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**INTERFERENCE MANAGEMENT IN LTE SYSTEM AND  
BEYOND**

Master's thesis for the degree of Master of Science in Technology submitted for inspection, in Vaasa, 30 March, 2015.

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## ACKNOWLEDGEMENT

My gratitude and appreciation first to Almighty God who is the source of life, opportunities and privileges that has made the completion of this thesis and by extension the degree program possible.

I am grateful to Professor Mohammed Elmusrati for accepting to be my instructor and supervisor. It is once in life opportunity to work with you and a very big learning curve for me, not only for immense knowledge gathered but also the level of professional guidance/support received all through this work. I am thankful to Professor Timo Mantere, Tobias Glocker, Ruifeng Duan, Reino Virrankoski, for their immense contribution in deepening my knowledge through the various courses taught in this master's degree program. For useful discussion/direction on MIMO during the difficult period in the wilderness, my tribute goes to Omar Ali Abu-Ella. The members of academic and nonacademic staff of the Faculty of Technology, Communications and Systems Engineering Group will always be remembered for their direct or indirect contribution to the success of this program.

I am highly indebted to the love of my life, my wife and best friend Mrs Grace Azuka Ezeobi for giving me the opportunity to live my dream. Her emotional support was vital while acknowledging the long separation and discomfort we both endured to accomplish this fit. I must acknowledge Mr. and Mrs. Gilbert Nwankwo (my parent-in-law) for supporting and providing for her for the duration of my study. My appreciation goes to my Mum, Mrs. Theresa Ezeobi for her prayers, my brother Dr Ifeanyi Ezeobi, my friends Engr Chinedu Alex Ezeigweneme and Engr John Jiya for their financial support during the difficult times. My classmates must be recognized for their support and positive contribution during the course work

Finally, I must commend the University of Vaasa and Finnish Government for making all these possible through the tuition free education.

Vaasa, Finland, March, 2015,

Ezeobi Chinonso Mmadueke

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**ABBREVIATIONS**

<b>1G/2G/3G/4G/5G</b>	First/Second/Third/Fourth/Fifth Generation Network
<b>3GPP</b>	Third Generation Partnership Project
<b>AWGN</b>	Additive-white-Gaussian-noise
<b>AMPS</b>	Analog Advanced Mobile Phone in America
<b>ARIB</b>	Association of Radio Industries and Business
<b>ATIS</b>	Automatic Terminal Information Services
<b>BER</b>	Bit Error Rate
<b>BLAST</b>	Bell-Labs Layered Space-Time Architecture
<b>bps/Hz</b>	bit per second per Herz
<b>BS</b>	Base Station
<b>CCB</b>	Cell Center Band
<b>CDMA</b>	Code division Multiple Access
<b>CEB</b>	Cell Edge Band
<b>CEPT</b>	European Conference of Postal and Telecommunications Administrations
<b>CCSA</b>	China Communications Standards Association
<b>CoMP</b>	Coordinated Multipoint transmission or reception
<b>C-NETZ</b>	Radio Telephone Network C (German: <b>Funktelefonnetz-C</b> )
<b>CSG</b>	Close Subscriber Group
<b>CSI</b>	Channel State Information
<b>D2D</b>	Device-to-Device
<b>dB</b>	Decibel
<b>DCA</b>	Dynamic Channel Allocation

<b>DoF</b>	Degree of Freedom
<b>ETSI</b>	European Telecommunications Standard Institute
<b>FDD</b>	Frequency Division Duplex
<b>FDMA</b>	Frequency Division Multiple Access
<b>FFR</b>	Fractional Frequency Reuse
<b>GSM</b>	Global System for Mobile Communications
<b>IA</b>	Interference Alignment
<b>ICI</b>	Inter-Cell Interference
<b>IMT</b>	International Mobile Telecommunication
<b>ISI</b>	Inter-symbol Interference
<b>ITU</b>	International Telecommunication Union
<b>LTE</b>	Long Term Evolution
<b>MAC</b>	Medium Access Control
<b>ML</b>	Maximum Likelihood
<b>MIMO</b>	Multiple Inputs Multiple Outputs
<b>MISO</b>	Multiple Input Single Output
<b>MMSE</b>	Minimum Mean Square Error
<b>MMW</b>	Millimeter-wave
<b>MUD</b>	Multiuser Detection
<b>NMT</b>	Nordic Mobile Telephone
<b>OSG</b>	Open Subscriber Group
<b>OFDMA</b>	Orthogonal Frequency Division Multiple Access
<b>OCI</b>	Other Cell interference

<b>OSIC</b>	Ordered Successive Interference Cancelation
<b>PDC</b>	Personal Digital Cellular
<b>PCC</b>	Primary Component Carrier
<b>RAN</b>	Radio Access Network
<b>SAE</b>	System Architecture Evolution
<b>SCC</b>	Secondary Component Carrier
<b>SIC</b>	Successive Interference Cancelation
<b>SIMO</b>	Single Input Multiple Output
<b>SINR</b>	Signal-to-Interference plus Noise Ratio
<b>SISO</b>	Single Input Single Output
<b>SNR</b>	Signal to Noise Ratio
<b>TACS</b>	Total Access System
<b>TDD</b>	Time Division Duplex
<b>TDMA</b>	Time Division Multiple Access
<b>TSGs</b>	Technical Specification Groups
<b>TTA</b>	Telecommunications Technology Association, Korea
<b>TTC</b>	Telecommunication Technology Commission, Japan
<b>UE</b>	User Equipment
<b>UMTS</b>	Universal Mobile Telecommunication System
<b>UTRA</b>	UMTS Terrestrial Radio Access
<b>VBLAST</b>	Vertical Bell Lab Layered Space-Time Architecture
<b>WCDMA</b>	Wideband Code Division Multiple Access
<b>ZF</b>	Zero Forcing



**SYMBOLS**

$P_{j,i}^{(l)}$	Received signal power for cell i from UE j in cell l
$\gamma_i$	relative power (boost or attenuation) gains for Cell center band
$\beta_i$	relative power (boost or attenuation) gains for Cell Edge Band
$S_i^{CCU}$	Dynamic scheduling for cell center user
$S_i^{CEU}$	Dynamic scheduling for cell edge user
$P_{th}$	SINR threshold
$\sigma^2$	Noise variance
$\alpha$	The interference-to-signal ratio
F	Frequency reuse factor
N	Noise
S	Signal
C	capacity
V	Signal space
Y/Z	Received Signal
x/s	Transmitted symbol
H	Channel matrix
$h_{ij}$	The channel gain from the ith receiver to jth transmitter
W	Precoder matrix
$H^H$	Hermitian transpose
$H^\dagger$	Pseudo-inverse
I	Identity matrix
$\lambda_i$	Channel gain

$M_R$	Received antenna
$M_T$	Transmit antenna
$R_{yy}$	Covariance matrix
$R_{sy}$	Cross-covariance matrix
$\varepsilon$	Error
G	Estimator
U	Orthonormal unitary matrix
$\Sigma$	Matrix of singular values
r	The rank of a matrix
$E_x$	Transmitted signal energy

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**Topic of the Thesis:** Interference Management in LTE and Beyond  
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**Department:** Department of Computer Science  
**Degree Programme:** Master's Programme in Telecommunication Engineering.  
**Major of Subject:** Communications and Systems Engineering  
**Year of Entering the University:** 2013  
**Year of Completing the Thesis:** 2015 **Pages: 101**

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**ABSTRACT**

The key challenges to high throughput in cellular wireless communication system are interference, mobility and bandwidth limitation. Mobility has never been a problem until recently, bandwidth has been constantly improved upon through the evolutions in cellular wireless communication system but interference has been a constant limitation to any improvement that may have resulted from such evolution. The fundamental challenge to a system designer or a researcher is how to achieve high data rate in motion (high speed) in a cellular system that is intrinsically interference-limited.

Multi-antenna is the solution to data on the move and the capacity of multi-antenna system has been demonstrated to increase proportionally with increase in the number of antennas at both transmitter and receiver for point-to-point communications and multi-user environment. However, the capacity gain in both uplink and downlink is limited in a multi-user environment like cellular system by interference, the number of antennas at the base station, complexity and space constraint particularly for a mobile terminal.

This challenge in the downlink provided the motivation to investigate successive interference cancellation (SIC) as an interference management tool LTE system and beyond. The Simulation revealed that ordered successive interference (OSIC) out performs non-ordered successive interference cancellation (NSIC) and the additional complexity is justified based on the associated gain in BER performance of OSIC. The major drawback of OSIC is that it is not efficient in network environment employing power control or power allocation. Additional interference management techniques will be required to fully manage the interference.

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**KEYWORDS:** Interference, space-time channels, Multiple-Input Multiple-Output, frequency reuse, LTE, Fifth generation network, Successive interference cancellation, degree of freedom.

## 1. INTRODUCTION

Wireless mobile communication has become integral part of our everyday lives. Our current life is overly reliant on small or smart devices that it is unimaginable what our lives would have been without such services in the past. The way we live and conduct business have changed over the past decade due to improved processing power of personal computers, the increase in the use of world wide web(internet), search engines and many different application like mobile TV, email and mobile media. Businesses are conducted over a long geographical area in seconds, country and regional boundaries have become blurred.

To support this new and ever increasing demand for wireless mobile applications services on the move, the existing technologies are constantly improved and new one developed/being developed to meet constantly dynamic demand. Long Term Evolution (LTE-4G) and Fifth Generation (5G) just to mention a few are products of these innovations in the wireless mobile application.

### 1.1 Evolution of Wireless Mobile Networks

The growth in mobile wireless technology and subscriber base in the last few years has been unprecedented. The improvement came with a major shift from fixed line to mobile cellular telephony. It is estimated that we had four times more mobile cellular subscription compared to fixed telephone line by the end of 2010 (Mshvidobadze 2012:1).

The first generation (1G) analog Cellular technology was introduced in 1981 with circuit-switched, only voice service based on analog radio transmission method and Frequency Division Multiple Access (FDMA). The regional standards are Nordic Mobile Telephone (NMT) in Saudi Arabia and Nordic countries, C-Netz in Germany, Portugal and South Africa, Total Access System (TACS) in UK and (AMPS) Analog Advanced Mobile Phone in America (Afif, Werner & Jose 2012:3).

First digital system with short message system and low data speed known as 2G (second generation) was adopted at the beginning of 1990s. The Global System for Mobile Communications (GSM) was developed in 1982 by European Conference of Postal and Telecommunications Administrations (CEPT), a system that was deployed internationally from 1991 which support international roaming. The 2G standard in other regions are D-AMPS (IS-136) and CDMAOne (IS-95A) in America, Personal Digital Cellular (PDC) for Japan. GSM uses a hybrid of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) compared to IS-95 that uses Code Division Multiple Access (CDMA) (Asif et al 2012:3).

Universal Mobile Telecommunication System (UMTS) was adopted by European Telecommunication Standards Institute (ETSI) as 3G standard while Wideband Code Division Multiple Access (WCDMA) was endorsed in America. Third Generation Partnership Project (3GPP) developed UMTS standards using both WCDMA and TD-CDMA (Time Division CDMA) also referred to as International mobile Telecommunication 2000 (IMT-2000) (Asif et al 2012:4). The evolution in 3G is the introduction of High Speed Packet Access (HSPA) in Radio Access Network (RAN) with option of High Speed Downlink Access (HSDPA) and High Speed Uplink Packet Access (HSUPA) also called 3.5G. The Fourth Generation (4G) and the fifth generation (5G) the focus of this thesis will be treated in two separate sub headings. **Figure 1** shows the summary of the evolution of mobile wireless communication (original idea of **Figure 1** is from Osseiran et al 2012:5 but has been updated).



1 G	2 G	2.5 G	3 G	3.5 G	3.75 G	4 G	5 G
AMPS CDPD C-Netz NMT TACS FDMA 25-30 KHZ	GSM IS-95A IS-136 PDC FDMA/ TDMA 200 KHz	GPRS HSCSD IS-95B FDMA/ TDMA 200 KHz	EDGE CDMA200 0 TDCDMA WCDMA IEEE 802- 16e (WiMAX) 5 MHz	CDMA 1xEV-DO CDMA 1XEV-DV HSDPA HSPA+ 5 MHz	LTE OFDMA 1.4-20 MHz 100 MHz	LTE-A IEEE 802.16m OFDMA 1.4-20 MHz 100 MHz	MMW OFDMA? 600 MHz
1981	1990	2000	2001	2006	2010	2015	2020

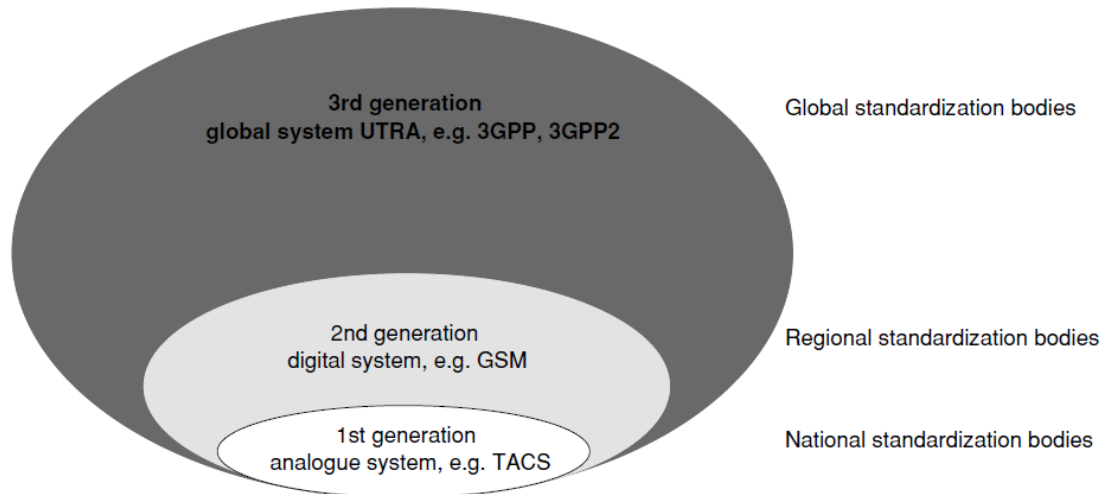
**Figure 1.** Evolution of Wireless Mobile Communication System.

### 1.2 Third Generation Partnership Project (3GPP)

First generation systems were regulated by national authorities or group of countries like in the case of NMT. Regional approach was adopted for second generation and also for third generation before the advent of the global standardization body called 3GPP which is made up of all the regional bodies. In the same way evolution occurred in wireless mobile communication technology, there was a need to have a harmonized global standard that will ensure global equipment compatibility required a single standardization organization; this gave rise to Third Generation Partnership project (3GPP). 3GPP is divided into five Technical Specification Groups (TSGs); TSG CN (core networks), TSG GERAN (GSM/EDGE radio access network), TSG RAN (radio access network), TSG SA (services and systems) and TSG T (terminals) with TSG CN for Network Standardization the most important group for UMTS system design (Tanner & Woodard 2004:10).

The 3GPP are made up of the following standardization regional organizations ARIB (Association of Radio Industries and Business), ATIS (Automatic Terminal Information Services), CCSA (China Communications Standards Association), ETSI (European Telecommunications Standard Institute), TTA (Telecommunications Technology Association, Korea) and TTC (Telecommunication Technology Commission, Japan) The

GSM Association, the UMTS Forum, the Global Mobile Suppliers Association, the IPv6 Forum and the Universal Wireless Communications Consortium are the representation of market partners (Toskala 2010:67). **Figure 2** summarizes the evolution of the standardization of the wireless mobile communication.



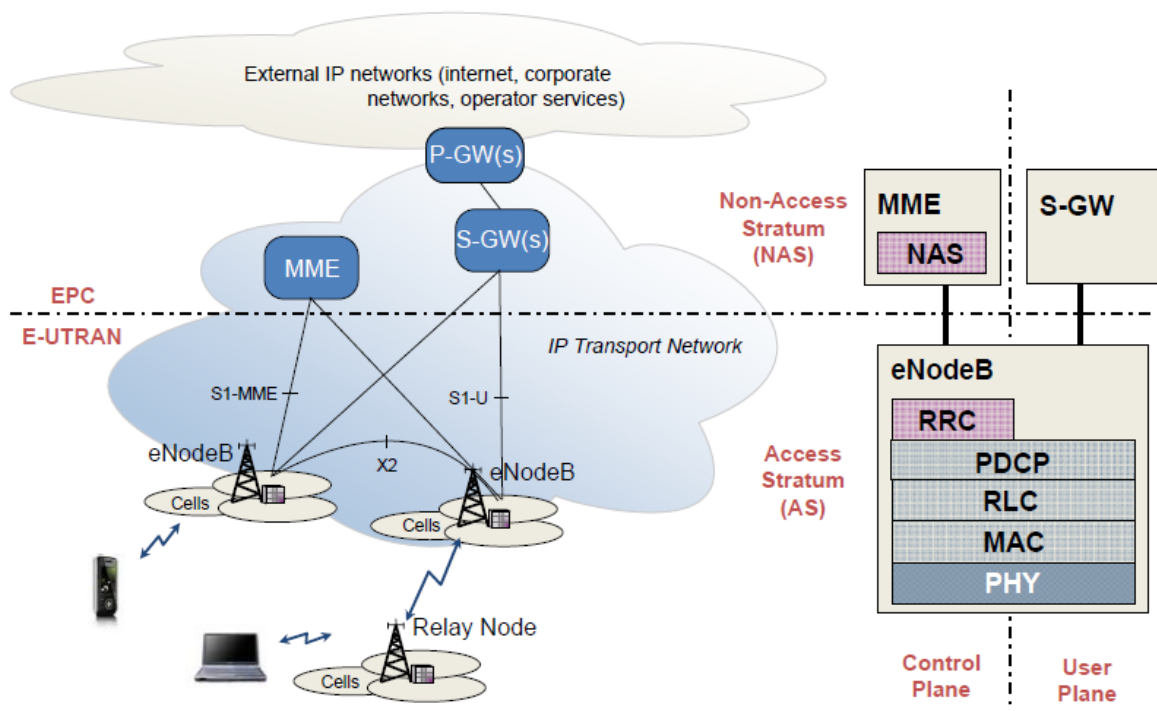
**Figure 2.**Standardization evolution of mobile wireless communication system (Tanner, Woodard 2004:10).

