff between efficiency and fairness, while satisfying the Quality of Service (QoS) requirements of real-time traffic.

1.4. Introduction to Transceiver Impairments and Non-Linear Power Amplifiers

Transceiver impairments effect the performance of wireless communication systems and different compensation techniques can be incorporated to mitigate the effects of these impairments. Transceiver impairments exist due to electronic components present in the transceivers and main contributors to transceiver impairments are power amplifiers, phase noise and IQ imbalance. In our thesis, we have focused on power amplifiers as main source of transceiver impairments and we have tried to establish the effects of transceiver impairments on optimal resource allocation.

Power amplifiers are an important component in modern communications system that amplify the transmit signal to a level which is required to overcome the losses that may be introduced in the transmitted signal between transmitter and the receiver. Power amplifiers have non-linear behavior which causes signal distortions at higher outputs.

These signal distortion are tightly controlled by the communications standard being used, and must be reduced if possible. This warrants a system level tradeoff between the power efficiency and the resulting distortion. For most commercial systems, this tradeoff is constrained by interference with adjacent users, thus, amplifier signal levels are reduced or "backed off" from the peak efficiency operating point.

1.5. Problem Statement

Effect of transceiver impairments on point-to-point systems is minimal because of limited number of antennas used and can be ignored while doing resource allocation in such systems. On the other hand, MIMO systems use large number of transmit and receive antennas that has significant cumulative transceiver impairment effect and cause severe impact on MIMO systems. Because of this significance of effect on MIMO systems, effect of transceiver impairments has to be incorporated while doing resource allocation in MIMO systems [1].

Most work on Massive MIMO incorporates a simplified model in which it is assumed that the transmitted signal is independent of the transceiver impairments but to obtain realistic results it is necessary to develop an accurate model of transceiver impairments to analyze the effects of transceiver impairments on Pareto boundary and on optimal resource allocation.

1.6. Thesis Goals

The presented thesis builds up the concept of resource allocation in wireless communication systems and elaborates different tradeoffs that effect optimal resource allocation. Concept of transceiver impairments in explained in length in this thesis. Non-linear power amplifiers are considered as main source of transceiver impairments in this study. RAPP model which is behavioral model of non-linear power amplifiers is used in this thesis to find realistic effects of transceiver impairments on different input signals which is then used to perform simulations on MATLAB to find effects of transceiver impairments on optimal resource allocation.

1.7. <u>Thesis Layout</u>

The presented thesis comprise of seven chapters. Chapter 2 elaborates resource allocation along with tradeoffs necessary to draw a balance between system aggregate throughput and user fairness. Chapter 3 will deal with formulation of Multi-objective Optimization Problem (MOP) and its effects on resource allocation. Chapter 4 will build basic concepts of non-linear behavior of power amplifiers and develop model to find effects of non-linear power amplifier on communication and resource allocation. Chapter 5 will give introduction to work already done on the subject. Proposed solution and algorithm is explained in chapter 6 followed by recommendation for future work in chapter 7.

Chapter 2

RESOURCE ALLOCATION

Spectrum is the most important resource in communication system which imposes a high cost on the high data rate transmission and can be effectively utilized by exploiting it in time and frequency domain. MIMO system employs multiple antennas at both transmitter and receiver which allows it to exploit spatial dimension along with conventionally used time and frequency domain. Thus, resources available in MIMO system can be considered as three dimensional consisting of time slots, subcarriers and spatial layers in time, frequency and space domain respectively.

Power is another resource available with the cellular operator which is always constrained while allocating power resources to the users in practical transmission systems.

The distribution of these resources to the users' i.e. how the time, frequency, and spatial resources are divided among users under power constraints is called "RESOURCE ALLOCATION".

2.1. Power Constraints

In real-world wireless communication systems, there are several important limitations on the transmitter and its transmitted signal that might vary according to the application. A combination of some or all of these constraints might be necessary for a practical system. These constraints may be based on:-

2.1.1. Physical Limitations

This constraint results from the practical consideration of radio design, which is captured by the per-antenna power constraint. It aims to prevent the amplifier at each transmit antenna from distortions or non-linearity by bounding the dynamic range of the power at each antenna.

2.1.2. Regulatory Constraints

These constraints results from rules and regulation that prevent the transmitter from having an arbitrary power level due to environmental safety as well as interference prevention with other cellular operators in the area. Regulatory constraints depend upon type of application, frequency, height of the antenna, population of that area per square mile and so on.

2.1.3. Interference Constraints

In MIMO system, QoS of any user can be improved by increasing the transmit power in the direction of user. In MIMO, each transmitted data signal will in general effect all users and by increasing the power to improve QoS of one user may cause interference to other users. Interference constraint is therefore imposed to control interference caused to other users in the cell.

2.1.4. Economic Decisions

The transmit power has certain cost attached to it and cellular operators manage transmit power to manage the long-term cost and revenue of running a base station.

2.2. User Fairness and System Throughput

Cellular operators want to maintain a high number of subscribers, decrease churn and attract new subscribers for which they have to provide and maintain good QoS and user fairness by which to ensure user satisfaction and user loyalty to the network. Fairness in wireless networking domain is generally attributed to resource sharing or allocation and implies that all users must get equal amount of resources all the time. The consequence of an unfair resource allocation among different individuals may lead to resource starvation, resource wastage or redundant allocation.

User fairness depends upon QoS and channel conditions and cellular operators have to perform a tradeoff between maximizing aggregate system throughput and maintaining user fairness. Two kinds of systems may be developed on the basis of user fairness and system throughput [6]:-

- If system is designed for maximum fairness then system throughput will suffer as too many resources will be wasted on users with poor channels. This will result in loss of revenue for the cellular operators.

- If system is designed for maximizing throughput then resources will be allocated to only those users that have good channels. This will result in starvation of users with poor channels.

Balance must be found between maximizing system throughput and ensuring that no user is starved.

2.3. Scheduling Algorithms for User Fairness

Pairing schedules traditionally used in VMIMO systems are RPS, RRS, OPS and PFS. All these algorithms are elaborated here. A good explanation of the concepts of these algorithms is presented in [12] and [13].

2.3.1. Random Pairing Scheduling (RPS)

As the name implies, RPS scheduling randomly selects any two users from total active users and pair them together without any consideration to their channel condition or fairness. Since this selection of users is not based on channel condition or fairness, it cannot promise achievement of either of throughput or fairness and all other scheduling algorithms provide better performance than RPS [14].

RPS is good for high mobility users and is more flexible than most other scheduling algorithms and does not require availability of full band CSI at the BS.

2.3.2. Round Robin Scheduling (RRS)

RRS algorithm selects users in a Round Robin fashion to provide resources. RRS also ignores channel conditions as RPS and each user is served in his turn which causes constant delay between two consecutive transmissions of any user. Since equal opportunity is provided to all users in RRS, it is considered as fairness extreme algorithm. This fairness comes at cost of throughput. Thus it supports all the advantages of RPS with absolute fairness [12].

2.3.3. Orthogonal Pairing Scheduling (OPS)

In VMIMO, throughput gain is directly proportional to the orthogonality between their channels to the BTS. There will be lesser interference between receivers if there is greater orthogonality between the columns of the VMIMO channel matrix. It selects users on the bases of RRS while the pairing of the user is selected based on orthogonality maximization.

2.3.4. Proportional Fairness Scheduling (PFS)

For maximizing system throughput, system favors users with good channel conditions which may starve users with channel poor condition. PFS tries to bring a balance between user fairness and system throughput by prioritizing the users on the bases of current channel condition along with the average opportunity provided to the user. It considers long term individual user fairness while maximizing average cell throughput.

2.3.5. Max-Min Fairness

It is a resource allocation scheme that tries to provide each user with a minimum equal throughput and maximize the minimum one. In max-min fairness, an individual's resource cannot be increased without decreasing another individual's resource allocation which is already less than the previous one. The purpose of maximizing minimal-value optimizations is to try to improve the resources of the individuals who get the least amount of resource. Max-min rate allocation always results in strictly equal rates and achieves maximum fairness. However, it may lead to severe inefficiency and decreases the aggregate throughput of the network.

2.4. Summary

How the time, frequency, and spatial resources are divided among users under power constraints is called "Resource Allocation". This chapter discussed resource allocation and reasons of power constraints. Special emphasis was given on the tradeoff between user fairness and system aggregate throughput and why is it importance to draw a balance between two. Some pairing schedules schemes were also outlined in the chapter which provide various options as to how to balance between fairness and system aggregate throughput.

Chapter 3

RESOURCE ALLOCATION PROBLEM

This chapter will deal with formulation of resource allocation problem and will define how multi-user objectives effect each other and how to formulate and solve multi-objective resource allocation problem.

3.1. Channel Gain Region

It was discussed in previous chapter that VMIMO groups multiple users to act virtually as a single receiver with multiple antennas. This grouping between adjacent users means that each data signal transmitted for any user will in general effect all other users and warrants careful handling of transmitted signal to avoid inter-user interference.

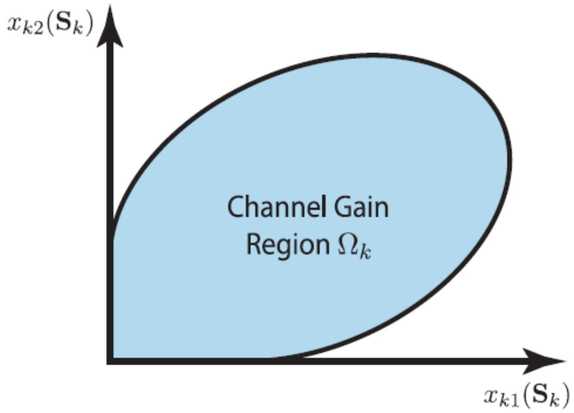

Figure 3.1. Channel Gain Region [1]

Each user wants to obtain maximum of the available resources and since system has same pool of resources to serve all users, it creates conflict between users over the resources. Resources of one user can be increased only at the cost of reducing resources for other user and these conflicting interests of users are characterized by channel gain region that highlight the inherent conflict and tradeoffs that appear when we want to maximize the performance of multiple users simultaneously.

3.2. Multi-objective Optimization Problem (MOP)

We have seen that each user has its own objective to be optimized i.e. to draw maximum possible resources. When we are transmitting to multiple users simultaneously, the number of conflicting objectives that needs to be optimized equals to the number of users. These conflicting individual users give rise to MOP to search for a transmit strategy that satisfies the power constrains and maximizes the performance of all users. MOP can be classified as linear, convex, quasi convex and monotonic problems as under:-

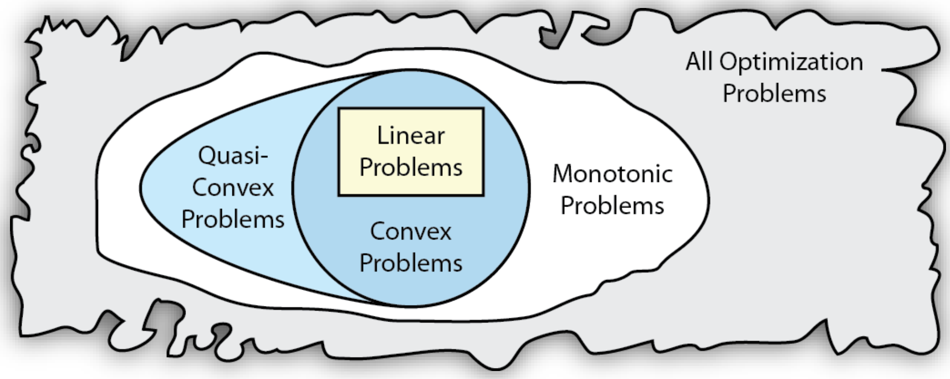

Figure 3.2. Types of MOP [1]

Many solutions are possible to MOP as many tradeoffs are possible between maximizing performance for individual users and maximizing the aggregate utility of the whole system. This tradeoff is illustrated by the Performance region.

3.3. Performance Region

System works out transmit strategy on the basis of channel gain region to maximize the performance of all users. This transmit strategy tries to balances the conflicting interests of multiple users while also satisfying the multiple system level constraints. Generally there is not a single solution and multiple transmit strategies can be worked out that simultaneously maximize the performance of all users. The subset of all such feasible operating points is called performance region. Performance regions is also known by other names as Rate Region, Capacity Region or MSE Region, etc.

3.3.1. Pareto Boundary

Boundary of performance region is called Pareto boundary which is a subset of the outer boundary and represents all efficient resource allocations solutions. Search for optimal resource allocation is basically the search for Pareto boundary.

3.3.1.1. Utopia Point

Utopia point represents unattainable upper bound of performance and lies outside the performance region. It is impossible to achieve utopia point.

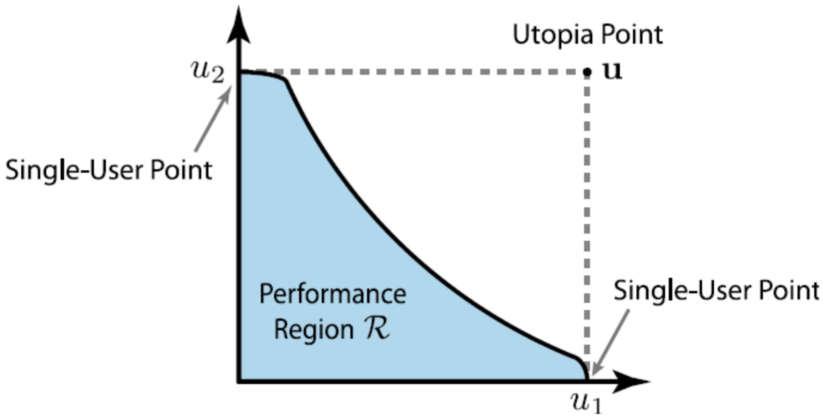

Figure 3.3. Utopia Point [1]

3.3.1.2. Pareto Optimal Point

Pareto optimal are points on Pareto boundary where performance of any user cannot be improved without degrading for others.

3.3.1.3. Weak and Strong Pareto Boundary

Pareto boundary is classified as weak or strong. At weak Pareto boundary we might be able to improve the performance of some of the users but not simultaneously for all the users. Whereas, at strong Pareto boundary, performance cannot be unilaterally improved for any user.

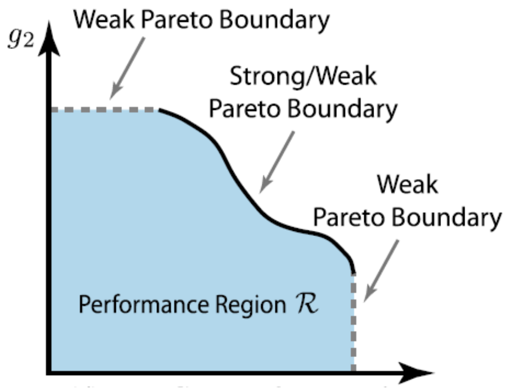

Figure 3.4. Strong and Weak Pareto Boundary of Performance Region [1]

3.3.2. **Which Pareto Optimal Point to Select?**

Performance region reflects tradeoffs between maximizing aggregate system performance and achieving user fairness. Various points can be selected from Pareto boundary which include:-

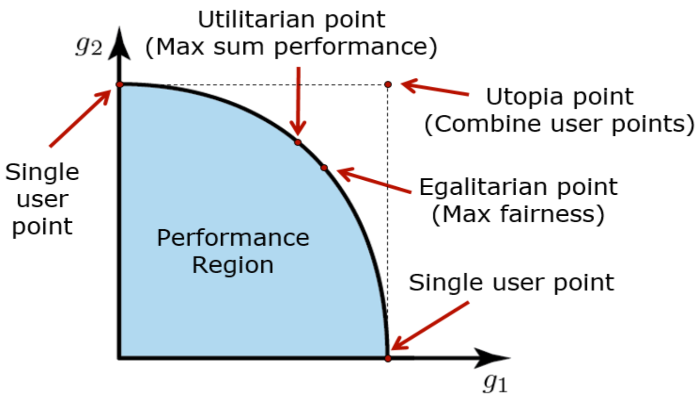

Figure 3.5. Various Points on Pareto Boundary [1]

- **Single User Point**. This point maximizes the performance of single user.
- **Utopia Point**. This point is unable to be achieved.
- **Utilitarian Point**. This point maximizes aggregate system performance.

- **Egalitarian Point**. This point provides max-min user fairness.

3.3.3. Shapes of Pareto Boundary

Shape of Pareto boundary can be convex or concave. This shape depends upon user coupling. Shape will be convex when users are strongly coupled and concave when users are strongly coupled. Practical performance regions are hybrids of these extremes. Convex problems are easy to solve than concave problems. Some possible shapes of Pareto boundary are:-

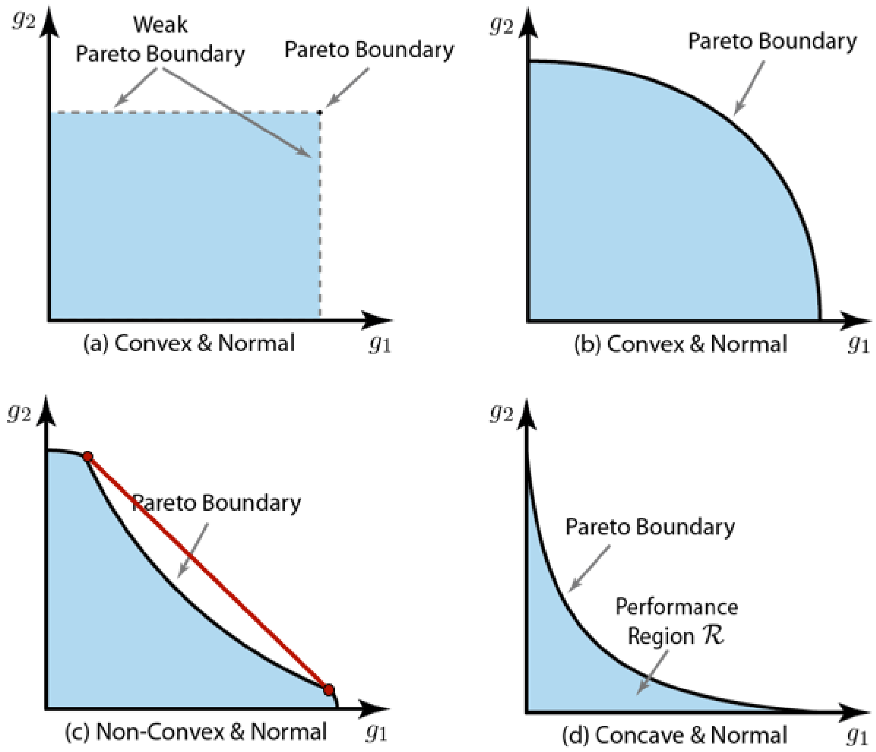

Figure 3.6. Shapes of Pareto Boundary [1]

3.4. Algorithms to Find Pareto Boundary

3.4.1. Bisection Method

The bisection method is an efficient line search procedure. A start interval is set by selecting a point outside the performance region. Utopia point may selected as that point. The line is then halved in each iteration and checked for feasibility at the midpoint of the current range and removing the portion of line that is found unfeasible. By repeating the procedure a feasible solution is found [1].

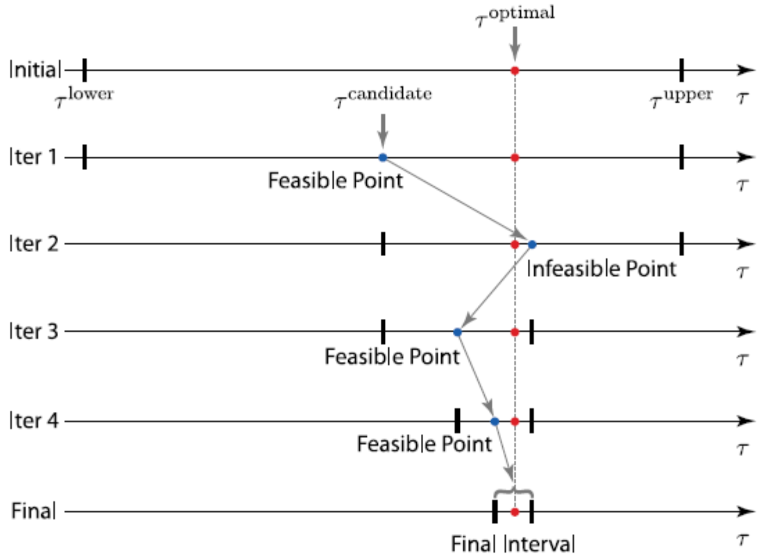

Figure 3.7. Bisection Method [1]

3.4.2. <u>**Poly back (PA) Algorithm**</u>

In PA algorithm, the sum information rate is maximized by approximating the performance region (around the optimal point) using a polyblock. The approximation is iteratively refined and parts that cannot contain the optimal point are removed.