### 1.3 Long Term Evolution (4G)

The dynamic and ever increasing demand for high data rate and data on the move led to introduction of broadband access technology referred to as Long Term Evolution in 3GPP release 8 in December 2008 to support or surpass the user demand. This is a Radio Access Network (RAN) of the Evolved Packet Core (EPS) (Abd-Elhamid, Najah & Hossain 2012:129). The System Architecture Evolution (SAE) in **Figure 3** is all IP-based system that ensures security, good Quality of Service (QoS) and revenue to the operator.

The components of the SAE are eNodeBs (eNBs) that combines some of the functions of the RNC (Radio Network Controller) in 3G, Mobility Management Entity (MMEs) which manages control plane signaling, Serving Gateways (S-GW) and Packet Gateways (P-GW) for user-plane data handling. eNBs are linked through the X2 interface while the linkage to

components of the network core is through S1 interface. The protocol stack in the right side of **Figure 3** shows each network entity with its corresponding protocol stack. Radio Resource Control (RRC) is a layer 3 protocol, while Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence protocol (PDCP) are layer 2 protocol and Physical layer is layer 1 protocol at eNB. The Access Stratum is located in eNBs and Non-Access Stratum (NAS) managed by various components in the core are the two major boundaries of the LTE SAE. This flat structure sometimes referred to as “functional split” enhances the performance of LTE cellular network.



**Figure 3.** LTE System Architecture Evolution (Lindstrom 2009: 5)

### 1.3.1 Home eNBs (Femtocells)

Femtocells are small indoor cells with coverage radius of about 10 meters which can sometimes be used interchangeably to mean Home eNode-B (Kolding, Schwarzbauer,

Pekonen, Drazynski, Gora, Pakulski, Pisowacki, Holma&Toskala 2010: 516). The HeNBs are customer premise equipment (CPE) used to boost capacity in homes or offices and can be classified as closed, open or hybrid. HeNB is closed when access is permitted for only Close Subscriber Group (CSG), Open if accessible to all EUTRAN UE users referred to as Open Subscriber Group (OSG), and hybrid when it has CGS but can still be accessed by any UE if there is a sufficient resource for the visitor. It has almost the same functionality with a regular eNBs with extra task of Serving HeNB gateway discovery and access control.

### 1.3.2 Key Features of LTE

**Spectrum and Carrier Aggregation (CA)**-The basic data requirement for low-mobility and high-mobility is 1Gbps and 100Mbps respectively (Afif et al 2012:7). CA is a mechanism to increase LTE operating bandwidth beyond 20MHz which can be contiguous or non-contiguous allocations. The carrier bandwidth is constant at 20 MHz while bigger bandwidths are aggregated by the required number of 20 MHz or less carriers depending on the demand (Toskala & Holma 2010: 492). This is a great capacity enhancement considering the fact that operators have only 20 MHz on a given frequency band.

**Multiple Inputs Multiple Outputs (MIMO)**-Multiple antenna elements are utilized both at transmit and receive end to exploit the multipath effect of the signals to increase reliability and increase data rate.

**Orthogonal Frequency Division Multiple Access (OFDMA)**-This is using narrow band orthogonal sub-carriers; 15 kHz is common in LTE for transmission of a wide band carrier. The distinct sub-carriers preserve orthogonality since all other sub-carriers have zero value at sampling instant of a single sub-carrier (Toskala et al 2010:471).

**Relaying**-Relay nodes are used to boost coverage and capacity especially in cell ages. The relays are strictly under the management of another eNB and therefore have in-bound or out-bound backhaul connection to a normal eNBs (donor cell) but no direct connection to the EPC.

**Coordinated Multipoint transmission or reception (CoMP)** - This is the dynamic control of transmission and/or reception of multiple antennas located in a different geographically separated area. It is a very good tool to mitigate Inter-Cell Interference (ICI) which deteriorates the performance of users in cell-edge locations.

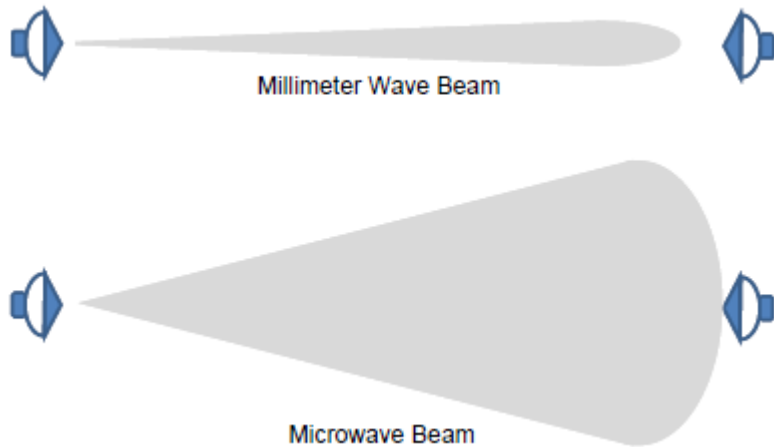
#### 1.4 Fifth Generation Networks-5G (Millimeter-wave)

The fifth generation network is being researched and proposed as a solution to scarcity challenge or over crowdedness of the current microwave frequency spectrum that been the main stay of terrestrial wireless network system that hitherto hinders the current wireless communication in meeting the large bandwidth demand for ever evolving smarter devices. There are set of free frequency spectrums (about tens of GHz) with bandwidth up to 600MHz assumed until recently to be inadequate for mobile communications due to unfavorable propagation characteristics like rain attenuation, atmospheric absorptions, substantial pathloss and low diffractions (Andrews, Buzzi, Choi, Hanly, Lozano, Soong and Zhang 2014:1065). This new set of frequency spectrum from 30GHz to 300GHz with a wavelength of one to ten millimeter being proposed is referred to as millimeter wave. The spectrums close to 38, 60,70,90 and 94GHz are considered to be in the family of millimeter wave from a mobile wireless communication perspective (Adhikari 2008: 2). The key features that will result in the expected 5G advancement are maximum base station denseness, millimeter wave, massive Multiple-Input Multiple-Output and robust interference management. The parameters that will require improvement from the current 4G to meet the specification of the future will be overall system capacity (an improvement of 1000 x of current 4G), latency (enhancement from 15ms in 4G round-trip latency to 1ms for 5G), energy efficiency of the base stations will be expected to reduce since the base station density is expected to increase and reduction in cost of the service will be as much important to equipment vendors, network operators and end users as the increase in bandwidth/data rate (Andrews et al 2014:1067). It is expected that network will progressively become more heterogeneous towards 5G evolution and the major challenge will be the integration of different Radio Access Technologies (RATs) like device-to-

device communications (D2D, Wi-Fi, 4G and 3G respectively). Additional complexity is introduced when the optimal associations of the multiple RATs operating at diverse frequencies and protocols have to be considered. The expected rise in BS denseness and heterogeneousness will be at detriment of mobility support, therefore new handoff methods or novel solution have to be introduced especially with millimeter waves communications (opportunistic handoff). The major drawback of millimeter-wave is huge power utilization of the electronics components .i.e. analog-to-digital converters (ADCs) and digital-analog converters (DACs). A novel semi-conductor technology will be needed to overcome this challenge. There are currently no written 5G standards but the following benchmark has been well-established through a rigorous industrial research:

- Less than one millisecond latency.
- 1Gbps minimum downlink data rate capability.
- More energy efficient when compared to 3G and 4G systems.

It is not yet evident weather there will be a standardization/regulation body like 3GPP for 5G but various regional activities like European Union project METIS, ITU working group, and ETSI future mobile submit held in November 2013 have started the process with studies of the essential permissive technologies. Rigorous studies on millimeter wave technology have also been done by technology advisory council of federal communications committee (FCC) in USA in the last few years. 3GPP have not officially started 5G standardization but Rel-14 or Rel-15 due in 2016-2017 is expected to contain some of these standards since Rel-12 already incorporated massive MIMO one of the main features of 5G technology(Andrews et al.,2014:1076). A radiation pattern comparison of Microwave and Millimeter-wave is shown on **Figure 4**.



**Figure 4.** Millimeter and Microwave Radiation Pattern (Adhikari 2008:4).

#### 1.4.1 Anticipated Interference Management Challenges in 5G Networks.

The fundamental test for interference management in 5G multi-tier networks will be as a result of the following deductions (Hossain, Rasti, Tabassum & Abdelnasser., 2014:118)

- Access restriction due to Close User Groups (CUG) might advance to varied level of interference.
- Expected denseness in BS deployment and heterogeneity will introduce its fair share of interference.
- Coverage holes and traffic inequality as a result of diverse transmit power of BS in the downlink.
- Resource assignment methods and channel accessing preferences of distinct frequencies will contribute to interference.

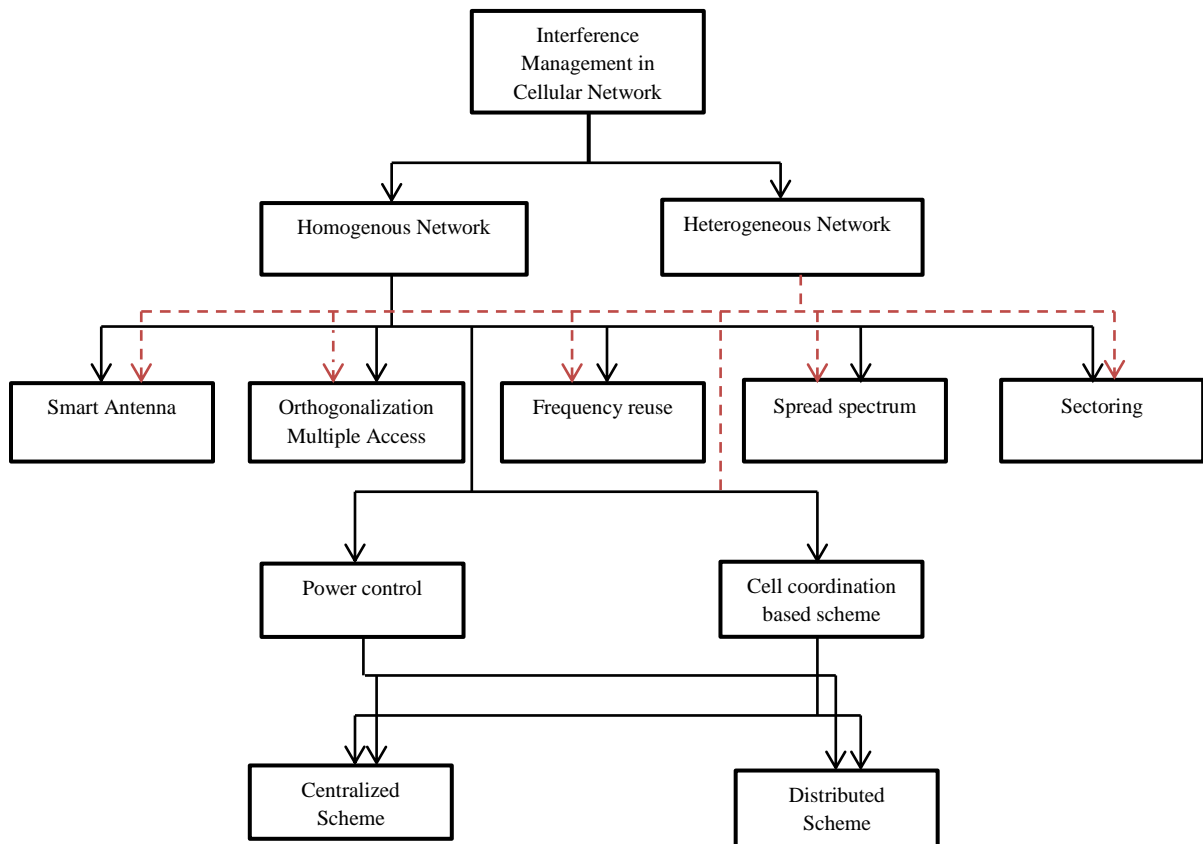
#### 1.5 Interference Management in cellular Network

Cellular network model are interference limited by design as a result of area of coverage/capacity analysis and cell planning. Interference in a cellular mobile network can broadly be categorized into homogenous and heterogeneous as applicable to 4<sup>th</sup> generation and 5<sup>th</sup> generation network, but in this thesis, the focus will be in homogenous networks.

The interference can result from other users (self-cell interference), or from other cells in a sectorial based cellular network (other cell interference) or from spatial multiplexing in case of MIMO based cellular network (co-antenna interference). Self-cell interference can be solved by ensuring orthogonality between users with the help of scheme like OFDMA or Walsh code in CDMA. Ensuring adequate antenna spacing will eliminate the co-antenna interference. Other cell interference in a MIMO cellular network system will be the main focus of this thesis and will be the focal point of the rest of the discussion in this work.

There are  $NM_T$  interference signals in a downlink MIMO cellular system where  $N$  is the significant neighboring base station and  $M_T$  is the number of transmit antennas (Andrew et al 2007:2). It has been established in literatures that there is no additional rise in the interference power due to the fact that transmit power is reduced by  $1/M_T$  in MIMO systems but the number of interfering signals grows with the number of surrounding base stations as mentioned earlier. The implication of increase in the number of interfering signals is that more antennas will be required at the receiver to fully repress OCI with linear receivers ( $M_R \geq M_T$ ) or  $M_R \geq (N + 1)M_T$  for interference dominated MIMO systems. The number of transmit antenna  $M_T$  in a cellular network is expected to be greater than the number of receiver antennas  $M_R$  in the downlink as a result of processing power, space and cost limit of the mobile terminal. Therefore, the solution is not to fully overcome OCI with spatial signal processing but to regard it as noise. If the interfering signal sources grow large as is the case of Massive MIMO, it can evolve to Gaussian with the help of central limit theorem (Andrews et al 2007:3). **Figure 5** is a summary of different interference management techniques in a mobile cellular network.





**Figure 5.** Interference management methods in Cellular Network

### 1.6 Motivation

Long Term Evolution network is gradually being introduced into most of the world market with attendant increase in data throughput, interference is sometime the cost associated with capacity increase to system designer and researchers. This is mainly as a result of limited spectrum of LTE which makes most of the operators to deploy single frequency in order to maximize system capacity. Even though single frequency is spectral efficient but it also has a high probability of interference to the network. In the last few years, there has been a shift from interference mitigation to interference management. The shift occurred

when researchers, system designers and Engineers found out that interference in itself can be exploited to the network advantage. My interest in interference management came from seeing the negative effect of interference first hand in a life network from my previous work experience in operator/vendor network environment (2G&3G) and then radio resource management course gave me the idea that is possible to improve or enhance the interference for the good of the network. These reasons prompted the choice of INTERFERENCE MANAGEMENT IN LTE AND BEYOND as thesis topic

### 1.7 Thesis Structure

The thesis is organized in six chapters, chapter one deals with evolution of wireless mobile networks from first generation to the emerging fifth generation, motivation, contribution of the thesis and chapter organization. Chapter two is review of some previous works on different interference management techniques employed in mobile wireless cellular network. Introduction of Interference channels, different interference management methods and 3GPP interference management defined standards is in Chapter 3. The fourth chapter is a comprehensive analysis of Space-Time Wireless Communications (MIMO) system that will be the enabler for 4G and 5G systems. System model and simulation based on MIMO systems expected to be a common denominator in 4G and beyond is in chapter five which involves discussion on interference management method adopted in this research. The main contribution of this thesis is in chapter five that analyzes of the outcome of the simulation and the result. Conclusion, suggestions for future work and recommendation based on the result obtained is in chapter six.

## 2. RELATED WORK IN INTERFERENCE MANAGEMENT IN LTE

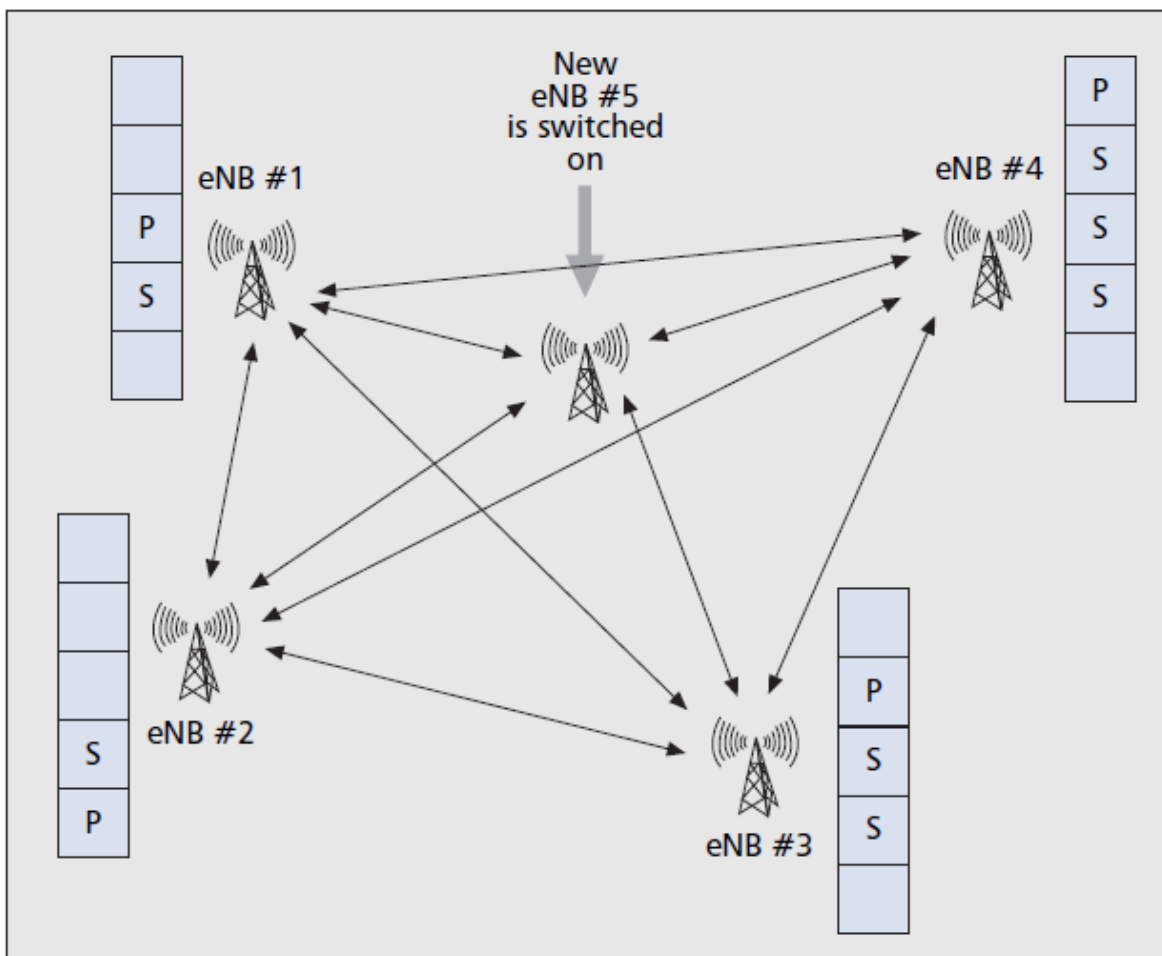
A search for “Interference Management in LTE” in IEEEXPLORE IEEE (Institute of Electrical and Electronics Engineers) data base on 3<sup>rd</sup> June 2014 produced 698 hits showing massive research work already carried out in managing interference in LTE. Some selected papers from IEEE were reviewed to gain understanding of previous work done in various aspect of Interference management in wireless mobile network, identify gap in research or to apply the concept in LTE and future generation of wireless mobile networks. The criteria for selection of the reviewed papers are based on the date of publication and the need to analyses as many different interference management techniques as possible.

### 2.1 Autonomous Component Carrier Selection

Interference Management In Local Area Environments for LTE-Advanced (Garcia, Pedersen & Mogensen 2009:110), proposed the use of Primary Component Carrier (PCC) and Secondary Component Carrier (SCC) as a method of managing interference in an LTE system. This method uses distributed and expandable system in the selection of primary and secondary carriers done locally by each cell. The advantage of the concept according to them is that there will be no need for a network wise centralized control. Their assumption is that each eNB always has one active component carrier referred to as primary component carrier and this PCC is selected naturally when the base station is first switched on. The PCC also provide full coverage to all the terminals under its coverage. An additional carrier called Secondary Component Carrier (SCC) is further proposed since it is anticipated that PCC may not be the optimal solution to all the offered traffic for cell edge users and mutual interference coupling with the neighbor cells. They further assumed that all the component cells not selected are not used by the cells, totally muted for both uplink and down link. The scheme is summarized in **Figure 6**.

The proposal is based on three Major hypotheses:

- Unconditional preference of primary over secondary component carriers; restraint on PCC re-selection while SCC can be reselected swiftly.
- Allocation of SCC to enhance cell capacity by the eNB if there is additional bandwidth requirement for the offered traffic.
- Request for additional SCCs by eNB will only be accommodated provided unreasonable interference to the neighbor cells.

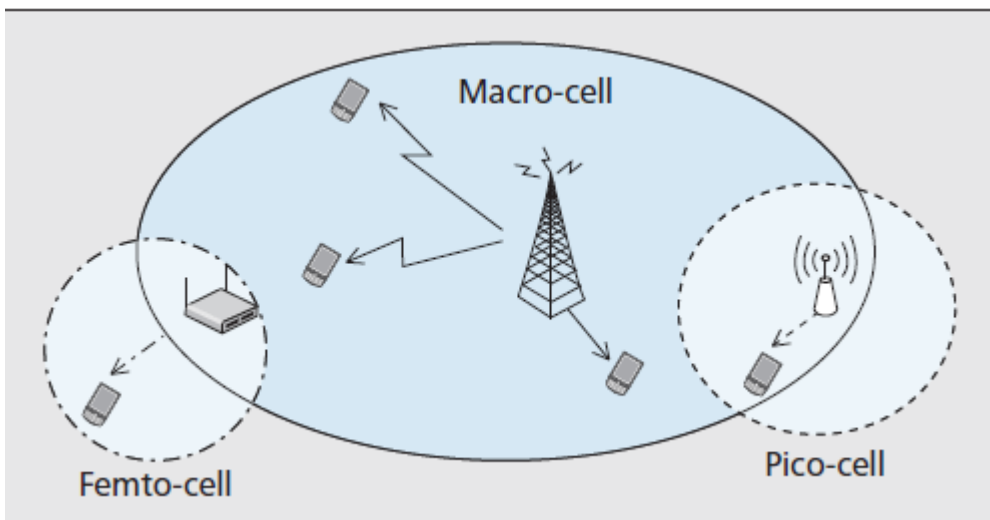


**Figure 6.** Autonomous component carrier selection Scheme (Garcia et al 2009:112)

They concluded that the proposed concept delivers expandable and adaptable frequency reuse mechanism which permits uncoordinated eNB deployment without extensive network planning. The result is significant in their opinion because this will take care of interference management in large-scale deployment of low power eNBs scenarios.

## 2.2 Interference Management in LTE Wireless Network

(Yang, Bell Laboratories and Alcatel-Lucent 2012: 8) discussed the industrial perspective in managing interference in LTE networks. Yang et al argued that even though single frequency design of the LTE has introduced higher system capacity but this capacity can be limited by Inter-Cell Interference (ICI) from other cells might result to SINR of cell-edge users to be degraded if has not been properly managed. The problem can be complicated for densely populated area like stadium, airport, shopping malls and office building where large deployment of small/ pico / femtocell LTE cells is expected with serious ICI effects. The interference management complexity is further compounded with heterogeneous LTE network where pico / femtocell are deployed within macro-cell network coverage to improve capacity (throughput) and to eliminate the coverage holes as depicted in **Figure 7**.



**Figure 7.** Heterogeneous wireless network (Yang et al 2012:8)

They proposed Fractional Frequency Reuse (FFR) and Coordinated Multi-Point (CoMP) as efficient way to ICI mitigation.

- FFR can be classified as Static FFR and Dynamic FFR. Static FFR can be further be categorized into soft and hard FFR methods. The hard FFR approach splits the available bandwidth into short non-overlapping frequency sub-carriers. Cell-edge and cell-center user are assigned different sub-carriers with the major drawback of spectrum under-utilization. While soft FFR permits the use of the same frequency for both cell-edge/cell-center users for transmission at reduced power level. Dynamic FFR accounts for channel/traffic conditions of each cell to optimize the system capacity. Combinations of scheduling algorithms and dynamic FFR have been found to produce higher rate gain according to Yang et al. The cost of dynamic FFR is extra control channel overhead due to large number of information transaction between the neighbor base stations.
- CoMP is a transmission/reception technique using multiple antennas that are appropriately located in such a way as to reduce or eliminate ICI (Yang et al 2012). Real time information must be exchanged through X2 interface among all the transmitting nodes to achieve this coordinated transmission. The CoMP can be categorized into Coordinated Beamforming ( User Equipment receives information from only one BS and neighboring base stations uses the beamforming/precoding procedure to cancel interference) and Joint Processing (User Equipment can receive information from multiple base stations). They found out that CoMP can improve the cell-edge user experience with extra overhead cost but the implementation is complicated as the number of base stations in the joint transmission increase.

They concluded that proper implementation of FFR and CoMP can significantly improve or eliminate the inter-cell interference (ICI) at additional overhead cost.

### 2.3 Inter-Cell Interference Coordination for LTE Systems

(Lee, Li and Tang 2012:4828) made important observation that some of the mobile terminal may not profit fully from MIMO scheme because they are incapable of multiple antenna support. Alternatively, network performance and data rate can be improved with inter-cell interference coordination (ICIC) methods. They further affirmed that some of the ICIC methods do not require any modification in mobile terminal or User Equipment. The paper developed a soft frequency reuse (SFR) algorithm, new ICIC method that considers fairness and throughput. SFR is a method of splitting the system spectrum into Cell Edge Band (CEB) and Cell Center Band (CCB). Users with substantial interference effect are categorized as Cell Edge Users (CEUs) while the remnants are referred to as Cell Center Users (CCUs).

#### Proposed SFR Algorithm

1. Collection of Reference Signal Received Power (RSRP) parameters from every user  $P_{j,i}^{(l)}$  : Received signal power for cell  $i$  from UE  $j$  in cell  $l$
2. Classification of User Equipment (UE) using the network set up power gain parameters  $\gamma_i$  &  $\beta_i$  : Relative power (boost or attenuation) gains for CCB and CEB.
3. “ Scheduling the CEUs in the CEB and the CCUs in the CCB using proportional fairness (PF) scheduler for each scheduling duration;”
4. Step 3 is repeated unless there is a significant change RSRP from any of the user or user related with the given cell has changed; alternatively return to step 2.

The UEs are categorized either as CEUs or CCUs based on the value of SINR using Equation (2.1) and dynamic packet scheduling.

$$S_i^{\text{CCU}} = \{j: \text{SINR}_j \geq P_{th}, j \in S_i\}, \quad (2.1)$$

$$S_i^{\text{CEU}} = \{j: \text{SINR}_j \leq P_{th}, j \in S_i\},$$

Where  $P_{th}$  is the SINR threshold.

It will be good to point out that they did not consider the distribution of the users in this algorithm even though they suggested the performance will be enhanced if considered.

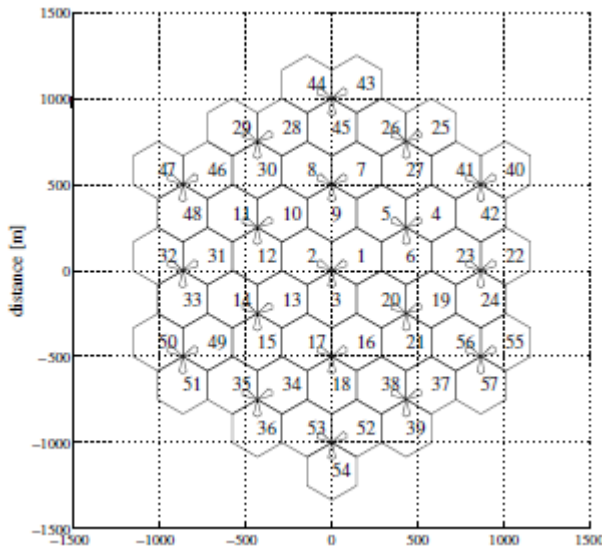
#### Proposed UE Classification algorithm

The projected algorithm for UE categorization to accomplish a good bargain between fairness and throughput represented by:

$$\{S_i^{CEU}, S_i^{CCU}\} = \operatorname{argmax}_{S_i^{CEU}, S_i^{CCU}} \frac{1}{\sum_{j \in S_i^{(i)}} \frac{1}{R_j^{(i)}}} \quad (2.2)$$

The algorithm will select UE in such a way to enhance the user with lowest throughput and considers comprehensive throughput of all the users into consideration.

ITU-R sector recommendation for IMT-Advanced technology evaluation and the LTE systems specifications formed the basis for their simulation. The three sectored cell antenna orientation used in simulation is show in **Figure 8** below.



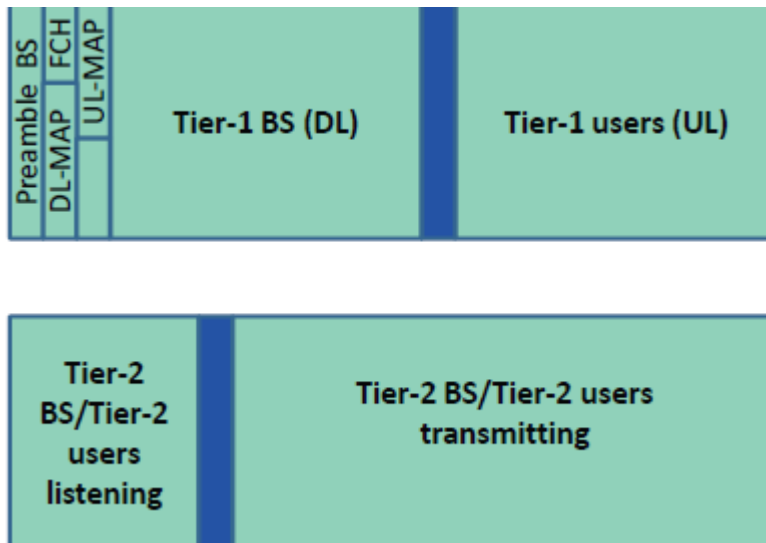
**Figure 8.** Cellular layout, antenna orientation, and configuration for Simulation (Lee et al 2012:4831)



The conclusion from their simulation is that the performance of Soft Frequency Reuse inter-cell interference coordination is dependent on the user categorization methods used. This proposed algorithm for SFR and user categorization has enhanced the cell edge throughput considerably and at the same time reduced the deterioration of the cell average throughput.

#### 2.4 Massive MIMO and Inter-Tier Interference Coordination

In this paper by (Adhikary, Safadi and Caire 2014), they divided the network into tier-1 and tier-2 according to **Figure 9**.



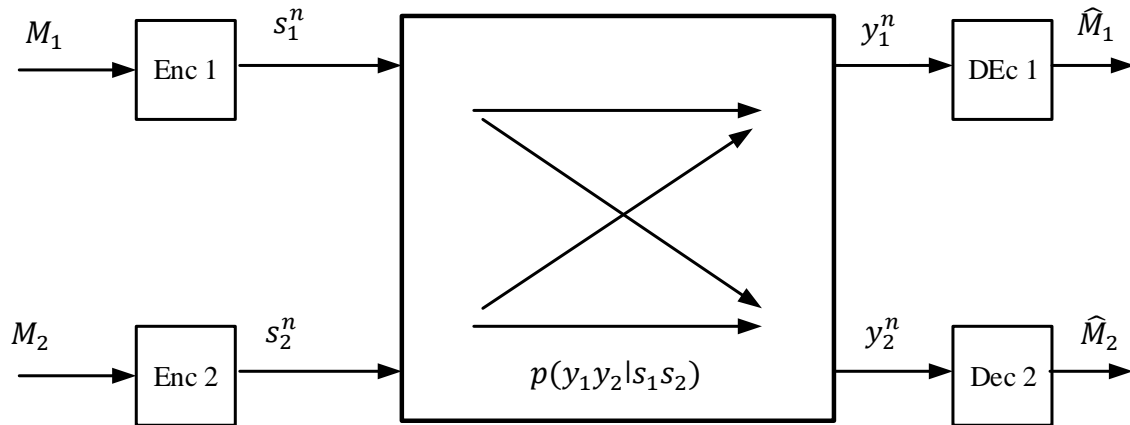
**Figure 9.** Frame structure of Tier-1 and Tier-2 network (Adhikary et al 2014:1)

The target of the scheme is to provide tier-1 base station (BS) with huge number of antennas (massive MIMO). The Channel can be modeled as Gaussian random vectors with limited number of main eigenmodes since tier-1 BS is usually mounted on a tower or roof top with possibility of covering its own users and tier-2 users under an approximately narrow angular spread. The inter-tier interference is alleviated by orthogonal transmission of the main eigenmodes of the channel vector from tier-1 BS to subgroup of selected tier-2 cells. Compared to eICIC, tier-2 throughput can be increased without meaningful reduction in tier-1 throughput.

The system model comprises of a macro cell (tier-1) of sole BS with  $M$  antennas and consisting of  $F$  tier-2 small cells with each one containing  $L$  antennas. The access method is OFDM/TDMA for both uplink and downlink while it operates in Time Division Duplexing (TDD). **Figure 9** represents the frame structure which includes control channel, tier-1 uplink/downlink subframes and a narrow guard channel.

### 3. INTERFERENCE CHANNELS

Interference is the resultant effect of a cellular system that re-uses the same carrier frequency or uses the same frequency in multiple antennas in a geographical location. The interference impacts on the system data rate, causes outage and reduces the cell edge user experience. An interference channel is a channel with multiple pairs of transmitter-receiver system with the possibility of a communication between one pair of transmitter-receiver interfering with another transmitter-receiver pair (Carleial 1978). In wireless communication systems, electromagnetic spectrum (frequency) is a scarce resources therefore  $M$  number of transmitter-receiver pair may simultaneously use a frequency set that is not completely isolated. Any communication channels shared as described above is referred to as *interference channel*. The discrete memory less interference channel model is shown in **Figure 10** for a  $2 \times 2$  input and output system.



**Figure 10.** Discrete interference channel model (Xu et al.2010:2)

Where  $M_1, M_2$  represent number of users, Enc/Dec represent encoders and decoders,  $s_1^n, s_2^n, y_1^n, y_2^n$  represents input and output streams.

An  $M$  interference channel have  $M(M-1)$  interfering links and only  $M$  communication capacity (rate) (Carleial 1978).

### 3.1 Gaussian Interference Channel

Additive-white-Gaussian-noise (AWGN) otherwise called Gaussian Interference channel is a simplified linear set of input and output of real numbers represented by the following formula.

$$Y = Hs + N \quad (3.1)$$

Or by the matrix

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_M \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} & \dots & h_{M1} \\ h_{12} & h_{22} & \dots & h_{M2} \\ h_{1M} & h_{2M} & \dots & h_{MM} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_M \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \\ N_M \end{bmatrix} \quad (3.2)$$

Where  $h_{ij}$  the signal transmissions coefficients of the given channel,  $N_M$  is the zero-mean Gaussian random variable noise term,  $s_M$  &  $Y_M$  are the input and output signal vectors.

### 3.2 Interference Management in Wireless Network

Interference management in a cellular network can be classified into two major groups, i.e. homogeneous interference management as depicted in **Figure 11** and heterogeneous interference management as in **Figure 7**. In this thesis, the discussion on interference management will be limited to homogeneous networks since heterogeneous network needs a better understanding of homogenous first and also is by far more challenging to predict for the next generation of mobile wireless networks. Inter-cell and intra-cell interference are the two major type of interference suffered by a wireless mobile communication network. Intra-cell interference results from power leakage from one channel to its adjacent channel/adjacency of the frequencies while inter-cell interference results from interference between same frequency used in different cells (Hamza, Khalifa, Hamza & Elsayed 2013: 1).

Interference management can sometimes be broadly categorized into *avoidance* and *mitigation* techniques. Mitigation techniques are used to alleviate the effect of interference during transmission or reception of the signal. The interference mitigation methods are interference randomization, interference cancellation and adaptive beamforming as listed and discussed in Chapter 1. Interference avoidance techniques are basically frequency

reuse planning algorithms discussed in Chapter 3 and summarized in **Figure 13**. Frequency re-use is frequency and time domain assignment of radio resources to the network elements in order to increase SINR so as to support as many users as possible. The essential concept of the frequency reuse algorithm is to classify cells into regions (cell edge users and center cell users) and to make sure that the maximum allowed power in eNB's are not exceeded.

Management of Interference in a mobile wireless network can also be implemented using the methods listed below;

- (A) Inter-Cell Interference Coordination (ICIC)
- (B) Interference Alignment (IA)
- (C) Multiple Input Multiple Output (MIMO)

### 3.2.1 Inter-Cell Interference

Inter-cell interference affects system performance in the uplink when base station receives power from user equipment not attached to it or in the downlink by user equipment receiving power from base station not assigned to it (Freitas, Silva & Cavalcante 2011:23).