3.4.3. <u>**Branch-Reduce-and-Bound (BRB) Algorithm**</u>

BRB algorithm is a systemic search method to find optimum point on Pareto boundary and proceeds by selecting lower and upper bounds on optimum. BRB algorithm as the name implies has three basic operations which include branching, reducing and bounding.

- <u>**Branching**</u>. Entire performance region is covered in a rectangular box ensuring that complete performance region is covered in that box. Divide the box into two sub boxes using bisection.

- **Reducing**. Search the boxes for possible solution and remove part that has no solution. This will reduce initial box to half.

- Bound. Improve bounds of selected box by searching for solutions.

- Continue dividing the box and proceeding with sub-box with largest value until optimal solution is found.

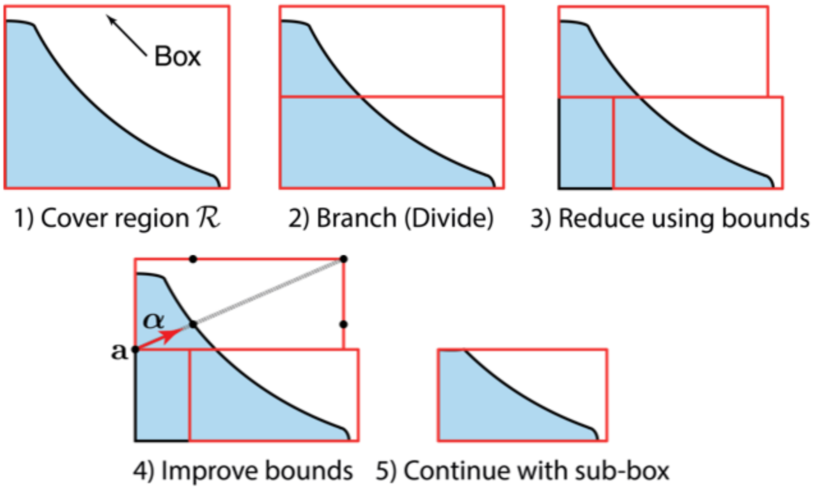

Figure 3.8. BRB Algorithm [1]

3.5. Summary

Each user wants to obtain maximum of the available resources and since system has same pool of resources to serve all users, it creates conflict between users over the resources. Resources of one user can be increased only at the cost of reducing resources for other user. Thus it can be safely said that each user has its own objective to be optimized. These conflicting user objectives give rise to multi-objective resource allocation optimization problem. This chapter explained relationship between multiple users being served together and explained characteristics of channel gain region and performance region. Pareto boundary and various points of interest on Pareto boundary were also discussed. This chapter also discussed few algorithms to find optimal point on Pareto boundary.

Chapter 4

MODELS OF POWER AMPLIFIERS

4.1. Non-Idealities in MIMO System

Practical wireless communication systems are effected by number of non-idealities which limit its performance and may include:-

- Insufficient channel knowledge
- High computational complexity
- Heterogeneous user conditions
- Limited backhaul capacity
- Transceiver impairments
- Constrained level of coordination between base stations

The focus of our study in this thesis will be transceiver impairments

4.2. Transceiver Impairments

Transceiver impairments exist mainly due to the electronic components present in the transceivers and have a significant effect the performance of wireless communication systems. It is imperative to study the effects of these impairments to formulate different compensation techniques to mitigate the effects of these transceiver impairments and improve the performance of wireless communication system. Transceiver impairments exist mainly because of:-

- Non-linear power amplifiers
- Phase noise
- IQ-imbalance

The focus of our study in this thesis is non-linear power amplifiers and its effects on wireless communication and resource allocation.

4.3. Non-Linear Power Amplifiers

Power amplifiers are an important component in modern communications system that amplify the transmit signal to a level which is required to overcome the losses that may be introduced in the transmitted signal between transmitter and the receiver. Power amplifiers also introduce certain problems in the communication system because of their non-linear behavior. Power amplifiers usually operate as a linear device under small signal conditions and become more non-linear with increasing drive levels and causes signal distortion which appear in the form of [8]:-

- Harmonic distortion
- Gain compression
- Inter-modulation distortion
- Phase distortion
- Adjacent channel interference
- In-band signal distortion
- Out-of-band spectral re-growth

These signal distortion are tightly controlled by the communications standard being used, and must be reduced if possible. This warrants a system level tradeoff between the power efficiency and the resulting distortion. For most commercial systems, this tradeoff is constrained by interference with adjacent users, thus, amplifier signal levels are reduced or “backed off” from the peak efficiency operating point.

4.3.1. Models of Non-Linear Power Amplifiers

Non-linear power amplifiers can be modeled as [4]:-

- Models based on the physical description of the power amplifier.
- Behavioral or Empirical models

A simplified diagram showing the classification of power amplifier models is shown below:-

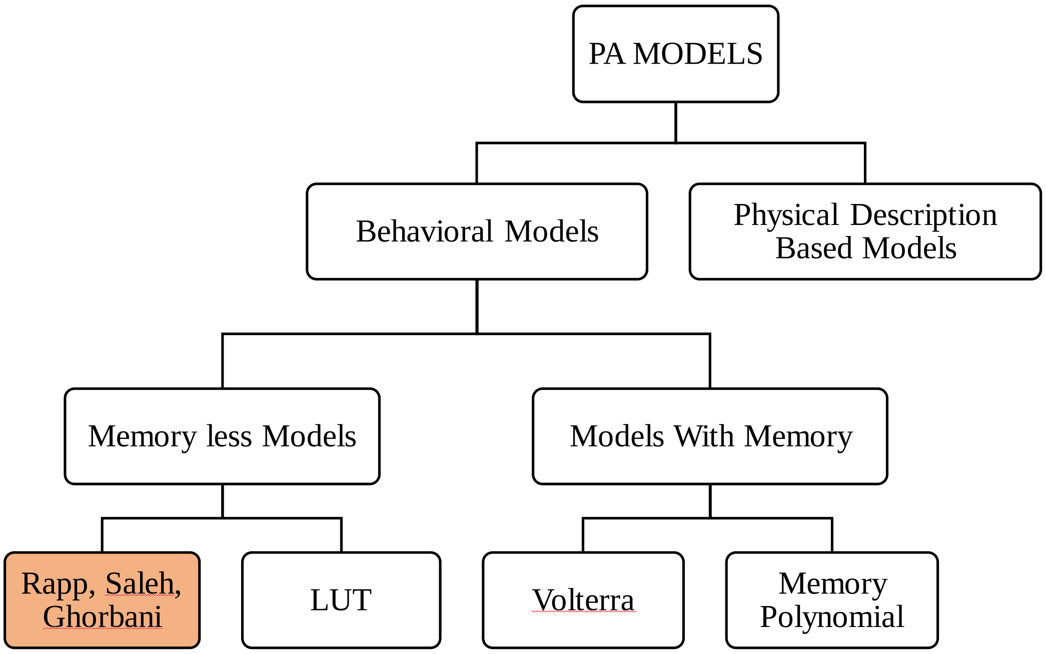

Figure 4.1. Power Amplifier Model Classification [4]

4.3.1.1. Models Based on the Physical Description of the Power Amplifier

Physical models are based on the physical description of the power amplifier and model some or all internal components of the power amplifier. Because of complexity of task involved, these models are quite complex and simulations using such models are also time consuming.

4.3.1.2. Behavioral or Empirical Models

Behavioral models only focus on behavior of the power amplifier and does not require building of any circuit components. Power amplifier is treated as a black box i.e., the internal structure of the power amplifier is not known. Various programing tools are used to develop these models which compares the input and output of power amplifier for analysis. Memory of these models have an important role to play and these behavioral models are classified as under:-

- Memory Less Models
  - Rapp Model
  - Saleh Model
  - Ghorbani Model
  - Look Up Table
- Models with Memory
  - Voltera
  - Memory Polynomial

The focus of our study in this thesis is Rapp Model.

4.3.2. Compensation Techniques

Non linearity of power amplifier can be compensated through various techniques some of which are:-

- Feed back
- Feed forward
- Pre-distortion

4.3.2.1. Feed Back

In case of feedback, a part of output signal is fed back for comparison and analysis purpose. It creates a scenario in which the output is following the input. Here the delay of the power amplifiers and other electronic components is very important due to which it is not suitable for the modern systems [4].