Cell planning and handoff are the tools used to manage inter-cell interference in a traditional cellular system deployment (Li, Wu & Laroia 2013:196). Cell planning involves locating the base stations in a hexagonal grids while taking into account the environmental and terrain characteristics of the area that will affect the behavior of such cells. A reassignment of a user from one cell to another as it moves across cell boundaries and ensuring that it connects to the best base station (in terms of SINR) normally referred to as "best connection" is known as handoff. Frequency reuse was later introduced when it was discovered that the two methods described above is inadequate in managing inter-cell interference. The available spectrum is split into non-overlapping narrowband frequency channels.

The capacity (rate) in a system without interference is

$$C = B \log_2 \left[ 1 + \frac{P}{\sigma^2 + \alpha P} \right] \quad (3.3)$$

$\sigma^2 \gg \alpha P$  – Noise Limited

$\sigma^2 \ll \alpha P$  - Interference limited

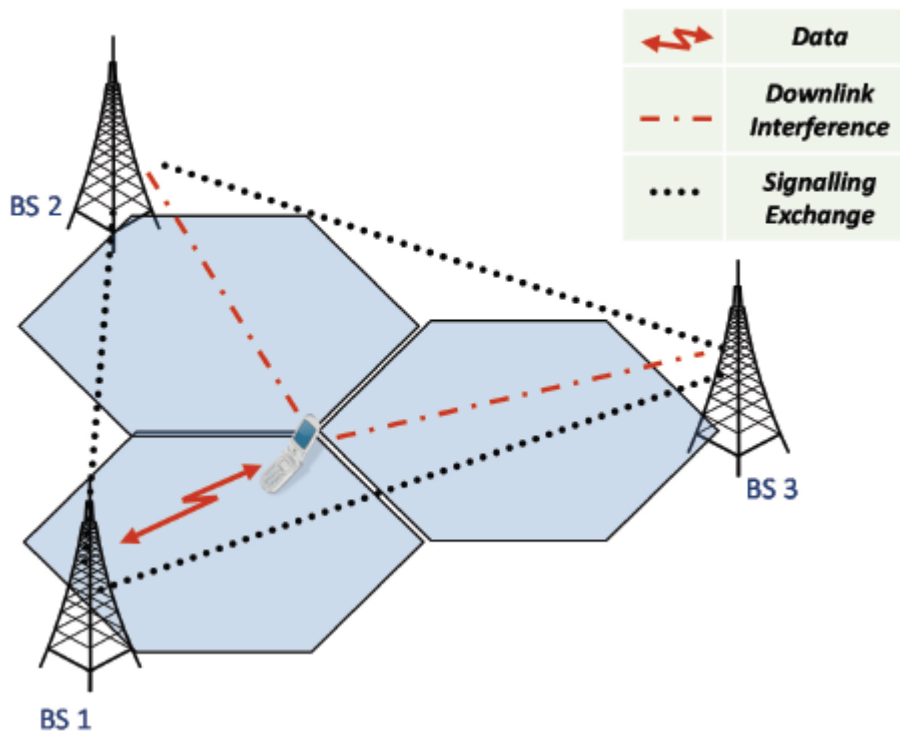
The possible ways to handle or alleviate interference are;

- To let  $\alpha$  remain unchanged.
- Alleviate interference by reducing  $\alpha$ .
- Eradicate interference by making  $\alpha = 0$

Time Division Multiple Access and Code Division Multiple Access systems are interference free with elaborate frequency planning and interference averaging in a spread spectrum respectively. Orthogonal Frequency Division Multiple Access System can experience co-channel interference at cell boundaries but can be interference free if the symbols are properly orthogonalized or accurate resource allocation. Inter-Cell interference is a challenge in LTE system hence the need for robust Inter-Cell Mitigation technique as discussed below.

The major challenge of LTE deployment is interference caused by the activity of the neighboring base station which can degrade the achievable target of a close User Equipment (Pateromichelakis, Shariat, Quddus & Tafazolli 2013). This scenario can be best described by **Figure 11** and occurs as a result of attenuation from the serving base station and interfering neighboring cells.

Any of the following Radio Resource Management (RRM) can be employed to handle the Inter-Cell Interference in a wireless network.



**Figure 11.** Downlink ICI (Pateromichelakis et al 2013:1)

- **Interference Averaging:** getting a predictable interference statics using spread spectrum in a wide bandwidth scenario like in CDMA.
- **Scheduling:** Careful allocation of time/frequency channels on neighboring cells to alleviate interference. Coordinated frequency reuse across base stations in the network.
- **Multuser Detection:** This is the method of detecting the desired and interfering signals to a user at the same time.
- **Power Control:** This involves reducing the transmit power of all the users to meet the minimum SINR target for all the users.
- **Handoff/Handover:** Concurrent communication of a user to two or more base stations to determine the best signal with minimum interference

The 3<sup>rd</sup> Generation Partnership Project (3GPP) has developed the following standards for Inter-Cell Interference Mitigation Approaches.

Inter-cell interference coordination method;

- Fractional, soft and flexible frequency reuse

- Dynamic Channel assignment

#### Inter-cell Interference randomization method

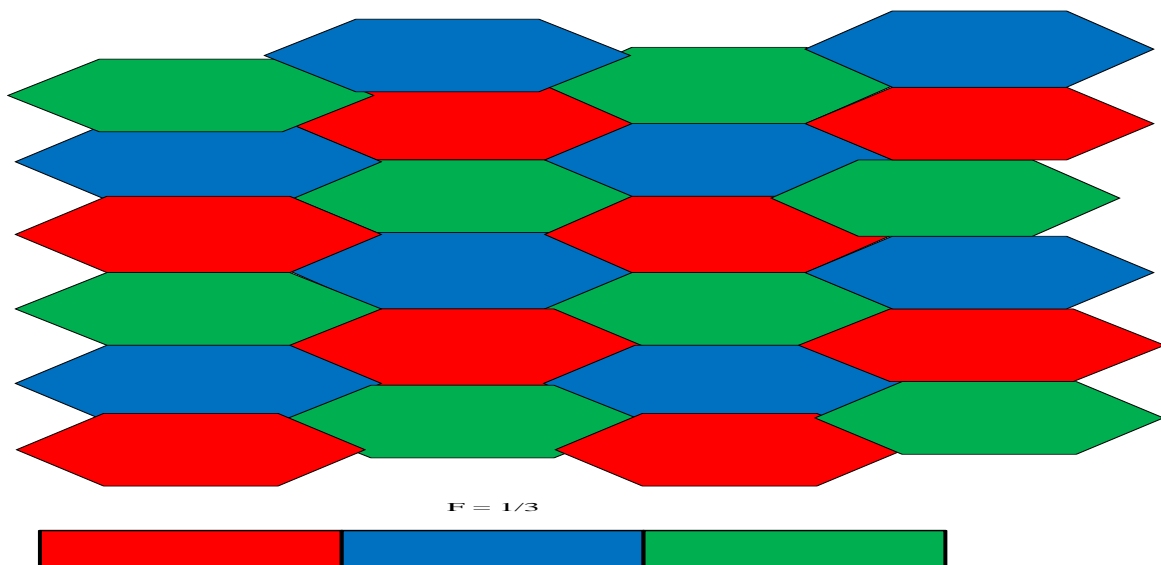
- Cell-specific scrambling
- Cell-specific interleaving
- Frequency-hopping
- Random subcarrier assignment

#### Inter-cell interference cancellation technique

- Interference rejection combining
- Interleaving division multiple access (IDMA)

#### 3.2.1.0 Frequency Reuse

The allocated spectrum is divided into non-overlapping narrowband frequency channel  $F$  (frequency reuse factor); every base station is assigned  $1/F$  of the channels in such a way that the spectrum is reused in each  $F$  cells that observes the frequency reuse distance.  $1/F$  is an indication of the rate and efficient use of allocated spectrum in a cellular system. The inter-cell interference can be alleviated by decreasing frequency reuse across base stations which in turn lowers the available bandwidth per cell of the cellular system.



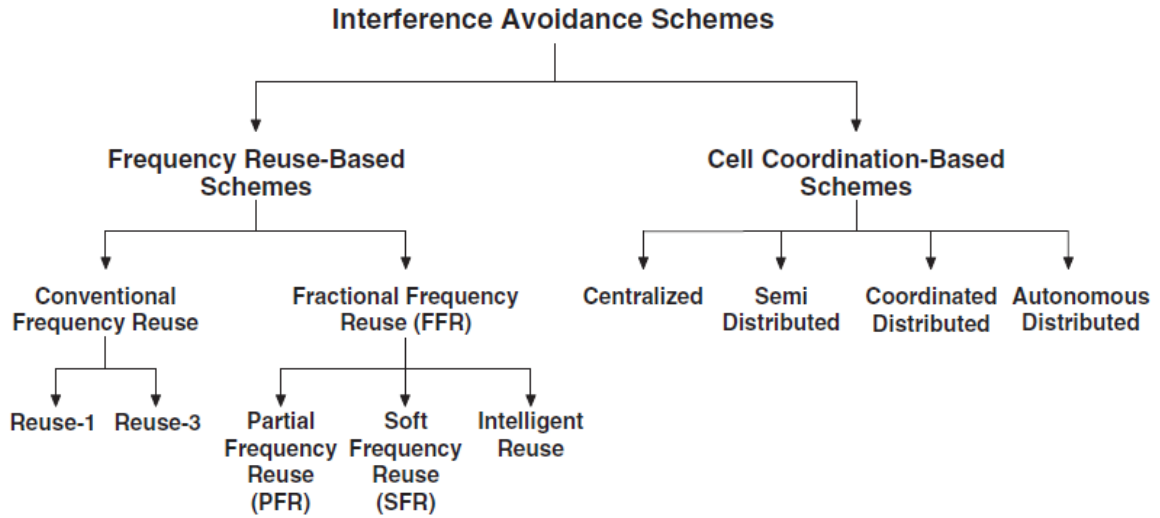
**Figure 12.** Frequency reuse pattern in a narrowband system with reuse factor of 3.



It was assumed from narrowband frequency reuse background that  $F > 1$  until the introduction of wideband CDMA with  $F=1$  with resultant higher capacity. In a spread spectrum, the signal is spread to the whole spectrum using a code. This universal frequency reuse leads to substantial interference but the interference is resolved by interference averaging (decreases interference variation in such a way that system capacity is only limited by averaging instead of worst-case interference) and frequency diversity of the wideband (limits channel variation due to multipath fading). **Figure 12** illustrates frequency reuse factor of 1 and 3 in a narrowband system.

In a bid to improve the performance of the users at cell edge, different versions of frequency reuse have been proposed;

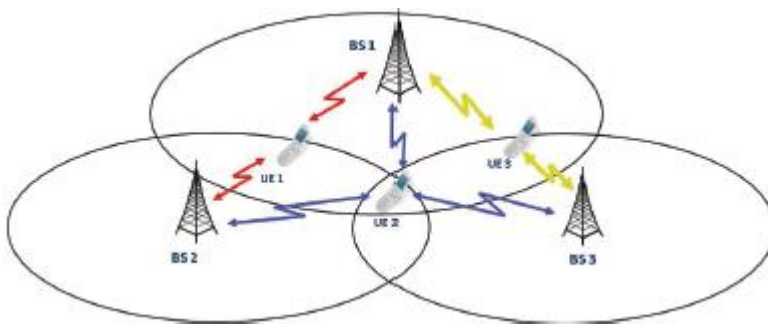
- Fractional Frequency Reuse (FFR) has been recommended in OFDMA to improve user experience at the cell edge. It is the method of splitting the entire spectrum into sub-band so that some of the subcarriers can be assigned at different point of the cell, this subcarrier reuse technique is to assign only a portion of the overall spectrum to every cell such that  $1 < F < 3$ .
- Soft Frequency Reuse (SFR) is further improvement of bandwidth efficiency of FFR through the use of power allocation based on user location. The aim is to allocate higher power to the cell edge users while lower power is allocated to cell center users while ensuring orthogonal cell planning.
- Flexible Fractional Frequency Reuse (FFFR), the entire frequency band is divided into multiple groups and each cell can borrow some of the subcarriers based on traffic requirement. The rented subcarriers can be allocated to the users with superior channel quality with less power requirement which will lead to inter-cell interference reduction. It will require feedback system of the Channel Quality Indicator of the user and resource allocation of the adjacent cells for the purpose of power allocation and resource borrowing.
- Dynamic Channel Allocation (DCA) is a technique of assigning radio resources to network elements based on cell load, traffic distributions and quality of service without prior frequency planning due to unpredictable varying traffic requirement and time-varying channel condition. The major drawback of this scheme is the heavy implementation/computational cost due to high signaling between the respective base stations and the feedback system requirement.



**Figure 13.** Inter-Cell Interference Avoidance Scheme (Hamza et al 2013:2).

### 3.2.1.1 Coordinated Multipoint (CoMP)

Coordinated Multipoint Transmission is targeted to enhance cell edge user performance with minimum system complexity. CoMP is the accepted foundation of coordination and cooperation methods proposed for MIMO-OFDM systems. Soft (inter-site) and softer (intra-site) handover procedures in CDMA might be treated as previous implementation of CoMP (Pateromichelakis et al 2013: 9). The basis of CoMP is that cell-edge user has the capacity to receive signals from different base stations and its performance can be improved if receptions from different cells are well coordinated (See **Figure 14**). The aim of the coordinated transmission is to achieve high data throughput at the cell edge and enhance overall system capacity. Intra-site CoMP is the coordination between different sectors of the same base station while Inter-site CoMP is the coordination among different base stations. The coordination is implemented using multiple antenna units (AUs).



**Figure 14.** Coordinated Multipoint Transmission (Pateromichelakis et al 2013)

The CoMP system architecture can be classified as either centralized or distributed coordination based on the way the coordination is carried out. A central unit is in charge of the management of ICI by centrally handling of all the feedback from the base stations. The backhaul of this architecture is implemented using Fiber optics to resolve latency and overhead cost due to the management of channel state information, signal and scheduling done centrally. S1/X2 interface (which can be Fiber) is used in distributed coordination to exchange cells channel state information and data in entirely meshed network. In this decentralized system, it is desirable to have a master cell that functions as scheduler that controls the resource assignment and retransmission to the slaves in a CoMP cluster.

### 3.2.1.2 Coordinated Beamforming/Scheduling

CB/CS is the component of coordination CoMP structure that supports speedy and stringent coordination using MIMO antenna efficiency through beamforming in a well-coordinated manner. The message data are exclusively accessible in CB/CS within the serving cells but the agreement is dynamically made in the CoMP set, at the end of the coordination the transmitter beam is formulated after the choice of the best serving users based on their geographical position. The beam-to-resources selection regulates the interference to neighboring users at the same time boosting signal strength of the desired users (Pateromichelakis 2013 :11).

### 3.2.1.3 Joint Processing

This is advanced downlink CoMP scheme introduced to accomplish spectral efficiency specification for LTE-A. A CoMP set in joint processing are number of base stations that coordinate to improve the cell-edge performance by jointly processing cell boundary users data as an exclusive entity. Joint processing differs from joint transmission of CoMP in the way the cell-edge user information is processed before transmission. The universal thing between them is the SINR of a terminal can be enhanced due to base station redundancy in sending identical data to the terminal. The data rate for improvement is shown in the equation below (Holma and Toskala 2012 : 211);

$$\text{No CoMP} \quad C = \log_2 \left[ 1 + \frac{S}{N+1} \right] \quad (3.4)$$

$$\text{CoMP} \quad C = \log_2 \left[ 1 + \frac{S+1}{N} \right] \quad (3.5)$$

### 3.2.2 Interference Alignment.

This is a radical new interference management method in wireless communication that boosts interference-free space for the desired signal with resultant decrease in the interference effect at the receiver. The objective of interference alignment is to coordinate various transmitters in such a way that their common interference is aligned at the receiver which makes it easy to apply interference cancellation algorithms. It is possible in this technique to confine the interference to one side of the signal space at the receiver while the remaining half will be accessible to the desired signal. The signal space increases proportionally as the number of users increases but the alignment can be done theoretically for any number of users. Implementation of interference alignment in a cellular network is not easy considering the fact that a non-intended receiver might have multiple parts and knowing that alignment at one receiver does not guarantee alignment at the other receivers. Massive dimensioning with aggressive increase in the number of transmitter-receiver pairs will be required to resolve this challenge in a cellular network but a realistic achievable method must have finite dimension (Sue & Tse 2008: 1037). Interference alignment targets the understanding of the degree of freedom, the first item in SNR estimation in information capacity of a wireless channel (Seng, Kannan & Viswanath 2014). Degree of freedom can also be described as the number of solvable signal spaces or correct capacity estimation in a high SNR's (Talebi). DoF is also the approximation of the sum capacity of the Shannon's wireless channels estimation.

#### 3.2.2.0 Interference Alignment in Cellular Networks.

It has been proven in literature that the Degree of freedom of K-cells and M users served by a base station is  $\frac{MK}{M+1}$  of the signal space. This means that DoF in each cell approaches the interference free setting as the number of users grows large. **Figure 15** shows 3 cells/ 3 user uplink interference alignment in a cellular network (Jafar). With the assumptions that;

- (1) Each transmitter uses the same signal space  $V$ .
- (2) The interference experienced by each base station is  $T_i V$ .

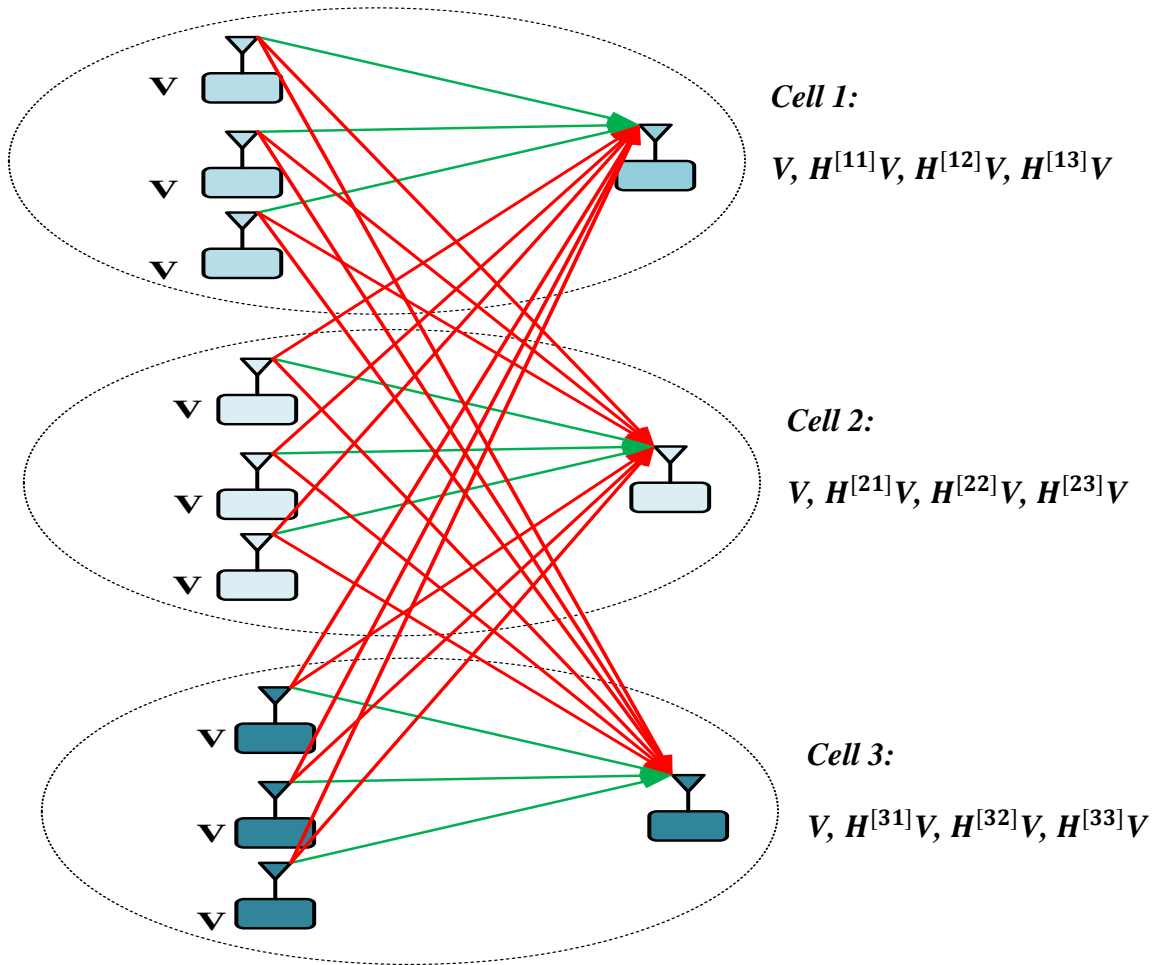
$$V \approx T_1 V \approx \dots \approx T_N V \tag{3.6}$$

The interference fills  $|V|$  dimensions of every base station while the  $M$  desired signals from the desired users has to fill  $M|V|$  dimensions at the desired base station. The signal space at the base station must be large enough to contain the interfering and the desired signals to avoid overlap. Every User Equipment accomplish overall of

$$\frac{V}{(M+1)V} = \frac{1}{M+1} \text{DoF} \quad (3.7)$$

And every cell accomplish

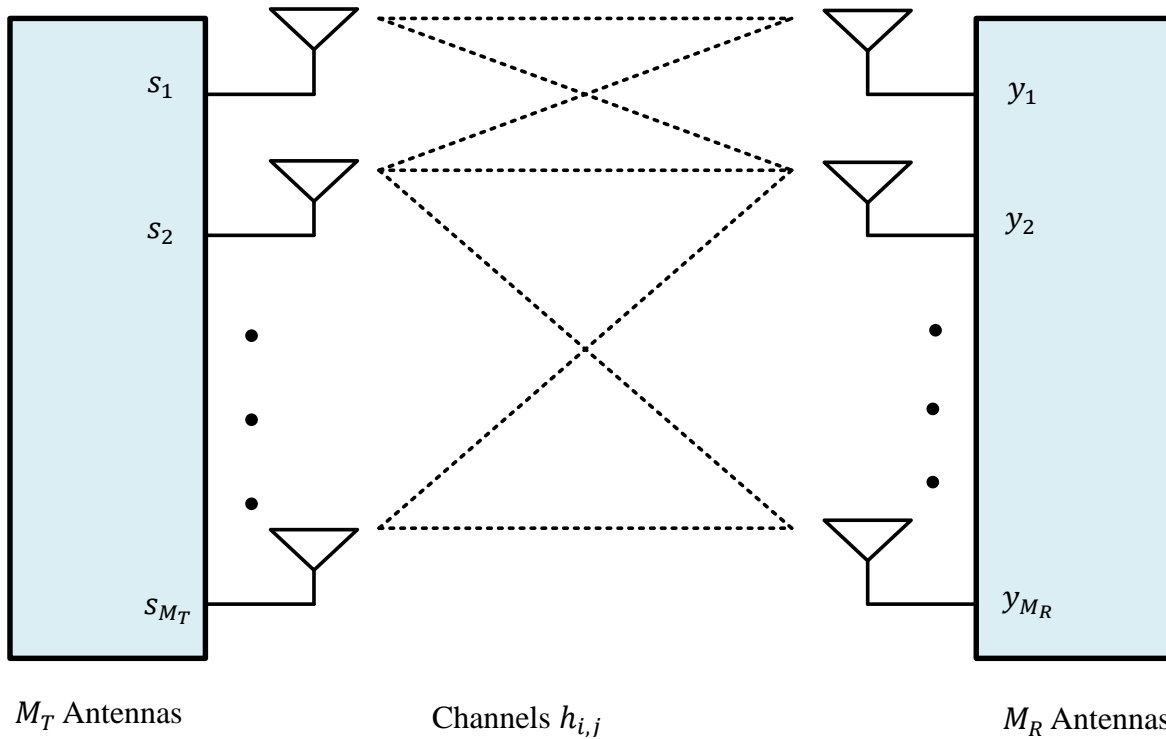
$$\frac{M}{M+1} \quad (3.8)$$



**Figure 15.** 3 cells and 3 user uplink interference alignment (Syed Jafar).

## 3.2.2.1 Degree of Freedom

The degree of freedom for different transmission scenarios can be described from **Figure 16**.



**Figure 16.** Multiple input Multiple out Antennas

- The Degree of freedom for a Point-to-Point is defined as signaling dimensions per channel use and mathematically (Freistal et al 2011:54);

$$C = B \log(1 + \text{SNR}) \quad (3.9)$$

DoF = B signaling dimensions per second.

- SISO  
DoF is directly proportional to bandwidth (limited resources) for single user case.  
DoF = 1 for SISO interference channel.

- MIMO  
DoF =  $\lim_{\text{SNR} \rightarrow \infty} \frac{C(\text{SNR})}{\log(\text{SNR})} = \min(M, N)$                       (3.10)

Capacity is approximately equal to DoF log(SNR).

SNR is Logarithm growth while DoF is a linear growth.

DoF is proportional to the number of antennas (space limited) for single user.

For Multi-User case, Degree of Freedom is proportional to the number of users.

DoF = min (M,N) for multiple access and broadcast channels.

DoF =  $\frac{4}{3}$  M for MIMO X channels.

### 3.2.2.2 Interference Alignment Concept and Challenges

Interference alignment is the elementary precoding scheme for interference channel and also a transmission method that encrypts signals linearly over numerous dimensions like time slots, frequency blocks, and antennas (Ayach, Peters & Heath 2013:36). The coding of transmission over various dimensions allows for interfering signal observed at every receiver to be aligned into a low-dimensional space. This enables interference alignment to boost the non-interfering symbols that simultaneously transmitted over the interference channels, referred to as multiplexing gain. Accomplishing the highest channel multiplexing gain or degree of freedom indicates that at high signal-to-noise ratio (SNR), the sum rate supported by interference alignment approaches the sum capacity.

This is represented mathematically in Equation (3.11) for  $k$ -user interference channel in which

$$Y_i = H_{i,i}V_iS_i + \sum_{j=1, j \neq i}^k H_{i,j}V_jS_j + N_i \quad (3.11)$$

Where  $Y_i$  is the output symbol or received signal,  $H_{i,i}$  is the channel matrix,  $V_j$  is precoding vector or matrix,  $S_i$  is the input matrix or vector and  $N_i$  is the noise observed at the receiver.  $W_i$  is the precoder matrix, if precoder is used at the receiver, this will result to

$$Y_i = W_i(H_{i,i}V_iS_i + \sum_{j=1, j \neq i}^k H_{i,j}V_jS_j + N_i) \quad (3.12)$$

In summary, interference alignment is the computation of a set of precoders in such a way that any user can cancel interference detected from every other user even when using straightforward linear receiver  $W_i$ . The IA feasibility conditions are shown below;

$$W_iH_{i,j}V_j = 0 \quad \forall j \neq i \quad (3.13)$$

$$\text{Rank}(W_iH_{i,i}V_i) = S_i \quad (S_i \text{ is the transmitted information symbols}) \quad (3.14)$$

Early literature on Interference alignment showed that the system ability to discover the IA precoders are proportional to the number of signal dimensions it can be coded. The more time slots, frequency blocks or antennas available for precoding will probably produce more resilience systems in interference alignment (Ayach et al 2013: 37).

The major limitation of IA is the assumptions that have made practical implementations in a wireless network currently unrealistic. Briefly, some of the challenges that made practical application difficult are next examined.

As the number of interfering signals grows, so also the number of dimensions needed to align them since IA is realized by coding the interference over numerous dimensions. It has shown in literature that for frequency domain alignment, the dimension needed for satisfactory alignment grows faster than exponentially with the number of users (Ayach et al 2013:37). The implication is that large resources will be required to align few users. The second challenge is at high SNR, the sum rates approaches sum channel capacity but this is not the case with low or moderate SNR where it is not possible to get close to theoretical sum rate maximum. In simple terms, IA is only possible in a high SNR scenario. Thirdly, a huge overhead cost is required to compute channel state information (CSI) for accurate precoders calculation either at the transmitter or receiver since precoder re-computation is necessary any time there is channel variation. Synchronization is a necessity in IA to eliminate timing and carrier frequency offsets between cooperating nodes otherwise extra interference term might be added to the system model which may render IA solution inefficient. In a nutshell, the huge overhead signaling cost is not only from CSI and synchronization but also from acquiring physical layer parameters and self-organization into alignment clusters.

### 3.2.3 Multiple Input Multiple Output (MIMO)

Channel coding is usually utilized in a single antenna transmission scheme to mitigate the effect of multipath fading but unused special domain can be exploited with multiple antennas. The preference of multiple antennas technique in a wireless network lies on the exploitation of multipath fading considered harmful to single antenna transmission. Multiple antennas can be employed in wireless communication to improve signal-to-noise-interference ratio, the error performance, bit rate or to achieve multiplexing gain, diversity gain and antenna gain (Mietzner, Schober, Lampe, Gerstacker, Hoerber, 2009: 1). Multiple antennas are very useful tool in alleviation of co-channel interference (a major problem of wireless network communication system). **Figure 17** outlines the advantages of multiple antennas over the single antenna transmission.

#### 3.2.3.1 Spatial Multiplexing

The technique of concurrent transmission of independent data (information) through a multiple antennas is called spatial multiplexing. In comparison to single antenna, the



transmit power per transmit is reduced by a component of  $1/M_T$  since using  $M_T$  transmit antennas the general bit rate is improved by  $M_T$  without additional bandwidth or transmit power. Additionally, channel coding is usually utilized to maintain predetermined error performance or quality of service. Bell-lab Layered Space-Time Architecture is a popular spatial multiplexing technique (Mietzner et al 2009).

In a single-antenna rigid bandwidth system, it is possible to have logarithmically increment in the capacity only by increasing the transmit power (hence SINR). This can be compared to MIMO system where capacity almost rises linearly with the lowest of  $M_T$  and  $M_R$  (where  $M_T$  is the number of transmit antenna and  $M_R$  is the number of receive antenna) without additional transmit power or bandwidth.

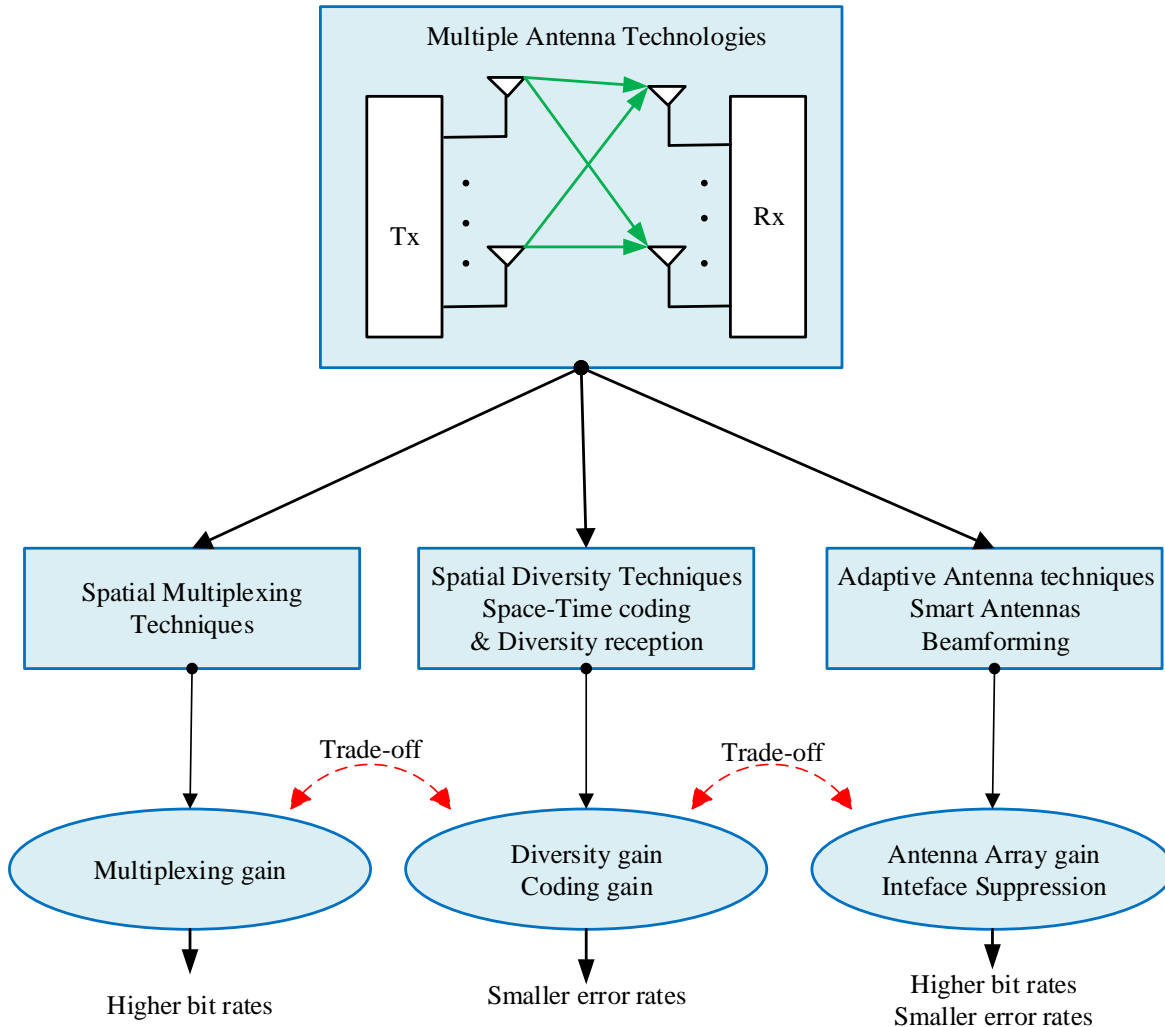
The fundamental concept of spatial multiplexing is to divide the information bit into the number of transmit antenna  $M_T$  sub-sequences (demultiplexing), modulated and then transmitted at the same time over all the transmit antennas at the same frequency. Interference cancellation algorithm is used to decode the transmitted sequence at the receiver. Channel coding is a necessity in spatial multiplexing so as to ensure that a particular error performance or quality of service is maintained. Majority of spatial multiplexing techniques utilizes one-dimensional encoding/decoding structures functioning only in time domain as opposed to space-time coding operating on both space and time.

### 3.2.3.2 Spatial Diversity

The objective of spatial diversity is to enhance the error performance of the system or in some cases the bit rates. The error performance of the system can be enhanced by transmitting or receiving the same information sequence through multiple antennas (diversity transmission or reception). The benefit is that redundant information can be contained in the spatial instead of time domain. The multipath fading of each transmission link is considered statically independent if the antenna spacing at both transmitter and receiver is adequately huge and the probability of degradation of all the links at the same time is extremely small (Mietzner et al 2009).

The large scale diversity (Macroscopic) is attributed to shadowing effects in wireless communication as a result of obstructions between transmitter and the receiver. This can be an advantage if the multiple antennas are spatially located and sufficiently separated to provide the diversity (the probability of all link degradation is far better than a single link). While small scale diversity (Microscopic) occurs in a rich-scattering situation with multipath fading, this can be exploited to advantage with the use of co-located antennas. A typical antenna separation of less than a wavelength is enough to achieve autonomous

fading link. The probability that all the links will be in deep fade at the same time reduces with increase in the number of antenna.



**Figure 17.** Advantage of multiple antenna scheme (Mietzner et al., 2009:2)

A microscopic diversity gain can be achieved with a single transmit antenna and multiple receive antennas by linear combining of each received signals, commonly referred to as diversity reception. In another way, Transmit diversity can be achieved by transmitting repetitive signals over multiple antennas different from spatial multiplexing that transmits independent bit sequence. Multiple antennas at the receiver is optional for transmit

diversity and channel knowledge is not required even though preprocessing is done before transmission for coherent detection at the receiver.