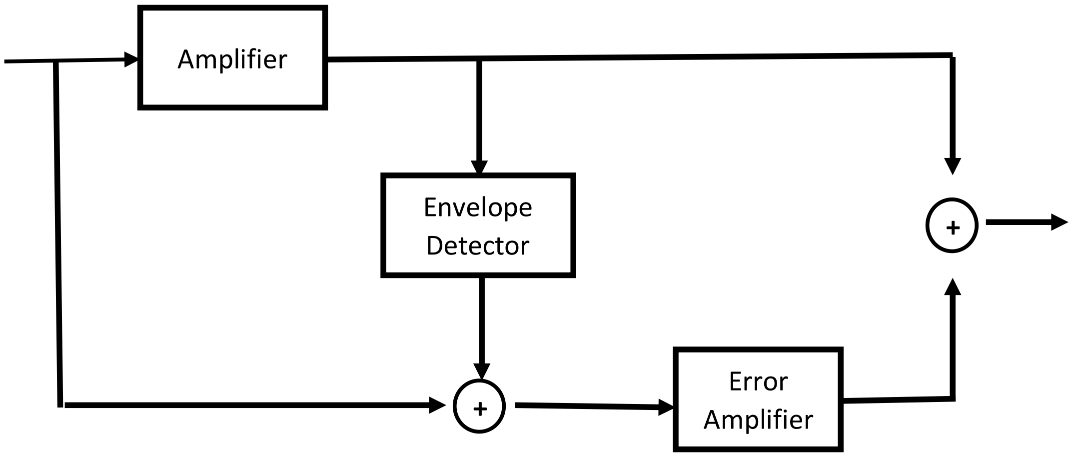

Figure 4.2. Feed Forward Technique [4]

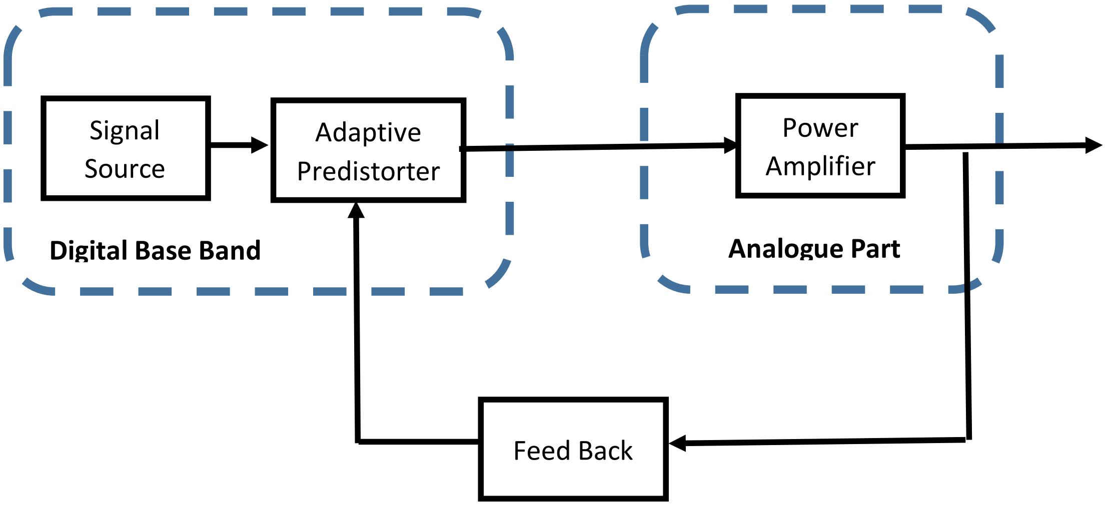

Figure 4.3. Pre-Distortion Technique [1]

4.3.2.2. <u>Feed Forward</u>

In feed forward technique the output of an additional error amplifier is subtracted from the actual output signal. The distortions in the main amplifier drive the error amplifier. The diagrammatic view of feed forward technique is shown in figure (4.2) [4]

4.3.2.3. <u>Pre-Distortion</u>

Pre-distortion system involves insertion of a nonlinear element prior to power amplifier such that the combined transfer characteristic of both is linear. The basic concept is to cancel out the effect of the power amplifier non linearity by applying the inverse effect before the signal is fed to the amplifier. Pre-distortion can be further classified as:-

- **Radio Frequency Pre-Distortion**. In radio frequency pre-distortion, a compressive characteristic, created by the nonlinearity in the lower path is subtracted from a linear characteristic to generate an expansive characteristic [8].
- **Digital Pre-Distortion**. It exploits processing power available from DSP [8].

4.3.3. Effects of Non-Linear Power Amplifiers on Orthogonal Frequency Division Multiplexing (OFDM)

The most commonly used modulation technique in high data rate multicarrier wireless communication is Orthogonal Frequency Division Multiplexing (OFDM). The OFDM system has many advantages like [8]:-

- Increased tolerance to inter-symbol interference and better spectral efficiency.
- Better response of frequency selective fading in multipath environment.
- Simplicity of implementation.
- Robustness to channel impairments.
- Narrowband interference.

OFDM operates at high PARR which has following demerits:-

- High PAPR causes spectral regrowth, which leads to adjacent channel interference.
- High PAPR drives the power amplifiers in their nonlinear region of operation.

4.3.3.1. <u>Linearization Techniques in OFDM</u>

To compensate these degradations, various linearization techniques are used which reduces the in-band signal distortion and out of band spectral re-growth to desirable level. Example of various architectures include [8]:-

- Linear Architecture
- Power Combiners
- Kahn Technique
- Envelope Tracking
- Doherty Technique

4.3.3.2. <u>PARR Reduction Techniques in OFDM</u>

The main aim of PAPR reduction technique is to reduce the envelope fluctuations of the signal which are to be transmitted by the power amplifier. PAPR reduction techniques are classified into following different approaches [8]:-

- Clipping Technique
- Coding Technique
- Probabilistic (scrambling) Technique
- Adaptive Predistortion Technique
- DFT-spreading Technique

The easiest way to reduce the PAPR is to clip the signal at the transmitter.

4.4. <u>Effect of Transceiver Impairments on Resource Allocation</u>

Transceiver impairments have a minor impact on point-to-point systems with low-order modulations that can be operated at low SNR. However, the degradations can be particularly severe in modern multi-cell systems using OFDM (which requires amplifiers with high dynamic range), high-order modulations (which require high SINRs), low-cost equipment (which are relatively non-ideal), and transmit-side interference mitigation (which needs accurate CSI and channel models) [1].

Effects of these impairments can be mitigated by proper modeling of all associated distortions followed by compensation algorithms and techniques as discussed in above paragraphs. Performance of communication systems can be improved and better predicted by considering effects of transceiver impairments in the resource allocation

4.4.1. Performance Requirements of Radio Frequency Components

In LTE, two kinds of performance requirements are imposed on each transmitter as under:-

- Power level and the quality of the intended transmission
- Limits the level of unwanted emissions that can be tolerated - Error Vector Magnitude (EVM)

4.4.2. EVM

The quality of the transmitted signal is judged by some specific requirements and the most important parameter that determines the quality of signal is EVM. It is a measure of the distortion generated due to the transceiver impairments in practical transmitters. EVM is the ratio between the average distortion magnitude and the average transmit magnitude. Effects of EVM can be seen diagrammatically in figure 4.4 below.

EVM defines the maximum possible SNR that can be achieved in a wireless communication link when we consider no interference, noise and propagation loss. Therefore, we can calculate the maximum possible modulation order and data rate that can be achieved.

EVM requirements in 3GPP Long Term Evolution (LTE) are 8%–17.5% at the transmitter, depending on the anticipated spectral efficiency [1]

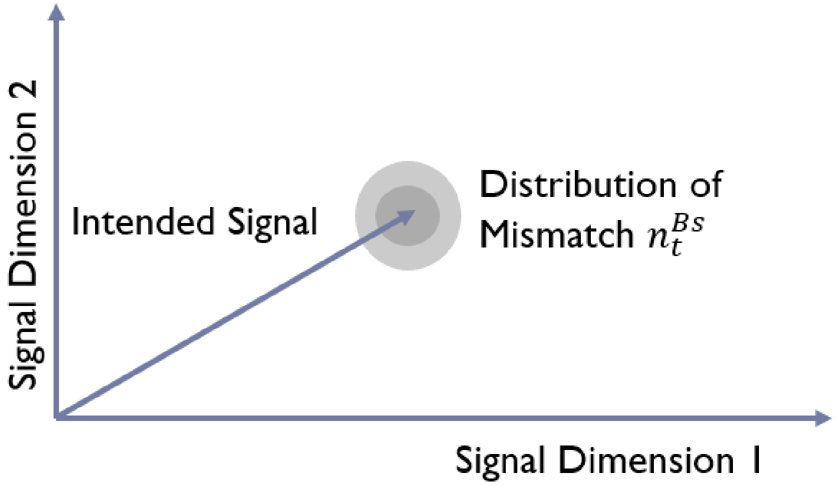

Figure 4.4. Error Vector Magnitude [1]

4.5. Summary

Various non-idealities effect communication system. Transceiver impairments exist because of non-linear power amplifier, phase noise and IQ imbalance. In this chapter transceiver impairments was discussed with special emphasis on non-linear response of power amplifiers. Various models of non-linear power amplifiers were also discussed along with compensation techniques. Models defined in this chapter will be subsequently used in coming chapters to develop real time model to find effects of non-linear power amplifiers on optimal resource allocation.

Chapter 5

PREVIOUS WORK

This chapter focuses on work that has already been done on the subject of developing power amplifier model and on optimal resource allocation.

5.1. Power Amplifiers

5.1.1. Power Amplifier Models

The book in [4] describes power amplifiers in length and makes a deliberate attempt to develop different models for power amplifiers. The book defines power amplifier models into physical and behavioral models as shown in figure 4-1 (Power Amplifier Model Classification). In this thesis we have used RAPP model which is a behavioral model to study the characteristics of non-linear power amplifier.

5.1.2. Effect of Power Amplifiers on Communication

Power amplifiers are an important component in modern communications system that amplify the transmit signal to a level which is required to overcome the losses that may be introduced in the transmitted signal between transmitter and the receiver. Power amplifiers also introduce certain problems in the communication system because of their non-linear behavior. Power amplifiers usually operate as a linear device under small signal conditions and become more non-linear with increasing drive levels and causes signal distortions. These signal distortion are tightly controlled by the communications standard being used, and must be reduced if possible. This warrants a system level tradeoff between the power efficiency and the resulting distortion. For most commercial systems, this tradeoff is constrained by interference with adjacent users, thus, amplifier signal levels are reduced or “backed off” from the peak efficiency operating point.

Effects of non-linear power amplifiers on communication using RAPP model have been studied in [5]. The output of a power amplifier which contains both input signal and transmitter noise is modeled mathematically as:-

$$Rapp(x) = \frac{x}{\left(1 + \left|\frac{x}{C}\right|^{2s}\right)^{\frac{1}{2s}}} \tag{5.1}$$

Where "C" is the output saturation amplitude and "s" is the non-linearity constant/ knee factor. In case of normalized Rapp Model we take C=1 and s=2. The normalized amplifier model therefore becomes:-

$$Rapp(x) = \frac{x}{(1 + |x|^4)^{\frac{1}{4}}} \tag{5.2}$$

This relationship is used in thesis in next chapter to incorporate effect of non-linear power amplifiers on optimal resource allocation.