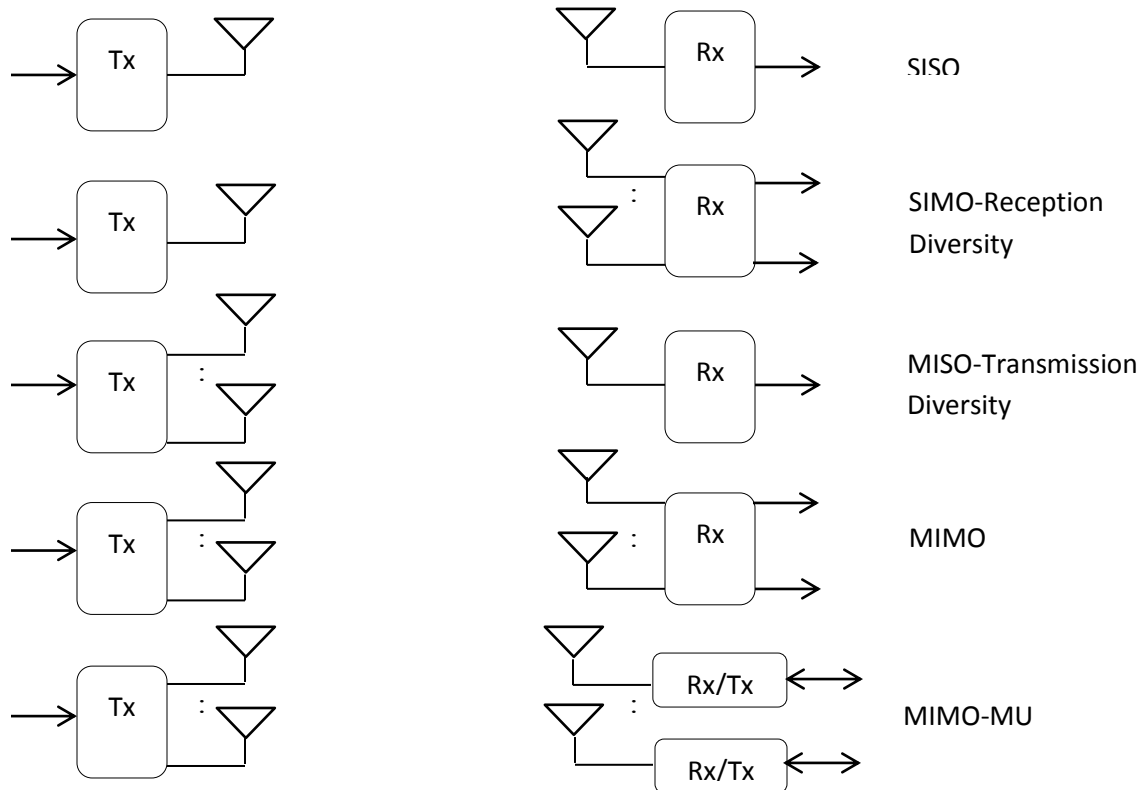
### 3.2.3.3 Smart Antennas and Beamforming

Multiple antennas are not employed only for improvement in data rates and error performance but it is a very useful tool to enhance SNR at the receiver or co-channel interference mitigation (CCI) in a multiuser environment (SINR).

Linear filtering in spatial domain referred to as beamforming is one of the tools used to enhance the Signal-to-Noise Ratios (SNR) and Co-Channel-Interference mitigation by directing the beam patterns of the transmit and receive antenna arrays of the desired signal in a particular direction while the unwanted or interfering signal restrained from having a harmful effect to the desired. Another name in literature of SNR gain is antenna gain or array gain.

#### 4. SPACE TIME CHANNELS

Space-time wireless communication is the application of multiple antennas at the transmitter and/or receiver for purpose of capacity increase or interference management, alternatively referred to as multiple antennas or smart antenna (Paulraj, Nabar & Gore 2003:1). Different antenna structures or realization in ST wireless communication is shown in **Figure 18**.



**Figure 18.** Space-time possible antenna arrangements (Paulraj et al 2003:7).

##### 4.1 ST Signal Models

The effect of multipath is to cause the transmitted signal from the transmitter to the receiver to arrive along many different paths. This can be as a result of diffraction, reflection and scattering by the environmental effect or the medium refraction. Next we consider the signal models for different antenna configurations in **Figure 18**.

#### 4.1.1 Single-Input Single-Output

Assuming that time-varying channels impulse response is represented by  $h(\tau, t)$ , input shaping filter at the transmitter by  $g(\tau)$  and through the propagation channel  $p(\tau, t)$ .  $h(\tau, t)$  is the complex envelope of the bandpass impulse response function and normally the bandwidth of a wireless mobile radio link varies between 0.01% to 0.1% of the center frequency (Paulraj et al, 2003:32).

For  $s(t)$  transmitted signal, the  $y(t)$  received signal is shown below for continuous system

$$y(t) = \int_0^t h(\tau, t) s(t - \tau) d\tau = h(\tau, t) * s(t) \quad (4.1)$$

Under the assumption of causal channel impulse response of  $\tau_{total}$  duration,  $y(t)$  and  $s(t)$  narrowband complex envelope signals and  $*$  is the convolution operator.

For discrete system SISO sampled signal model

$$y(t) = h(\tau) * (\sum_l \sqrt{E_s} s[l] \delta(t - lT_s)) + n(t) = \sum_l \sqrt{E_s} s[l] h(t - lT_s) + n(t) \quad (4.2)$$

$T_s$  is the single symbol duration and  $1/T_s$  is approximately equal to the transmission bandwidth. Equation (4.2) may be rewritten as

$$Y[k] = \sum_l \sqrt{E_s} s[l] h[k-l] + n[k], \quad k=0,1,2,\dots \quad (4.3)$$

If sampled at  $t = kT_s + \Delta$  ( $k = 0,1,2,\dots$ ) and  $\Delta$  is the sampling delay.

#### 4.1.2 Single-Input Multiple-Output

Studying a SIMO channels with  $M_R$  receive antenna, it can be disintegrated into  $M_R$  SISO Channels.

$$h(\tau, t) = [h_1(\tau, t) \ h_2(\tau, t) \ \dots \ h_{M_R}(\tau, t)]^T \quad (4.4)$$

This shows that SIMO channels can be expressed as a  $M_R \times 1$  vector as shown in Equation (4.4) and the received signal at the  $i^{th}$  receiver is

$$y_i = h_i(\tau, t) * s(t), \quad i = 1, 2, \dots, M_R \quad (4.5)$$

This may be written as

$$y(t) = \mathbf{h}(\tau, t) * \mathbf{s}(t), \quad \text{provided that } y_i = [y_1(t) \ y_2(t) \ \dots \ y_{M_R}(t)]^T \quad (4.6)$$

The sampled signal model for SIMO frequency flat channel is

$$y[k] = \sqrt{E_s} \mathbf{h} \mathbf{s}[k] + \mathbf{n}[k], \quad (4.7)$$

While that of SIMO frequency selective is

$$[y[k] \dots y[k + T - 1]] = \sqrt{E_s} \mathbf{H} \mathbf{S} + \mathbf{N} \quad (4.8)$$

#### 4.1.3 Multiple-Input Single-Output

In studying MISO system with  $M_T$  transmit antenna, you will discover that it is comparable to  $M_T$  SISO links and therefore can be expressed as  $1 \times M_T$  vector  $\mathbf{h}(\tau, t)$

$$\mathbf{h}(\tau, t) = [h_1(\tau, t) \ h_2(\tau, t) \ \dots \ h_{M_T}(\tau, t)]^T \quad (4.9)$$

The received signal  $y(t)$  can be written as

$$y(t) = \sum_{j=1}^{M_T} h_j(\tau, t) * s_j(t) \quad (4.10)$$

Equation (4.10) can be represented as

$$y(t) = \mathbf{h}(\tau, t) * \mathbf{s}(t), \quad \text{provided } \mathbf{s}(t) = [s_1(t) \ s_2(t) \ \dots \ s_{M_T}(t)]^T \quad (4.11)$$

The sampled signal model for MISO frequency flat channel is

$$y[k] = \sqrt{\frac{E_s}{M_T}} \mathbf{h} \mathbf{s}[k] + \mathbf{n}[k] \quad (4.12)$$

while MISO frequency selective channel is expressed as

$$y[k] = \sqrt{\frac{E_s}{M_T}} [h_1 h_2 \dots h_{M_T}] \begin{bmatrix} s_1[k] \\ s_2[k] \\ \vdots \\ s_{M_T}[k] \end{bmatrix} + n[k] \quad (4.13)$$

#### 4.1.4 Multiple-Input Multiple-Output

Studying MIMO system with  $M_T$  transmit antennas and  $M_R$  receive antennas, the MIMO channel is  $M_T \times M_R$  matrix  $\mathbf{H}(\tau, t)$  for  $j^{th}$  transmit antenna ( $j = 1, 2, \dots, M_T$ ) and  $i$ th receive antenna ( $i = 1, 2, \dots, M_R$ ) and can be represented as shown

$$\mathbf{H}(\tau, t) = \begin{bmatrix} h_{1,1}(\tau, t) & h_{1,2}(\tau, t) \dots & h_{1,M_T}(\tau, t) \\ h_{2,1}(\tau, t) & h_{2,2}(\tau, t) \dots & h_{2,M_T}(\tau, t) \\ \vdots & \vdots & \vdots \\ h_{M_R,1}(\tau, t) & h_{M_R,2}(\tau, t) \dots & h_{M_R,M_T}(\tau, t) \end{bmatrix} \quad (4.14)$$

The received signal at the  $i$ th receiver is

$$y_i(t) = \sum_{j=1}^{M_T} h_{i,j}(\tau, t) * s_j(t), \quad i = 1, 2, \dots, M_R \quad (4.15)$$

Equation (4.15) can also be represented as

$$y(t) = \mathbf{H}(\tau, t) * \mathbf{s}(t) \quad (4.16)$$

where  $\mathbf{s}(t) = [s_1(t) \ s_2(t) \ \dots \ s_{M_T}(t)]^T$  is  $M_T \times 1$  vector and  $y_i = [y_1(t) \ y_2(t) \ \dots \ y_{M_R}(t)]^T$  is  $M_R \times 1$  vector.

MIMO sampled signal model is expressed as

$$y[k] = \sqrt{\frac{E_s}{M_T}} \mathbf{H} \mathbf{s}[k] + \mathbf{n}[k] = \sqrt{\frac{E_s}{M_T}} \mathbf{H} \mathbf{s} + \mathbf{n} \quad (4.17)$$

The time index  $k$  can be ignored in Equation (4.17) since the output at any instant of time is not reliant on the prior input.

The MIMO sampled signal for frequency selective channels is represented as

$$y(t) = \sqrt{\frac{E_s}{M_T}} \begin{bmatrix} h_{1,1} & \cdots & h_{1,M_T} \\ \vdots & \ddots & \vdots \\ h_{M_R,1} & \cdots & h_{M_R M_T} \end{bmatrix} \begin{bmatrix} s_1[k] \\ \vdots \\ s_{M_T}[k] \end{bmatrix} + \mathbf{n}[k] \quad (4.18)$$

#### 4.2 Transmission Modes.

3GPP has a specification for both transmission mode and receiver classes for user equipment/base station to enhance interference management in both uplink and downlink for LTE system as listed in **Table 1** for transmission mode and **Table 2** for receiver mode.

**Table 1.** Transmission Modes defined by 3GPP

Transmission Modes	Description	Use case
1) Single-Antenna port	SISO OR SIMO	Line-of-sight, Single-antenna, eNBs.
2) Transmit Diversity	MISO or MIMO with SNR diversity gain.	Far from eNBs, Rural arrears, high mobility, Large cells.
3) Large-delay CDD	Open-loop Spatial Multiplexing SU-MIMO	Close to ENBs, small cells, Urban areas, high mobility.
4) Closed-loop Spatial Multiplexing	Closed-loop Spatial Multiplexing SU-MIMO with codebook-based precoding.	Close to ENBs, small cells, Urban, in-building & low mobility.
5) Multi-User MIMO	Multi-User MIMO with codebook-based precoding.	Close to ENBs, lower data rates.
6) Closed-loop Spatial Multiplexing	Single-Layer MIMO with codebook-based precoding.	Far from eNBs, suburban or rural arrears, low mobility
7) Single-Antenna port 5	Single-Layer Beamforming(SISO or SIMO).	Low density area, Line-of-sight.
8) Dual-Layer <sup>1</sup>	2-Layer Beamforming for SU-MIMO or MU-MIMO	High-usage Macro cells, any environment, low mobility.
9) Up to 8 Layer <sup>2</sup>	Multi-Layer Beamforming for SU-MIMO and MU-MIMO.	High-usage Macro cells, any environment, low mobility.

1 3GPP Release 9 and later, 2 3GPP Release 10 and later



**Table 2.** 3GPP Reference Receiver (Sequans Air, 2012:5).

<b>Receiver Type</b>	<b>Reference Receiver</b>
Type 0	RAKE
Type 1	Diversity receiver (RAKE)
Type 2	Equalizer
Type 2i	Equalizer with interference awareness
Type 3	Diversity equalizer
Type 3i	Diversity equalizer with interference awareness
Type M	Multiple input multiple output

### 4.3 Capacity of MIMO Channels

Capacity of a MIMO channels can be classified as a deterministic, fading and frequency selective fading MIMO channels. This classification will be useful in understanding the maximum spectral efficiency and the maximum error-free data rate that can be supported by a stable ST wireless channel.

#### 4.3.1 Capacity of a Deterministic MIMO Channels

With the assumption that channel matrix  $\mathbf{H}$  is known to the receiver through training bits and tracking, we can examine a case where  $\mathbf{H}$  is deterministic and  $s$  (transmit symbol) is a circularly symmetric complex Gaussian vector (Paulraj, Gore, Nabar & Bolcskei 2004:203). The equivalent information for  $s$  with covariance matrix  $R_{ss}$  is represented as

$$I = \log_2 \det \left( I_{MR} + \frac{E_s}{M_T N_o} \mathbf{H} R_{ss} \mathbf{H}^H \right) \frac{b/s}{Hz} \quad (4.19)$$

The resultant MIMO channel capacity is given as

$$C = \max_{R_{ss}} \log_2 \det \left( I_{MR} + \frac{E_s}{M_T N_o} \mathbf{H} R_{ss} \mathbf{H}^H \right) \frac{b/s}{Hz} \quad (4.20)$$

This maximization is done over all the feasible covariance matrices input that met the condition  $\text{Tr}(R_{SS}) = M_T$  ( $\text{Tr}(\cdot)$  is the trace operation of argument matrix). Therefore, with a bandwidth of  $B$  Hz, the highest achievable data rate over this MIMO channel is  $BC$  bps.

Generally, it is a challenge in practical application to obtain channel knowledge at the transmitter but the transmit vector  $s$  can be chosen reasonably  $R_{SS} = I_{M_T}$  (spatial white). This means that the signals are equally powered (equi-powered) and independent at the transmitting antennas. Equation (4.19) and (4.20) reduces to (4.21) and (4.22) respectively,

$$I = \log_2 \det \left( I_{M_R} + \frac{E_s}{M_T N_o} H H^H \right) \quad (4.21)$$

$$C = \sum_{i=1}^r \log_2 \left( I + \frac{E_s}{M_T N_o} \lambda_i \right) \quad (4.22)$$

$r$  is the rank of channel ( $\lambda_i = 1, 2, \dots, r$ ) and non-zero positive eigenvalues of  $H H^H$ . It can be seen from Equation (4.22) that the spectral efficiency of a MIMO channel is the summation of the respective SISO channels having channel gain of  $\sqrt{\lambda_i}$  ( $i = 1, 2, \dots, r$ ) and  $\frac{E_s}{M_T}$  transmit power. The increase in performance can be clearly seen when you consider that there is  $r$  b/s/Hz increase for every 3-dB rise in transmit power compared to 1 b/s/Hz in a traditional SISO channels and this data pipe can be accessed with channel knowledge (Paulrag et al. 2004:204).

#### 4.3.2 Capacity of Fading MIMO Channels

Studying of a fading MIMO channels can be done with the following assumptions; (a) Ergodic block fading channel model (channel does not vary over the block of sequential symbols). (b) The typical SNR of  $\rho = \frac{E_s}{N_o}$  at each receiver. (c) Channel  $H = H_w$ ,  $h_{i,j}$  ( $i = 1, 2, \dots, M_R$ ,  $j = 1, 2, \dots, M_T$ ) normalized  $\varepsilon\{|h_{i,j}|\}^2 = 1$  and  $\text{Tr}(R_{SS}) = E_s$ . The maximum information rate connected to fading channel can be expressed as in Equation (4.22) (when channel is unknown to the transmitter) and (4.33) (when channel is known to the transmitter).

$$C = \max_{\sum_{i=1}^r \gamma_i = M_T} \sum_{i=1}^r \log_2 \left( 1 + \frac{E_S \gamma_i}{M_T N_o} \lambda_i \right) \quad (4.33)$$

Where  $\gamma_i = \varepsilon \{|s_i|^2\}$  ( $i = 1, 2, \dots, r$ ) is the transmit energy in  $i$ th sub-channel and satisfies  $\sum_{i=1}^r \gamma_i = M_T$ . (Paulraj et al. 2003:68).

The capacity of a fading channel can further be categorized into ergodic and outage capacity. Ergodic capacity is considered when the transmitted codewords stretch a limitless number of autonomous fading blocks. While outage capacity is applicable where there is delay and the transmitted codewords span only one block. Outage capacity is valuable tool when analyzing unknown channel at the transmitter and  $H$  is random but does not vary for each channel use. Outage capacity can also be represented for known channel at the transmitter with great enhancement in the performance.

#### 4.3.3 Capacity of Frequency-Selective Fading MIMO Channels

The analysis of the capacity of frequency-selective channels can be accomplished by splitting the bandwidth ( $B$ ) under consideration into  $N$  sub-channels, with each subdivision having a bandwidth of  $B/N$  Hz that can be assumed to be frequency-flat if  $N$  is adequately big. If  $i^{th}$  sub-channel is represented with  $H_i$  ( $i = 1, 2, \dots, N$ ), and the power is equally distributed, then the capacity of a deterministic channel can be obtained from Equation (4.21) as

$$C_{FS} = \frac{1}{N} \sum_{i=1}^N \log_2 \det \left( I_{MR} + \frac{E_S}{M_T N_o} H_i H_i^H \right) \quad (4.34)$$

This implies that the capacity of a frequency selective MIMO channel is the sum of the capacity of frequency flat sub-channels (Paulraj et al, 2003:82) and the ergodic capacity is

$$\bar{C}_{FS} = \varepsilon \{C_{FS}\} = \varepsilon \left\{ \frac{1}{N} \sum_{i=1}^N \log_2 \det \left( I_{MR} + \frac{E_S}{M_T N_o} H_i H_i^H \right) \right\} \quad (4.35)$$

The outage capacity for frequency selective MIMO channels can also be characterized in like manner. The outage capacity of a frequency selective fading channel is bigger than the outage capacity of a frequency flat channel when considering low outage rates.