5.2. Optimal Resource Allocation

Most researchers normally consider a simplified model assuming that the transmitted signal is independent of the transceiver impairments. This approach of not considering transceiver impairments has little effect when studying point-to-point communication systems as its effect is marginal in these systems. However, the effect of transceiver impairments in MIMO systems is severe because of multiple antennas employed at both transmitter and receiver sides. Because of such huge impact of transceiver impairments, they have to be incorporated in studying MIMO systems.

Extensive work has been done on resource allocation in [1] and [2] in which different parameters effecting resource allocation have been discussed. For transceiver impairments, the study considers a generalized impairment model in which combined influence of all impairments is considered rather than separately modeling behavior of each hardware [1]. Combined effect of transceiver impairments of all factors is considered as a constant value between 8% - 17.5% and the study does not incorporate any realistic model of calculating transceiver impairment effects on each input because of different factors.

In [1] and [2], effect of transceiver impairments on resource allocation has been worked out for EVM value 0, 0.05, 0.1 and 0.15. Result is as under:-

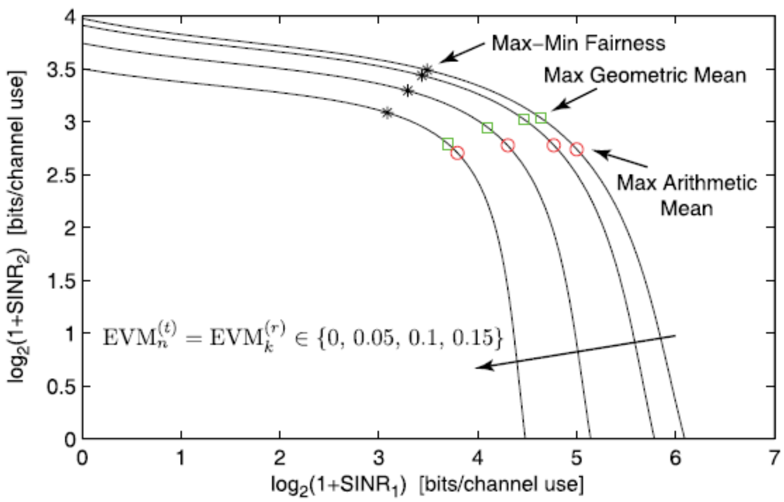

Figure 5.1. Effect of Transceiver Impairments on Pareto Boundary for EVM Value = 0, 0.05, 0.1 & 0.15 [1]

Chapter 6

MODEL AND SIMULATION RESULTS

6.1. Introduction

Effect of transceiver impairments on point-to-point systems is minimal because of limited number of antennas used and can be ignored while doing resource allocation in such systems. On the other hand, MIMO systems use large number of transmit and receive antennas because of which cumulative effect of transceiver impairments becomes significant and causes severe effect on MIMO systems. Because of this significance of effect on MIMO systems, effect of transceiver impairments has to be incorporated while doing resource allocation in MIMO systems [1].

Most work on Massive MIMO incorporates a simplified model in which it is assumed that the transmitted signal is independent of the transceiver impairments but to obtain realistic results it is necessary to develop an accurate model of transceiver impairments to analyze the effects of transceiver impairments on Pareto boundary and on optimal resource allocation.

6.2. Prior Work

Researchers normally consider a simplified model assuming that the transmitted signal is independent of the transceiver impairments.

Researchers while incorporating effect of transceiver impairments rely on generalized impairment model in which combined influence of all impairments is considered rather than separately modeling behavior of each hardware [1].

Effect of transceiver impairments is mostly considered as a constant value between 8% - 17.5% at the transmitter side.

6.3. Behavioral Model to Study Impact of Power Amplifier Non Linearity on Optimal Resource Allocation

Transceiver impairments exist because of:-

- Non-linear power amplifier
- Phase noise
- IQ imbalance

In this study, we have focused on non-linear power amplifier as main source of transceiver impairments. To model effects of power amplifiers, we have used RAPP model to find realistic effects of transceiver impairments on different input signals. This model is then implemented in MATLAB to simulate the effects and find effect of transceiver impairments on Pareto boundary and on optimal resource allocation.

6.3.1. System Model

The received downlink signal y $\in C$ is modeled as:-

$$y = h^T x + n \quad (6.1)$$

When we want to incorporate the impact of transceiver impairments on the transmitted signal, the system model expressed in equation 6.1 is modified as:-

$$y = h^T (x + n_t^{Bs}) + n_r^{UE} + n \quad (6.2)$$

Where, n_t^{Bs} and n_r^{UE} are the additive transmitter-distortion and receiver-distortion, respectively. The transmitter-distortion, n_t^{Bs} describes the mismatch between the data signal x designed by the resource allocation and what is actually transmitted by the Radio Frequency hardware.

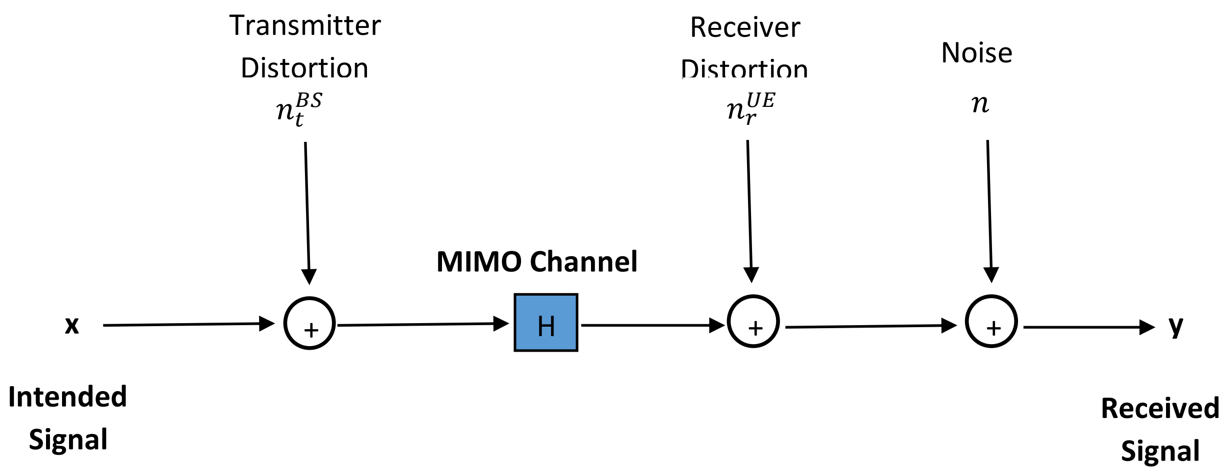

Figure 6.1. Channel Model

6.3.2. Development of Mathematical Model for Non-Linear Power Amplifiers

When we are incorporating effect of transceiver impairments, the input signal and the distortion caused because of non-linear power amplifier can be modeled as a function of x and is expressed mathematically as:-

$$f(x) = x + n_t^{Bs} \tag{6.3}$$

Equation 6.2 is modified as:-

$$y = h^T f(x) + n \tag{6.4}$$

When we consider power amplifier non-linearity as main source of transceiver impairments then its effect is given as:-

$$f(x) = Rapp(x) = \frac{x}{\left(1 + \left|\frac{x}{C}\right|^{2s}\right)^{\frac{1}{2s}}} \tag{6.5}$$

Where "C" is the output saturation amplitude and "s" is the non-linearity constant/ knee factor. In case of normalized Rapp Model we take C=1 and s=2. The normalized amplifier model then becomes:

$$Rapp(x) = \frac{x}{(1+|x|^4)^{\frac{1}{4}}} \tag{6.6}$$

From equation 6.3 and 6.6, we can find value of n_t^{Bs} as:-

$$n_t^{Bs} = Rapp(x) - x = \frac{x}{(1+|x|^4)^{\frac{1}{4}}} - x \tag{6.7}$$

Now, we calculate the Error Vector Magnitude (EVM) by using the relation:-

$$EVM = \sqrt{\frac{(n_t^{Bs})^2}{x^2}} \tag{6.8}$$

From equation 6.7

$$EVM = \sqrt{\frac{(Rapp(x) - x)^2}{x^2}} \tag{6.9}$$

The hardware impairment value, kappa k is calculated as:-

$$k = EVM^2 \tag{6.10}$$

6.4. Simulation Settings

In simulation we have considered $K_t = 2$ transmitters that serve $K_r = 2$ users. Each transmitter has 2 antennas and per-array power constraints of $q_l = 10\ dB$ are used. Each user is close to one of the transmitters. The rate region is generated for a single random channel realization where the channel h_{jk} between transmitter j and user k is generated as uncorrelated Rayleigh fading.

6.4.1. Simulation Parameters

The input signal is made dependent on the transceiver impairments by using Rapp model developed which was developed in earlier part of this chapter. We simulate the results for input signal values of x = 0.5, 0.6, 0.7, 0.8, 0.9 and 1. The other simulation parameters are:-

Parameter	Value
Input Signal	0.5, 0.6, 0.7, 0.8 and 0.9
EVM	Calculated from table 6-2
Hardware Impairments (k)	Calculated from table 6-2
Rapp Model Variables:	
Non Linearity constant (s)	2
Output saturation amplitude (C)	1

Table 6.1 Simulation Parameters

6.5. Simulation Results

6.5.1. Evaluation of Developed Mathematical Model

We are using RAPP model in our study and we have worked our mathematical relationship to find values of EVM and Kappa for different input values in equation 6.9 and 6.10. Using these equations, different values of EVM and Kappa are as under:-

Input Signal	EVM	Percentage %	Hardware Impairments (k)
0.5	0.015	3	0.000225
0.6	0.03	5	0.0009
0.7	0.0524	7.5	0.00246
0.8	0.0822	10.3	0.00676
0.9	0.1185	13.2	0.014
1	0.1591	15.9	0.025

Table 6.2 EVM and Hardware Impairment Values for Input Signal

6.5.1.1. <u>Analysis</u>

EVM factor is the effect of transceiver impairments and is normally considered as a constant value by most of the researchers. The permissible range of EVM value in Long Term Evolution (LTE) is between 8%-17.5% [1]. The values of EVM generated though our mathematical model for different values of input signal lie well within the range. This verifies our developed mathematical model.