#### 4.4 Space Time Coding

Coding is used in multi-antenna system to boost the link throughput and to reduce error as much as possible. The objective is interpreted in form of maintaining the set target (performance criteria), diversity gain, the coding gain and array gain. This can be broadly discussed as Space-Time Diversity coding and Spatial Multiplexing.

##### 4.4.1 Space-Time Diversity Coding

The space-time diversity coding aims to achieve the overall possible spatial diversity in the MIMO channel through the accurate design of the transmitted space-time codewords. Alamouti scheme and delay diversity are two of such space-time coding technique that does not require channel knowledge at the transmitter to realize full spatial diversity.

Alamouti scheme is realized with a MIMO channel with two transmit and unspecified number of receive antennas. In the first symbol period, antenna 1 transmits  $\mathbf{s}_1$  while antenna 2  $\mathbf{s}_2$  respectively. In the next symbol period, antenna 1 transmits the negative conjugate of  $\mathbf{s}_2$  ( $-\mathbf{s}_2^*$ ) and antenna 2 transmits conjugate of  $\mathbf{s}_1$  ( $\mathbf{s}_1^*$ ). Only two autonomous data symbol can be transmitted simultaneously over a symbol period in Alamouti scheme (spatial rate is 1,  $r_s = 1$ ), this translates to  $2M_R$ th-order diversity and can be expressed mathematically as

$$\mathbf{z}_i = \sqrt{\frac{E_s}{2}} \|\mathbf{H}\|_F^2 \mathbf{s}_i + \mathbf{n}_i, \quad i=1,2 \quad (4.36)$$

$\mathbf{z}_i$  is the received signal,  $\mathbf{n}_i$  is the scalar processed noise and  $\mathbf{s}_i$  is the transmitted symbols.

The Alamouti scheme can be employed for a MIMO channels with more than two transmit antennas by the use of orthogonal space-time block coding (OSTBC) though with reduction in spatial rate ( $r_s < 1$ ). The attraction of OSTBC in practical systems is due to low complexity in the receiver design.

Delay Diversity can be likened to transmit diversity with  $1 \times 2$  MIMO channel  $M_T = 2$  and  $M_R = 1$ . This scheme involves translation of spatial diversity into frequency diversity by

launching a signal data from antenna 1 and its delayed version from the second antenna with the assumption that the induced delay is equivalent to one symbol period. The channel can be expressed as

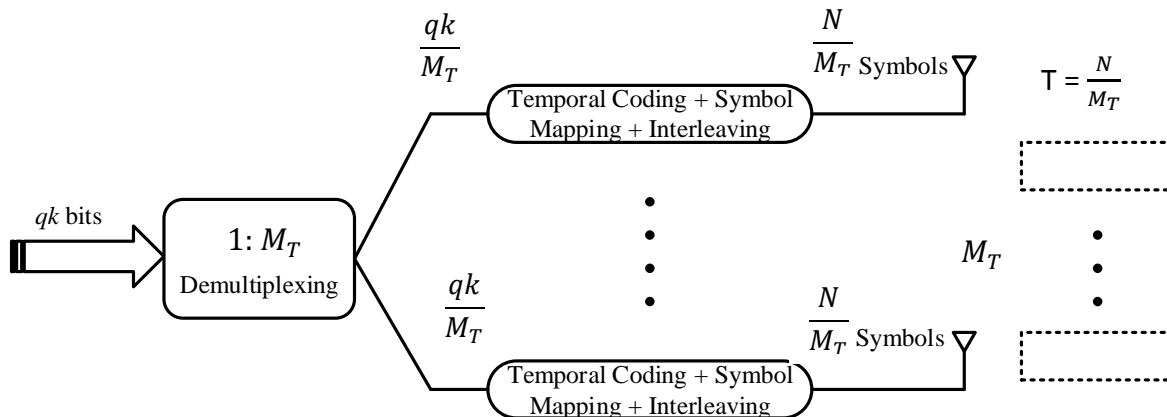
$$h[k] = h_1\delta[k] + h_2\delta[k-1], k = 1, 2, \dots, \quad (4.37)$$

where  $\mathbf{h}_1$  and  $\mathbf{h}_2$  are the channel gains corresponding to antenna 1 and antenna 2 respectively. If we assume that  $\mathbf{h}_1$  and  $\mathbf{h}_2$  are independent and identically distributed (IID) zero-mean circulant symmetric complex Gaussian (ZMCSCG) random variables with unit variance, the channel can be viewed as two-path SISO channel with independent path fading and equal path energy (Paulraj et al., 2003:108). Maximum-likelihood (ML) detector can be employed at the receiver to recover the data for full second-order diversity. Rank and determinant criteria in literature can be used to extend delay diversity coding scheme to a general case of space-time codeword design to achieve full  $M_R M_T$ th-order diversity gain.

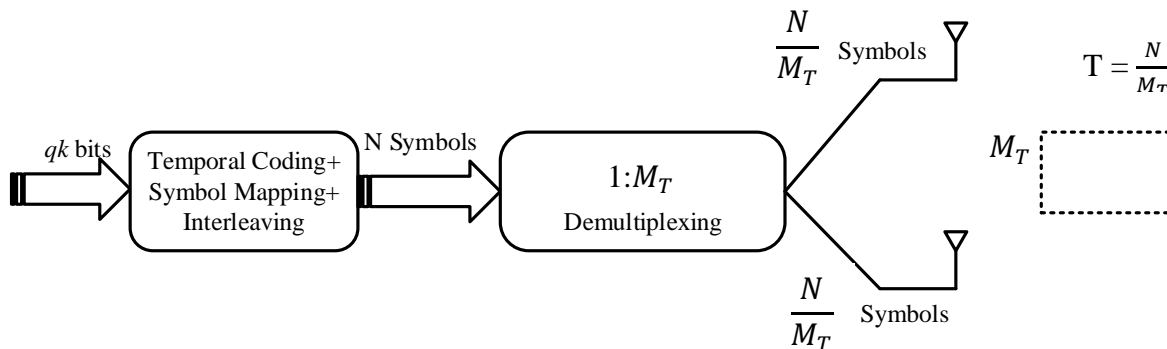
#### 4.4.2 Spatial Multiplexing

$M_T$  separate data symbols are propagated every symbol period such that  $r_s = M_T$  in spatial multiplexing and the goal is fully exploit maximum possible transmission rate. Detecting or de-multiplexing of SM signals is still a huge challenge and can be implemented with horizontal and vertical encoding spatial multiplexing.

In Horizontal Encoding(HE), the data streams is decomposed into the number of transmit antennas  $M_T$  first and then symbol mapping, interleaving and encoding are separately done before transmitting through the matching antenna. If  $qk$  bits are transmitted for example, the spatial rate is  $r_s = M_T$  while the signaling rate will be  $qr_t M_T$  bits per transmission (Paulraj et al., 2004:2008). The scheme is summarized in **Figure 19** and can accomplish  $M_R$ th-order diversity because the symbol can be transmitted by one antenna with the possibility of many receiver antennas. The technique has  $M_R$  realizable array gain and coding gain dependent on the type of temporal code used.



**Figure 19.** Horizontal encoding (Paulrag et al. 2004:209)



**Figure 20.** Vertical Encoding (Paulrag et al. 2004:209)

Interleaving, symbol mapping and temporal coding are performed on the bit stream first before decomposition into  $M_T$  antenna streams in the case of Vertical Encoding (VE) as illustrated in **Figure 20**. It has the same spatial rate of  $r_s = M_T$  and signaling rate of  $qr_t M_T$  b/s/Hz just like the HE but can accomplish much more diversity gain in  $M_T M_R$ th-order as long as the optimal code design is implemented. The drawback of VE is receiver complexity as a result of joint decoding required to decode the signals at the receiver. The

scheme has  $M_R$  realizable array gain and coding gain is also dependent on the type of temporal code used as mention earlier for HE.

Numerous combinations/modifications of Horizontal and Vertical econding scheme are feasible depending on the objective and the cost constraint. Diagonal Encoding (DE) is a product of such combination/modification, such that bits stream is first subjected to HE before splitting it into frames/slots and the frames are fed through antenna rotator that rotates the frame in a round robin pattern. The attraction of DE is that it maintains the complexity of HE, diversity gain of  $M_T M_R$ th-order and full spatial rate of  $M_T$  if codeword of sufficient length is implemented. The famous Diagonal-Bell Labs Layered Space Time Architecture utilizes diagonal encoding with space-time triangular block with initial no transmission. The initial wastage is a requirement to exploit the stream-by-stream low-complexity decoding algorithm (Paulraj et al., 2004:208). Even though DE can accomplish  $M_R$  Maximum array gain, it can also result to non-trivial rate loss specifically for short block lengths of codeword.

#### 4.5 MIMO Receivers

The section starts with the review of mathematical tools that will be helpful in the design and analysis of MIMO receivers. The MIMO receivers can be broadly categorized into Linear and non-Linear receivers. The attraction of the linear receivers is in its ability to treat the transmitted streams of data as interferences except the desired streams that are then decoded independently. The reduction or alleviation in interference signals from other transmit antennas can be managed easily. The simplest linear receiver of a MIMO system channel model is inversion of the channel effect as shown below.

$$y = Hs + n \quad (4.38)$$

is

$$H^{-1}y = s + H^{-1}n \quad (4.39)$$

The challenge with Equation (4.39) is that it contains a noise term  $H^{-1}\mathbf{n}$  and also in general cases, it may not be feasible to do matrix inverse due to the following reasons:

- Inverse only exist for square matrices, i.e. equal number of receive and transmit antennas  $M_R = M_T$ .
- Even with square matrix, inverse only exist for full rank matrices not with rank deficient matrices.

However, a generalized definition of inverse of matrices when the number of receiver antennas  $M_R$  is greater or equal to the number of transmit antenna  $M_T$  ( $M_R \geq M_T$ ) is

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{M_R} \end{bmatrix} = \begin{matrix} \begin{matrix} \downarrow \\ \downarrow \\ \downarrow \\ \downarrow \\ \downarrow \end{matrix} \\ \begin{matrix} M_R \\ \downarrow \\ \downarrow \\ \downarrow \\ \downarrow \end{matrix} \end{matrix} \begin{matrix} \xrightarrow{M_T} \\ \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1M_T} \\ h_{21} & h_{22} & \dots & h_{2M_T} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ h_{M_R1} & h_{M_R2} & \dots & h_{M_RM_T} \end{bmatrix} \end{matrix} \cdot \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_{M_T} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{M_R} \end{bmatrix} \quad (4.40)$$

This will result to  $M_R$  equations and  $M_T$  unknown which implies more equations than unknowns; hence the system might not have exact solution (infinite solution). One of the mathematical tools to solve this kind of system is called minimum error solution. This simply means among all possible transmit vector  $\bar{\mathbf{s}}$ , choose the minimum error vector, note that error is can be expressed as

$$\varepsilon = \| \mathbf{y} - \mathbf{H}\mathbf{s} \|^2 \quad (4.41)$$

Where  $\mathbf{y}$  is the measurement,  $\mathbf{H}$  is the channel matrix and  $\mathbf{s}$  is the transmitted unknown.  $\mathbf{s}$  has to be chosen in such a way that the error in  $\mathbf{y} - \mathbf{H}\mathbf{s}$  will be minimal and it is known as least-square error solution.



The norm of a vector for real matrices can be computed as shown below;

$$\|y - Hs\|^2 = (y - Hs)^T (y - Hs) = \bar{y}^T \bar{y} - \bar{s}^T H^T \bar{y} - \bar{y}^T H \bar{s} + \bar{s}^T H^T H \bar{s} \quad (4.42)$$

$$\frac{d\|y - Hs\|^2}{d\bar{s}} = 0 - H^T \bar{y} - H^T \bar{y} + H^T H \bar{s} + H^T H \bar{s} = -2H^T \bar{y} + 2H^T H \bar{s} \quad (4.43)$$

The minimum value or the optimal solution for  $s$  can be found when the differentiation of the norm is set equal to zero,  $\frac{d\|y - Hs\|^2}{d\bar{s}} = 0$ .

$$-2H^T \bar{y} + 2H^T H \bar{s} = 0 \quad \longrightarrow \quad (H^T H) \bar{s} = H^T \bar{y} \quad (4.44)$$

$$\hat{s} = (H^T H)^{-1} H^T \bar{y} \quad (4.45)$$

Equation (4.45) is an estimate of  $s$  or approximate solution that minimizes the least squares error, since we started on the premise that the number of equations is greater than the number of unknown therefore it will not have a unique solution.

If  $\mathbf{H}$  is complex as in case of baseband where data is always complex, Equation (4.45) becomes

$$\hat{s} = (H^H H)^{-1} H^H \bar{y} \quad (4.46)$$

Where  $H^H$  is the H hermitian and

$$(H^H H)^{-1} H^H = H^\dagger \quad (4.47)$$

$\mathbf{H}^\dagger$  is the pseudo-inverse of  $\mathbf{H}$  or left inverse of  $\mathbf{H}$ .

If the inverse of  $\mathbf{H}$  exists, then the pseudo-inverse reduces to conventional  $\mathbf{H}$  inverse.

#### 4.5.1 Zero-Forcing Receiver

The objective of ZF is inversion of the channel matrix and elimination of inter-symbol interference for SISO/SIMO channels and Multi-Stream Interference (MSI) for MIMO

channels. From earlier discussion, it may not always be feasible to invert the channel matrix, ideal channel inversion that will eliminate ISI will need infinite impulse response filter (IIR) at the receiver but ZF is a Finite impulse response filter (FIR). Oversampling with adequate length can readily address this problem in practical systems.

The ZF filter for MIMO channel can be deduced from Equation (4.46),

$$G_{ZF} = \sqrt{\frac{M_T}{E_s}} H^\dagger$$

Where  $G_{ZF}$  is  $M_R \times M_T$  that represents the inverse of the channel matrix and  $H^\dagger$  is defined in Equation (4.47).

The ZF receiver output is realized as shown

$$Z = s + \sqrt{\frac{M_T}{E_s}} H^\dagger \mathbf{n} \quad (4.48)$$

This demonstrates that the ZF front-end decomposes the matrix channel into  $M_T$  parallel scalar channels with additive noise. Decoding is done in each scalar channels while disregarding noise correlation in each stream. Even though ZF receivers can eliminate MSI by transforming joint decoding into  $M_T$  single stream decoding thereby reducing receiver complexity but it is at the cost of noise enhancement which affects the performance of the receiver. The realizable diversity order is shown in literature to be  $M_R - M_T + 1$  (Paulrag et al., 2004:210).

#### 4.5.2 Minimum Mean Squared Error (MMSE) Receiver.

MMSE is a linear approximation to ML in bid to greatly reduce the computational complexity associated with ML receivers. The MMSE uses a Bayesian approach to minimize the squared error by treating the transmitted symbol vector as random variable. It has a robust performance when compared to ZF receiver, since it alleviates the MSI without noise enhancement with corresponding error reduction. It may not be possible for MMSE receiver to overcome the entire interfering signal since every  $M_T$  antenna in every

$N$  base station will be regarded as independent interferer, i.e.  $NM_T$  interferers but 10-25 percent capacity can be obtained by just cancellation of the pilot and common channel signals of the most vigorous interfering bases station. The MMSE receiver is considered a linear estimator and can be realized by the expression below

$$\hat{s} = \bar{C}^T \bar{y} \quad (4.49)$$

Where  $\bar{y}$  is the measurements vector,  $\bar{C}^T$  is the linear estimator and  $s$  is the transmitted vector to be estimated.

The optimal choice of  $\bar{C}^T$  to minimize the error is

$$G_{MMSE} = \min_G \varepsilon\{\|\bar{s} - s\|^2\} = \min_G \varepsilon\{\|\bar{C}^T \bar{y} - s\|^2\} \quad (4.50)$$

The squared error can be computed as

$$(\bar{C}^T \bar{y} - s)(\bar{C}^T \bar{y} - s)^T = \bar{C}^T \bar{y} \bar{y}^T \bar{C} - s \bar{y}^T \bar{C} - \bar{y}^T \bar{C} s^T + s s^T \quad (4.51)$$

Let us define some variables at this point

$$\varepsilon(\bar{y} \bar{y}^T) = R_{yy} \quad (4.52)$$

$$\varepsilon(s \bar{y}^T) = R_{sy} \quad (4.53)$$

$$\varepsilon(\bar{y} \bar{s}^T) = R_{ys} = R_{sy} \quad (4.54)$$

Where  $R_{yy}$  is the covariance of matrix of  $y$  and  $R_{sy}$  is the cross-covariance of the matrix  $y$ .

Equation (4.51) can be rewritten as (4.55) based on the definitions from Equations (4.52-4.54).

$$\bar{C}^T R_{yy} \bar{C} - R_{sy} \bar{C} - \bar{C}^T R_{ys} + R_{ss} = \bar{C}^T R_{yy} \bar{C} - 2\bar{C}^T R_{ys} + R_{ss} \quad (4.55)$$

It can be observed that Equation (4.55) is clearly a function of  $\mathbf{C}$  and the minimum error can be computed as

$$\frac{\delta F(C)}{\delta \bar{C}} = 2R_{yy}\bar{C} - 2R_{ys} = 0, \text{ for minimization} \quad (4.56)$$

The optimal linear minimum mean squared error estimator (LMMSE) is

$$\bar{C} = R_{yy}^{-1}R_{sy} \quad (4.57)$$

Recall that Equation (4.49) is the LMMSE estimator of real vectors while Equation (4.58) expresses same for complex vectors.

$$\hat{s} = \bar{C}^H \bar{y} = R_{yy}^{-1}R_{sy}\bar{y} \quad (4.58)$$

Using the system model of equation (4.40), these quantities  $R_{ss}$ ,  $R_{sy}$  and  $R_{yy}$  can be derived,

$$\varepsilon\{s\bar{s}^H\} = \begin{bmatrix} s_1 \\ s_2 \\ \cdot \\ \cdot \\ s_{M_T} \end{bmatrix} \begin{bmatrix} s_1^* & s_2^* & \dots & s_{M_T}^* \end{bmatrix} = \begin{bmatrix} |s_1|^2 & s_1 s_2^* & \dots & s_1 s_{M_T}^* \\ s_2 s_1^* & |s_2|^2 & \dots & s_2 s_{M_T}^* \\ \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \dots & \cdot \\ s_{M_T} s_1^* & s_{M_T} s_2^* & \dots & |s_{M_T}|^2 \end{bmatrix} \quad (4.59)$$

It will be observed that the diagonal elements of the matrix in Equation (4.60) are the transmit powers while off the diagonal are the correlation between the transmitted symbols of different antennas.