6.5.2. <u>Effect of Transceiver Impairments on Different Input Values</u>

We have simulate different input values to obtain the results both with and without transceiver impairments to draw comparison and analysis.

6.5.2.1. <u>Input Value = 0.5</u>

Simulation output is as under:-

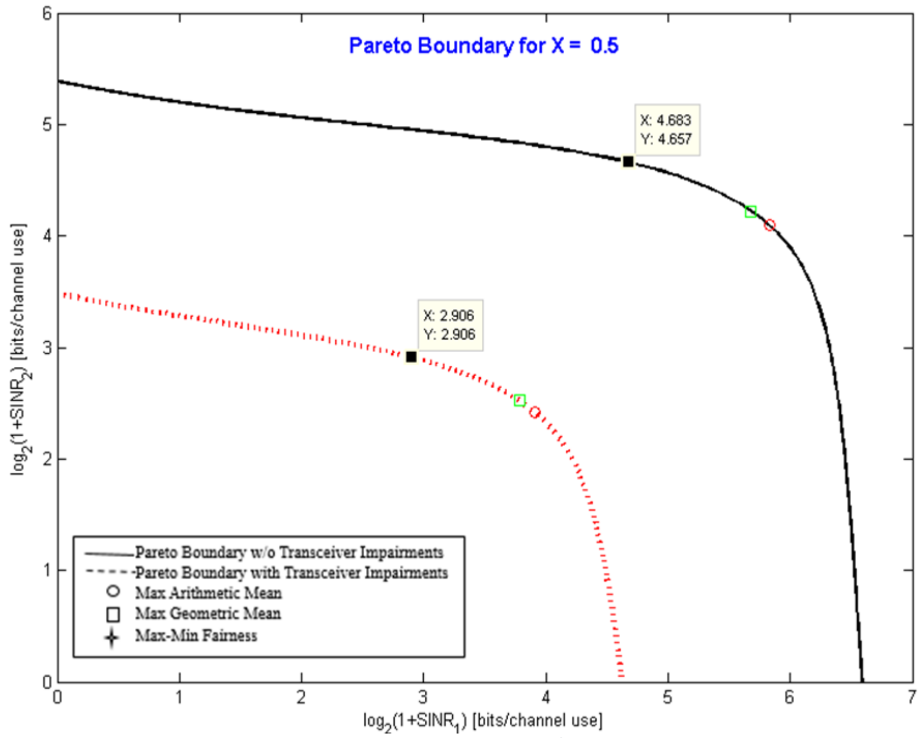

Figure 6.2 Simulation Results for x = 0.5

6.5.2.1.1. Analysis

In the simulation we are calculating the effects of transceiver impairments on optimal resource allocation and optimal resource allocation deals with allocation of power to users and derivation of Pareto boundary to find optimal solution. The graph is showing two user case in which x-axis shows power of user 1 and y-axis shows power of user 2. Solid line is the Pareto boundary without considering the effect of transceiver impairments and dotted line is the Pareto boundary while considering the effect of transceiver impairments. We are also calculating max-min fairness point, maximum geometric mean point and maximum arithmetic mean point for both cases.

Simulation results clearly show that the transceiver impairments had a major impact on max-min fairness point, maximum geometric mean point and maximum arithmetic mean point. We can also observe that the size of performance region has also reduced however, general shape of performance region has remained unchanged.

From the result we can conclude that transceiver impairments have a major effect on optimal resource allocation.

6.5.2.2. Input Value = 0.6, 0.7, 0.8 and 0.9

Simulation output for x = 0.6, 0.7, 0.8 and 0.9 is as under:-

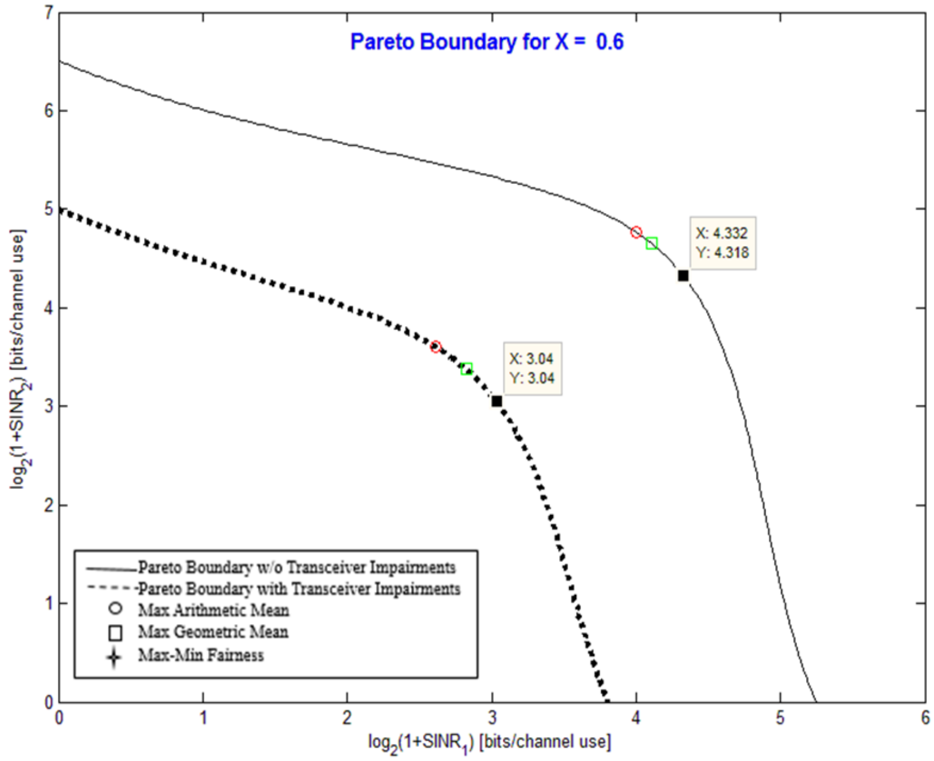

Figure 6.3. Simulation Results for x = 0.6

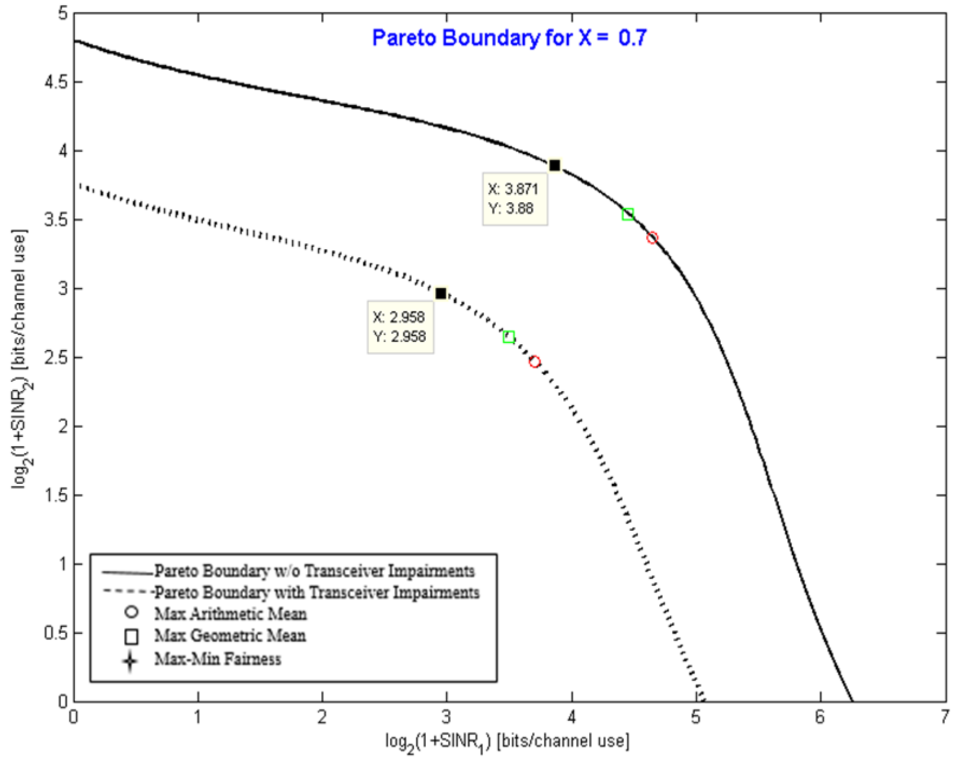

Figure 6.4 Simulation Results for x = 0.7

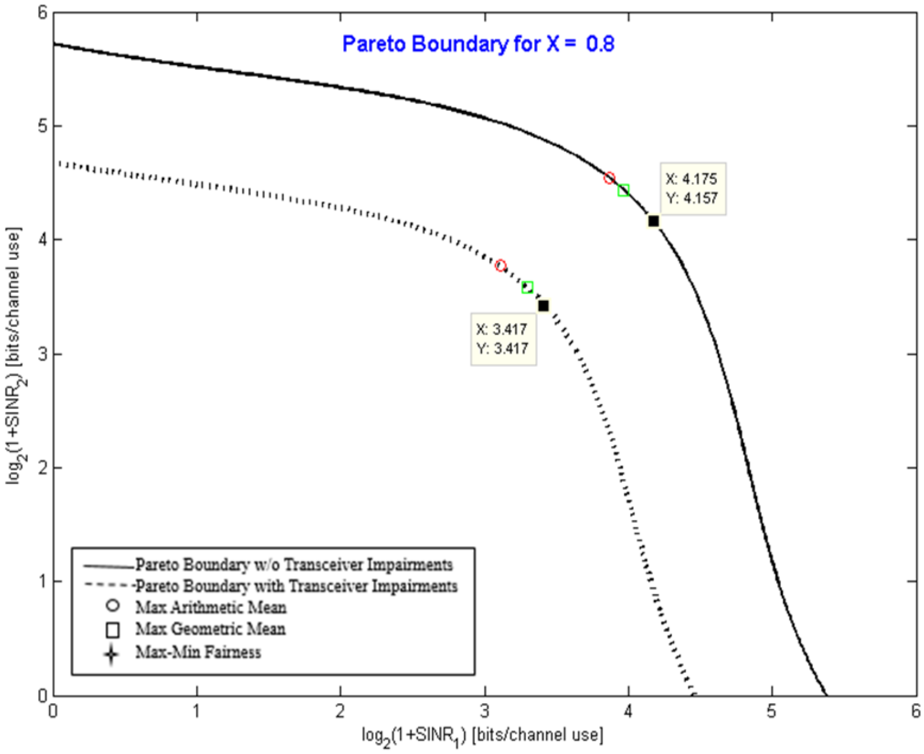

Figure 6.5 Simulation Results for x = 0.8

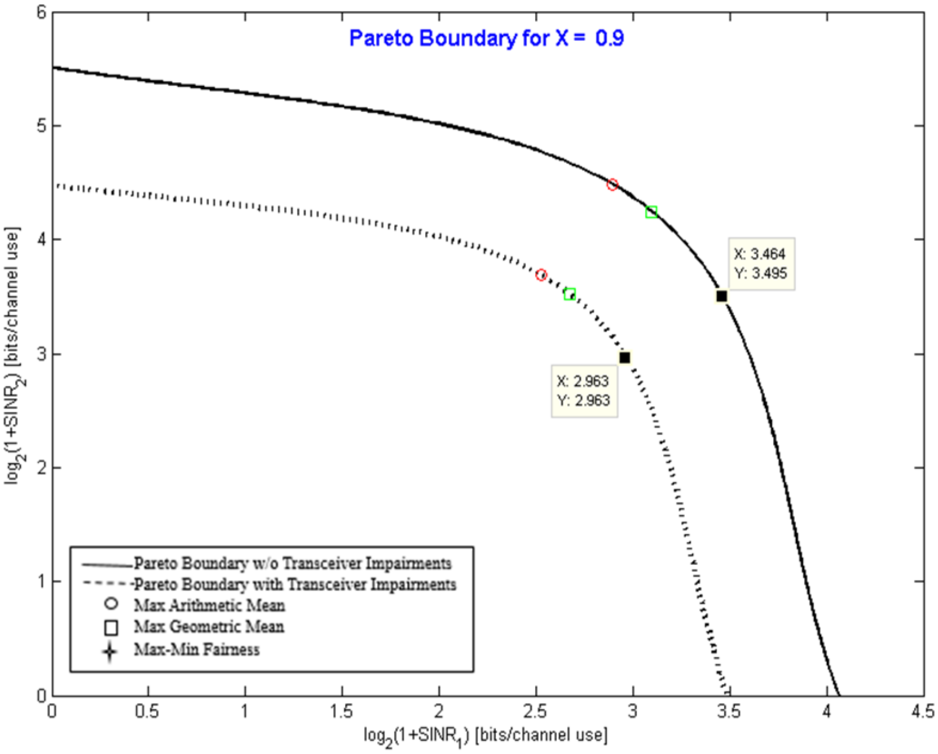

Figure 6.6 Simulation Results for x = 0.9

6.5.2.2.1. Analysis

We have already drawn some conclusions in 6.5.2.1.1 and now we have carried out simulations for input signal = 0.6, 0.7, 0.8 and 0.9 to verify our findings. In the figures again, solid line is the Pareto boundary without considering the effect of transceiver impairments and dotted line is the Pareto boundary while considering the effect of transceiver impairments. We are also calculating max-min fairness point, maximum geometric mean point and maximum arithmetic mean point for both cases.

Simulation results again clearly shows that the transceiver impairments had a major impact on max-min fairness point, maximum geometric mean point and maximum arithmetic mean point. We can observe again that the size of performance region has also reduced however, general shape of performance region has remained unchanged.

From the result we can conclude that transceiver impairments have a major effect on optimal resource allocation.

6.5.2.3. Comparative Results for Different Input Value

Now we are going to simulate different input values together and draw plots both with and without transceiver impairments to find a comparative look at all the results to solidify our findings

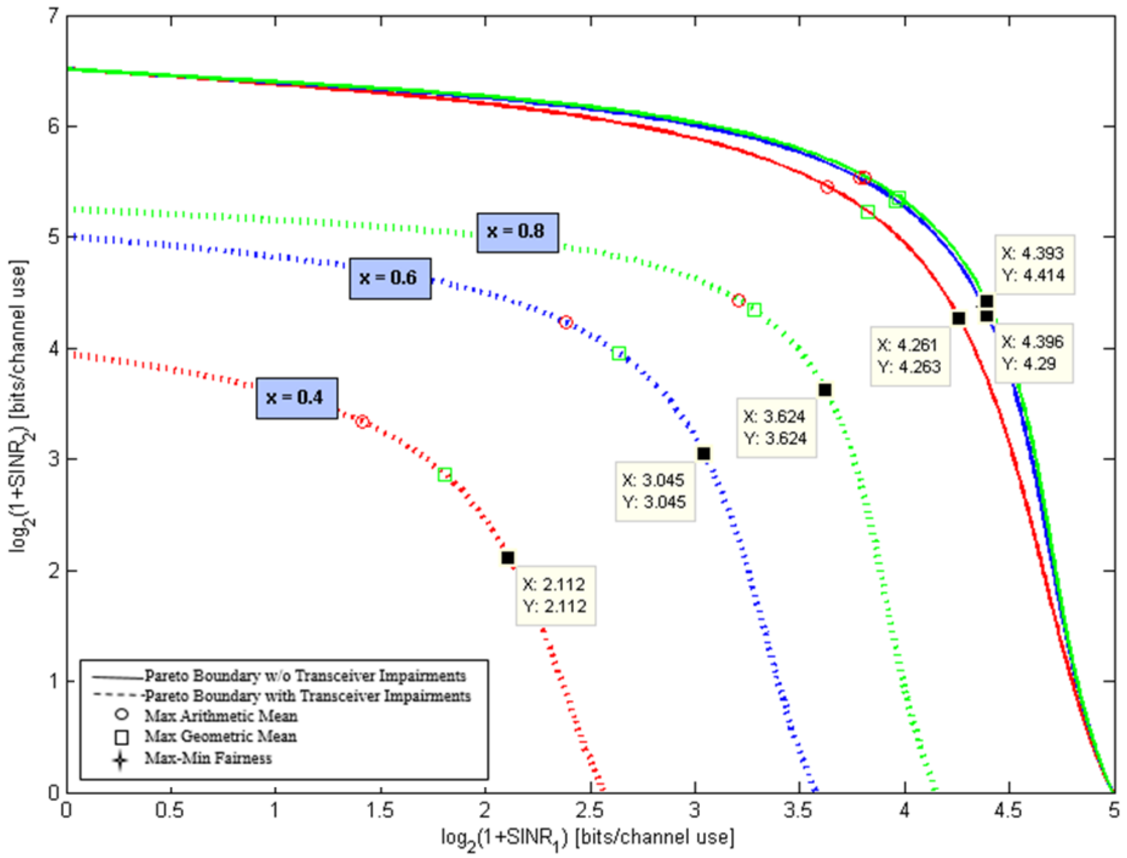

Figure 6.7 Simulation Results for x = 0.4, 0.6 and 0.8

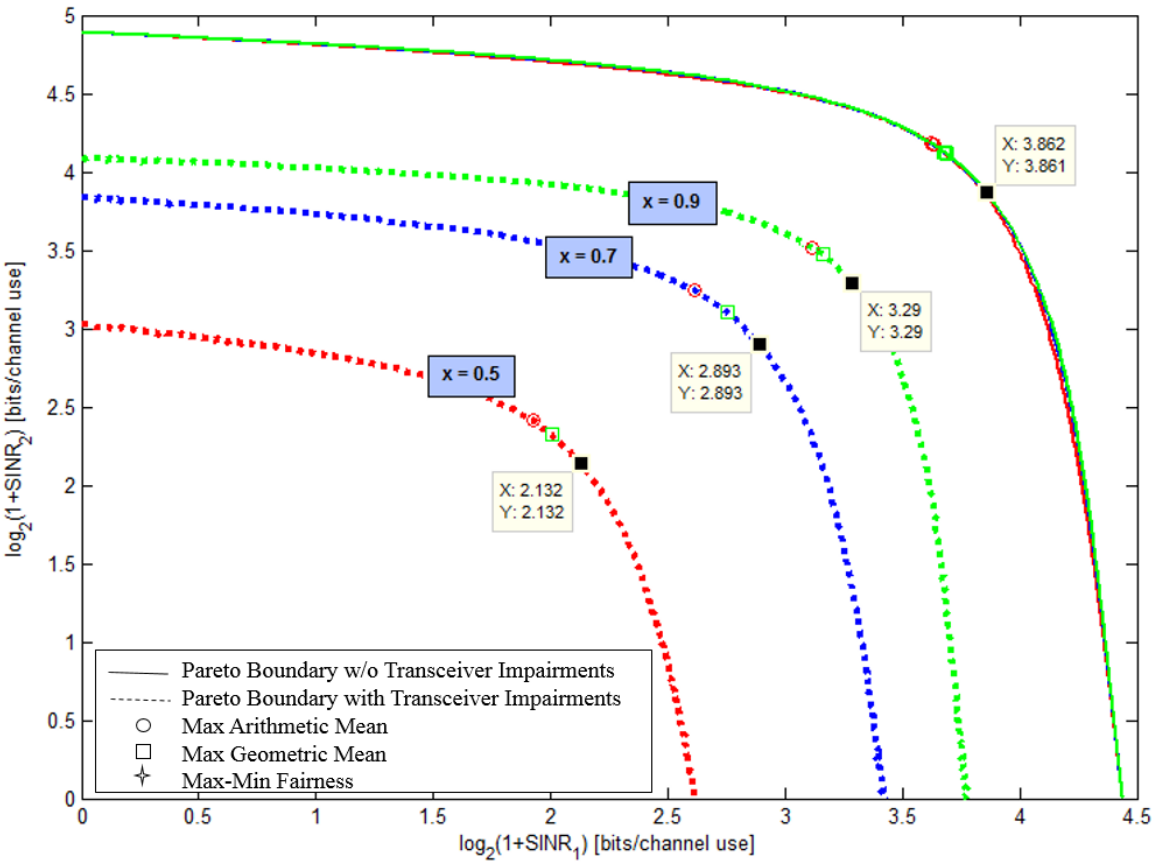

Figure 6.8 Comparative Results for x = 0.5, 0.7 and 0.9

6.5.2.3.1. Analysis

In the graph we have plotted different input values together both with and without transceiver impairments. Solid line shows Pareto boundary without considering transceiver impairments with dotted line show Pareto boundary with transceiver impairments. Max-min fairness point, maximum geometric mean point and maximum arithmetic mean point have also been calculated for all cases.

Simulation results again clearly shows that the transceiver impairments had a major impact on max-min fairness point, maximum geometric mean point and maximum arithmetic mean point. We can observe again that the size of performance region has also reduced however, general shape of performance region has remained unchanged.

From the result we can conclude that transceiver impairments have a major effect on optimal resource allocation.

6.5.3. Effect of Transceiver Impairments on Three Users

Now we are going to carry out simulation to find effect of transceiver impairment on three users simultaneously. This simulation is performed for input signal 1. In this simulation we are not calculating max-min fairness point, maximum geometric mean point and maximum arithmetic mean point. Focus of simulation is only to see the effects of transceiver impairment on Pareto boundary in 3 user case.

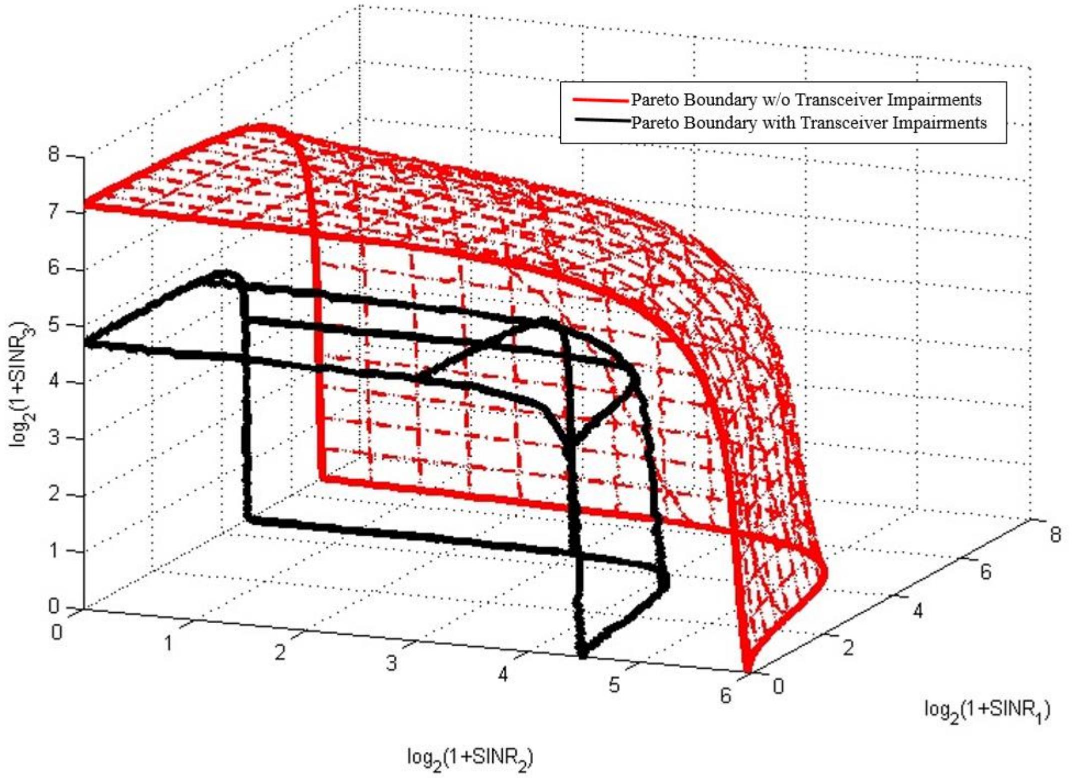

Figure 6.9 Simulation Results for Effect of Transceiver Impairments on 3 Users with input Signal = 1

6.5.3.1. Analysis

The simulated graph is a three dimensional graph that plots power of three users on x, y and z-axis respectively. Pareto boundary considering the mutual effect of three uses on each other is shown in three dimensional as well. Like previous simulations, results are calculated both with and without transceiver impairments. Red line shows Pareto boundary without considering effect of transceiver impairments and black line is showing Pareto boundary while considering effect of transceiver impairments.

Simulation results again clearly shows that the transceiver impairments had a major impact on size of performance region, however, once again general shape of performance region has remained unchanged.

From the result we can conclude that transceiver impairments have a major effect on optimal resource allocation.

6.6. Conclusion

Massive MIMO is a new research area and has the potential to support high data rate and mobility requirements of future wireless communication systems. In this work we focused on non-linear power amplifiers as main source of transceiver impairments to find its effects on performance region and optimal resource allocation. Models mostly employed in theory does not incorporate the effect of transceiver impairments on the transmitted signal. In our work we have derived a new system model that incorporates the impact of transceiver impairments on the transmitted signal and by employing this new system model we have achieved realistic results of performance region and optimal resource allocation.

Chapter 7

FUTURE WORK

Massive MIMO technology is still at the research stage and has a great potential to cope up with the ever increasing demand of data rates and mobility. Since it is a new area of research, there are many unsolved directions in this area of study.

In this work we focused on non-linear power amplifiers as main source of transceiver impairments and developed a system model which produces realistic results showing the effect of transceiver impairments on performance region and optimal resource allocation. Future work can be done on following lines:-

- More realistic transceiver impairment model may be developed that incorporates all causes of transceiver impairments i.e. non-linear power amplifiers, phase noise and IQ imbalance. This model will give more realistic results on effects of transceiver impairments on performance region and optimal resource allocation.

- In our study we focused on RAPP model which is memory less behavioral model of non-linear power amplifier. Further work can be done by incorporating memory based behavioral models to further improve the compensation techniques.

- Further work may also be based on physical models of non-linear power amplifiers.

- Behavioral model of non-linear power amplifier developed in this study may be extended to explore impact of transceiver impairments on other communication aspects of MIMO as well.

BIBLOGRAPHY

[1] E. Bjornson and E. Jorswieck, “Optimal resource allocation in coordinated multi-cell systems," Foundations and Trends in Communications and Information Theory, vol. 9, no. 2-3, pp. 113-381, 2013

[2] E. Bjornson and E. Jorswieck, “Optimal resource allocation in coordinated multi-cell systems: Matlabcode," Tech. Rep., July 2014

[3] Emil Bjornson, Michail Matthaiou and M´erouane Debbah, “Massive MIMO with Non-Ideal Arbitrary Arrays: Hardware Scaling Laws and Circuit-Aware Design”, arXiv:1409.0875v3 [cs.IT] 29 Apr 2015

[4] Atso Hekkala, “Compensation of transmitter nonlinearities using predistortion techniques: Case studies of envelope tracking amplifiers and radio-over-fibre links”, Doctorate thesis, University of Oulu, Finland, 2014.

[5] S. Ali, G. Markarian, and E. Arikan, "Novel Predistortion Algorithm for OFDMA", presented in the 69th IEEE conference, VTC Spring 2009, Barcelona, Spain, Apr. 2009.

[6] P. D. Morris and C. R. N. Athaudage, “Fairness Based Resource Allocation for Multi-User MIMO-OFDM Systems” IEEE 0-7803-9392-9/06/$20.00. 2006

[7] Emil Björnson, Mats Bengtsson, and Björn Ottersten, “Pareto Characterization of the Multicell MIMO Performance Region With Simple Receivers”, IEEE transactions on signal processing, VOL. 60, No. 8, August 2012

[8] Shatrughna Prasad Yadav and Subhash Chandra Bera “Nonlinearity Effect of Power Amplifiers in Wireless Communication Systems”, International Conference on Electronics, Communication and Computational Engineering (ICECCE), 2014

[9] E. Bj¨ornson, M. Bengtsson, and B. Ottersten, “Pareto characterization of the multicell MIMO performance region with simple receivers,” IEEE Transactions on Signal Processing, vol. 60, no. 8, pp. 4464–4469, 2012.

[10] E. Bj¨ornson, P. Zetterberg, and M. Bengtsson, “Optimal coordinated beamforming in the multicell downlink with transceiver impairments,” in Proceedings of IEEE Global Communication Conference, 2012.

[11] E. Bj¨ornson, P. Zetterberg, M. Bengtsson, and B. Ottersten, “Capacity limits and multiplexing gains of MIMO channels with transceiver impairments,” IEEE Communications Letters, To appear, 2013.

[12] Bo Huang; Xuming Fang; Qing Chen; Rong He; Wu Chen, "A Pairing Scheduling Scheme for Virtual MIMO Systems," Wireless Communications Networking and Mobile Computing (WiCOM), 2010 6th International Conference on , vol., no., pp.1,6, 23-25 Sept. 2010.

[13] Yang Chao; Fan Bin; Qian Yu; Wang Wen-bo, "Adjustable determinant pairing scheduling for virtual MIMO system," Intelligent Signal Processing and Communication Systems, 2007. ISPACS 2007.

[14] 3Gpp TSG-RAN1 WG1 #43. “UL Virtual MIMO Scheduling.” R1-051423, Seoul, Korea, November, 2005.

[15] Parkvall, S.; Dahlman, E.; Furuskar, A.; Jading, Y.; Olsson, M.; Wanstedt, S.; Zangi, K., "LTE-Advanced - Evolving LTE towards IMT-Advanced," Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th , vol., no., pp.1,5, 21-24 Sept. 2008.

[16] Zimran Rafique, Boon-Chong Seet and Adnan Al-Anbuky. "Performance Analysis of Cooperative Virtual MIMO Systems for Wireless Sensor Networks". Sensors, 13, 7033-7052; doi:10.3390/s130607033, 28 May 2013

[17] Fredrik Rusek, "5G - Massive MIMO", Internet: www.sharetechnote.com/html/5G_MassiveMIMO.html [Dec.20,2015]