It will be reasonable to assume that the transmitted symbols are uncorrelated, hence the matrix reduces to

$$R_{ss} = \begin{pmatrix} P_d & 0 & 0 & 0 \\ 0 & P_d & 0 & 0 \\ 0 & 0 & P_d & 0 \\ 0 & 0 & 0 & P_d \end{pmatrix} = P_d I_{M_T} \quad (4.60)$$

Equation (4.60) will be used to derive  $R_{yy}$

$$R_{yy} = \varepsilon\{\bar{y}\bar{y}^H\} = \varepsilon\{(H\bar{s} + \bar{n})(H\bar{s} + \bar{n})^H\} = \varepsilon\{H\bar{s}\bar{s}^H H^H + \bar{n}\bar{n}^H + H\bar{s}\bar{n}^H + \bar{n}\bar{s}^H H^H\} \quad (4.61)$$

Condition number of the channel matrix otherwise known as singular value determines the noise improvement of the linear filter, the enhancement will be huge with small singular value (Cho, Kim, Yang & Kang 2012:322). Since the noise and the transmitted symbol are uncorrelated, the second and the third term on the right side of Equation (4.61) are zero, i.e.  $\bar{n}\bar{s}^H H^H = H\bar{s}\bar{n}^H = 0$  and this reduces to equation (4.62).

$$R_{yy} = HR_{ss}H^H + \sigma_n^2 I = P_d HH^H + \sigma_n^2 I \quad (4.62)$$

Equation (4.62) is the covariance matrix of the received symbol vector  $\bar{y}$ . The  $R_{ys}$  can be computed by the same method as shown below;

$$R_{ys} = \varepsilon\{\bar{y}\bar{s}^H\} = \varepsilon\{(H\bar{s} + \bar{n})\bar{s}^H\} = \varepsilon\{H\bar{s}\bar{s}^H + \bar{n}\bar{s}^H\} = HR_{ss} = P_d H \quad (4.63)$$

The identity matrix  $I_{M_T}$  is omitted in Equation (4.62) and (4.63) because the received signal vector is a scalar and the linear minimum mean-squared estimator in Equation (4.57) and (4.58) can be rewritten since all the quantities have been derived as

$$\bar{C} = (P_d HH^H + \sigma_n^2 I)^{-1} P_d H = P_d (P_d HH^H + \sigma_n^2 I)^{-1} H^H \quad (4.64)$$

$$\hat{s} = P_d H^H (P_d HH^H + \sigma_n^2 I)^{-1} \bar{y} = P_d (P_d HH^H + \sigma_n^2 I)^{-1} H^H \bar{y} \quad (4.65)$$

At high SNR region, the noise power is negligible compared to transmit power ( $\sigma_n^2 \ll 1$ ), the MMSE receiver is approximately equals Zero-Forcing receiver as shown.

$$\bar{C} \approx P_d (P_d H H^H)^{-1} H^H \approx (H H^H)^{-1} H^H \quad (4.67)$$

$$G_{MMSE} = G_{ZF} \quad (4.68)$$

At low SNR region,  $P_d$  is negligible compared to the noise power ( $P_d \ll 1$ ), the MMSE approximately performs as matched filter.

$$\bar{C} = P_d (\sigma_n^2 I)^{-1} H^H = \frac{P_d}{\sigma_n^2} H^H \quad (4.69)$$

$$G_{MMSE} = N_o^{-1} \sqrt{\frac{E_s}{M_T}} H^H \quad (4.70)$$

MMSE receiver better performance compared to ZF with the same diversity order of  $M_R - M_T + 1$ .

#### 4.5.3 Successive Interference Cancellation Receivers

Non-Linear receivers have been proven to produce attractive compromise between complexity and performance even with the case of single antenna systems. The performance of signal detection in MIMO system can be enhanced with non-linear receivers without huge increment in complexity just by the use of successive interference cancellation. Vertical Bell Lab Layered Space-Time Architecture (V-BLAST) is a non-linear MIMO receiver that uses successive interference cancellation technique commonly referred to as Successive interference cancellation receivers. It comprises of a set of linear receivers where the effect of each of the estimated or decoded symbol is cancelled or stripped away layer by layer. The algorithm of the scheme starts by using ZF or MMSE to randomly detect a transmitted data symbol while treating other transmitted symbols as interference and can be illustrated with using the MIMO channel system model.

$$\bar{y} = \bar{h}_1 s_1 + \bar{h}_2 s_2 + \dots + \bar{h}_{M_T} s_{M_T} + \bar{n} \quad (4.71)$$

Considering the pseudo-inverse or left-inverse of H

$$Q = H^\dagger \quad (4.72)$$

By definition

$$\bar{q}_i^H \bar{h}_j = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \quad (4.73)$$

Equation (4.73) is a unique property that can be exploited to cancel the interference by left multiplying by  $\bar{q}_i^H$ .

$$\tilde{y}_1 = \bar{q}_i^H \bar{y} = \bar{q}_i^H (\bar{h}_1 s_1 + \bar{h}_2 s_2 + \dots + \bar{h}_{M_T} s_{M_T}) + \bar{q}_i^H \bar{n} \quad (4.74)$$

$$\tilde{y}_1 = s_1 + 0 + \dots + 0 + \tilde{n} \quad (4.75)$$

Equation (4.75) can now be employed to decode  $s_1$ , under the assumption that  $s_1$  is correctly decoded.

$$\tilde{y}_2 = \bar{y} - \bar{h}_1 s_1 = (\bar{h}_1 s_1 + \bar{h}_2 s_2 + \dots + \bar{h}_{M_T} s_{M_T}) + \bar{n} - \bar{h}_1 s_1 \quad (4.76)$$

$$\tilde{y}_2 = \bar{h}_2 s_2 + \bar{h}_3 s_3 + \dots + \bar{h}_{M_T} s_{M_T} + \bar{n} \quad (4.77)$$

By removing the effect of  $s_1$ , Equation (4.77) shows the new MIMO system has been reduced to  $r \times (t-1)$  matrix. The process is repeated until all the transmitted symbols are successfully decoded. The benefit of SIC scheme is the gradually increment of diversity order as the process proceeds. This can be clearly seen when the last stage of the scheme is considered after it must have decoded  $(t-1)th$  term, what will be left is  $\tilde{y}_{M_T} = \bar{h}_{M_T} s_{M_T} + n_{M_T}$  which is effectively  $r \times 1$  channel with  $r$ th-order diversity. Though SIC is optimal with good CSI but wrong estimation of the transmitted symbol and incorrect CSI will render it unreliable.

#### 4.5.4 Maximum Likelihood Receivers

Maximum likelihood multiuser detection established to reduce bit error probability when the channel state information of the interfering signal is known but obtaining CSI from the neighboring base station is still a very big challenge in practice. ML is an excellent receiver that employs vector decoding according to Equation (4.78) to scan entire possible vector symbol  $s$  during the optimization process.

$$\hat{s} = \arg \min_s \left\| y - \sqrt{\frac{E_s}{M_T}} Hs \right\|_F^2 \quad (4.78)$$

The search is usually done to all the vector symbol prospects for all possible transmitted signal vectors. The major drawback is in the complexity of the receiver which is in order of exponential of number of transmit antennas  $M_T$ , a scan of  $A^{M_T}$  is possible with brute force algorithm implementation (Paulraj et al 2003:149). The complexity of the ML receiver is reduced slightly when alternatively sphere decoding is implemented. Sphere decoders fails with huge numbers of interfering signals or antennas but can be effective for limited number of receiver antennas and neighboring base station  $NM_T$  (Andrews et al 2007:4).

The key objective of the sphere decoding is to minimize the complexity of calculation of the algorithm by scanning for points within the hypersphere of radius  $R$  over the received signal  $y$ , instead of the whole signal vector symbol (Paulraj et al 2003:150).

#### 4.5.5 MIMO Beamforming

Beamforming is the conventional use of directional transmission and reception of antenna arrays but from interference management perspective, it is signal processing techniques used for boosting the signal of the desired user while limiting interferers signal. This is slightly different in context of MIMO since there is no physical sense of direction but can be seen as transmission in one spatial dimension. This technique needs thorough interference statistics of every user at the transmitter which makes it appropriate for self-



cell interference alleviation and reduction in self-cell interference also reduces OCI. This can be illustrated by the use of MIMO system model of Equation (4.40).

$$\bar{y} = U\Sigma V^H s + \bar{n} \quad (4.79)$$

Where  $U\Sigma V^H$  is the single value decomposition of the channel matrix  $H$  ( $H = U\Sigma V^H$ ),  $U$  is the orthonormal unitary matrix ( $\|U_i\|^2 = 1, U_i^H U_j = 0$  if  $i \neq j$  &  $U^H U = I$ ),  $V$  is the orthonormal unitary matrix ( $\|V_i\|^2 = 1, V_i^H V_j = 0$  if  $i \neq j$  &  $V^H V = V V^H = I$ ) and the  $\Sigma$  is the matrix of singular values or non-negative rectangular diagonal matrix ( $\sigma_1, \sigma_2 \dots \sigma_t \geq 0$  &  $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_t \geq 0$ ). The rank of a matrix  $r$  is equal to the number of non-zero singular values.

$$\bar{y} = [u_1 \ u_2 \ \dots \ u_{M_T}] \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_{M_T} \end{bmatrix} \begin{bmatrix} v_1^H \\ v_2^H \\ v_{M_T}^H \end{bmatrix} s + \bar{n} \quad (4.80)$$

Assuming transmitted symbol vector of  $\bar{s} = \bar{v}_1 \tilde{s}_1$ ,  $\tilde{s}_1$  is the transmitted symbol,  $\bar{v}_1$  is the dominant transmission mode and the abstract direction in  $n$  dimensional space in the direction of  $s$  transmission. The resultant transmission will be.

$$\bar{y} = [u_1 \ u_2 \ \dots \ u_{M_T}] \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_{M_T} \end{bmatrix} \begin{bmatrix} v_1^H \\ v_2^H \\ v_{M_T}^H \end{bmatrix} \bar{v}_1 \tilde{s}_1 + \bar{n} \quad (4.81)$$

$$\bar{y} = [u_1 \ u_2 \ \dots \ u_{M_T}] \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_{M_T} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tilde{s}_1 + \bar{n} \quad (4.82)$$

$$\bar{y} = [u_1 \ u_2 \ \dots \ u_{M_T}] \begin{bmatrix} \sigma_1 \\ 0 \\ 0 \end{bmatrix} \tilde{s}_1 + \bar{n} \quad (4.83)$$

$$= \sigma_1 \bar{u}_1 \tilde{s}_1 + \bar{n} = \sigma_1 \tilde{s}_1 \bar{u}_1 + \bar{n} \quad (4.84)$$

Where  $\sigma_1$  is the channel gain associated with the transmission,  $\bar{u}_1$  is the dominant direction of reception. Since Equation (4.84) is like a SISO channel, received beamforming can be employed at the receiver using  $\bar{u}_1$  as maximum ratio combining.

$$\tilde{y}_1 = u_1^H \bar{y} = u_1^H (\sigma_1 \tilde{s}_1 \bar{u}_1 + \bar{n}) = \sigma_1 \tilde{s}_1 + u_1^H \bar{n} = \sigma_1 \tilde{s}_1 + \tilde{n}_1 \quad (4.85)$$

$$\text{SNR} = \sigma_1^2 \frac{P}{\sigma_n^2} \quad (4.86)$$

Where  $\sigma_1^2$  is the largest singular value and also the gain associated with the dominant transmission mode,  $\sigma_n^2$  is the noise power and  $P$  is of the power in the transmitted symbol.

This technique of MIMO Beamforming is referred to as Maximal Ratio Transmission (MRT). The benefit of MRT is the uncomplicated transmission and reception method for MIMO system compared to MIMO-ZF, MIMO-MMSE and MIMO-VBLAST. The attraction of MRT is that it has optimal capacity at low transmit power, since at low SNR you will be using only few dominant modes and the total  $r \times t$  diversity order is realizable.

In (Andrews, Choi and Heath Jr, 2007), it has been summarized the prospective techniques of other cells interference (OCI) in literature and their major drawback with respect to practical implementation as reproduced in **Table 3**. Some of the techniques have great potential but additional effective research needs to be done to overcome the instantaneous channel information needed for most of the schemes.

**Table 3.** Other cell interference alleviation scheme summaries (Andrews, Choi and Heath Jr, 2007:5).

<b>Technique</b>	<b>Benefit</b>	<b>Key Shortcomings</b>	<b>Prospect</b>
Frequency reuse	Reduces OCI very simply and effectively.	Low spectral efficiency, frequency planning	Not promising as a long-term solution
Maximum likelihood MUD	Optimum co-reception of signal and interference	Very high complexity, OCI awareness	Moore's law will help, but prohibitive in near future
MMSE MUD	Suppresses OCI with much lower complexity than ML	Requires awareness of OCI, many mobile antennas; simpler versions have only	Requires instantaneous OCI knowledge, under present investigation by industry

		modest performance gain	
OCI-blind MMSE	Like ZF spatial receiver with lower noise enhancement	Enhances OCI rather than suppressing it: very poor performance	Will provide only incremental gain(10-25%), but likely to be implemented
Other-cell interference cancellation	Good performance vs complexity	Complexity still high, awareness and accuracy of OCI knowledge crucial	Promising in the long-to provide additional gain over OCI-blind receivers
Stream Control	Reduces OCI; increase robustness	Lowers the data rate	Adaptive stream control is feasible and useful
Multuser diversity	Decreases required transmit power or increases data rate	Competes with other forms of diversity like frequency diversity; log log N growth(i.e. rapidly diminishing returns)	Likely to be useful in terms of scheduling, but not very effective for OCI reduction.
Cooperative encoding, i.e. dirty paper coding	Optimal performance in theory	Requires very accurate channel knowledge and real-time intercell coordination	Unlikely to be practical in foreseeable future, if ever
Closed-loop MIMO diversity	Achieves optimum diversity performance	Sacrifices spatial dimensions for a multiplexing, channels known at Tx	Likely to be implemented, can lower OCI somewhat
Beamforming	Reduces OCI	Sacrifices spatial dimensions, channel known at Tx	Has important merits, but implementation difficulties
Cooperative transmission	Reduces OCI, multuser diversity gain relative to frequency reuse	Requires simple cooperation between base stations	Feasible in the short-term
Distributed antenna systems	Reduces OCI through lowered transmit power; better coverage; ease of maintenance	Requires new infrastructure deployment paradigm	Feasible in the short-term with large infrastructure investment

#### 4.6 Massive MIMO

The major drawback of a point-to-point multi-antenna system is that it necessitates the use of costly multiple antenna devices. Multi-user MIMO offers alternative since a single antenna array can handle a collection of independent mobile stations which can be low-cost single antenna terminals. Additional capacity can be hypothetically created by simple installation of extra antennas at the base stations. Multi-user MIMO considered to be more

propagation environmental receptive when compared to a point-to-point MIMO (Marzetta 2010:1). The transmit power for both uplink and downlink can probably be decreased with big antenna arrays by using coherent combining with the resultant increased antenna aperture (Hoydis, Brink and Debbah 2013:1).

Massive MIMO is therefore the use of infinite number of multiple-input multiple-output (MIMO) in time-division duplexing (TDD) at the base station (BS) serving a fixed number of terminal devices. MIMO channels are considered almost-orthogonal when the number of antennas at the base station is greater than the number of terminal for each resource of signal and almost-optimal solution can be obtained with uncomplicated multiplexing/demultiplexing procedures (Boccardi, Heath, Lozano, Marzetta and Popovski 2014). Massive MIMO is expected not only to be decisive technology to improve energy and spectral efficiency of wireless communication but the enabler of broadband services for LTE and beyond (Abu-Ella 2014:14). If the number of antennas at the base station is far greater than the number of users, a straightforward precoding/detecting method can eliminate inter-cell interference, fast fading and thermal noise in a massive MIMO system and system performance can only be restricted by pilot contamination (Hoydis et al 2013:1).

Though massive MIMO appears very attractive but the need for channel knowledge and estimation has been the major inhibition to deployment. User mobility is restricted as a result of the limitation to obtain and use channel knowledge in coherent time (coherent time also determines the number of users that can be served). Orthogonal pilot signals are fixed and had to be reused, this leads to pilot contaminations and coherent interference that increases proportionally with the increase in the number of antennas. The pilot time does not depend on the number of antennas at the base station but is commensurate with the number of serviced devices (Marzetta 2010:1).

#### 4.6.1 Massive MIMO capability

The attraction of the massive MIMO depends on uncomplicated signal processing from the entire antennas at the cell site and phase coherency. Few of the advantages of Massive MIMO in the next generation of network are (Larsson, Edfors and Marzetta 2014:2):

- Massive MIMO facilitates meaningful decrease in air interface latency by depending on the law of large numbers and beamforming to escape fading dips which restricts latency. The system performance of the wireless communication is degraded by fade when transmission from base station to terminal device has to travel through multiple paths existing between them. This fade varies in signal strength and can sometime interfere destructively contributing to the challenge of designing/building low-latency network.
- 100 time radiated energy efficient and 10 times capacity increment compared to ordinary MIMO makes massive MIMO very attractive. Energy can be directed with high precision to small regions in space when you have substantial number of antenna which results to energy efficiency. The principle of coherent superposition of wavefronts makes it possible for the base station to shape wavefronts emitted by the entire antennas constructively towards the desired terminals and destructively in the direction of the interferers, the interference can further be smoothed by the very simple ZF receivers. Robust spatial multiplexing used in massive MIMO leads to capacity enhancement mentioned earlier.
- In Massive MIMO the accuracy and linearity of every specific amplifier and RF chain of every antenna does not count so much but the combined action, therefore costly ultra-linear 50W amplifiers used in current systems can be replaced with hundreds of inexpensive milli-watt power amplifiers. The dependent of massive MIMO on the law of large numbers guarantees that fading, noise and hardware inadequacy averages out with the aggregation of signals from substantial number of antennas in the air. The same characteristic is the reason why massive MIMO is not

only robust against fading and failure of the few antennas but provides excess degree of freedom.

- Finally Massive MIMO facilitates the multiple access layer and can prevent intentional jammer. Each sub-channel in Massive MIMO-OFDM has considerably identical channel gain resulting to each terminal having access to the whole bandwidth. A smart application of joint decoding and channel estimation will significantly reduce the intentional jamming problem.

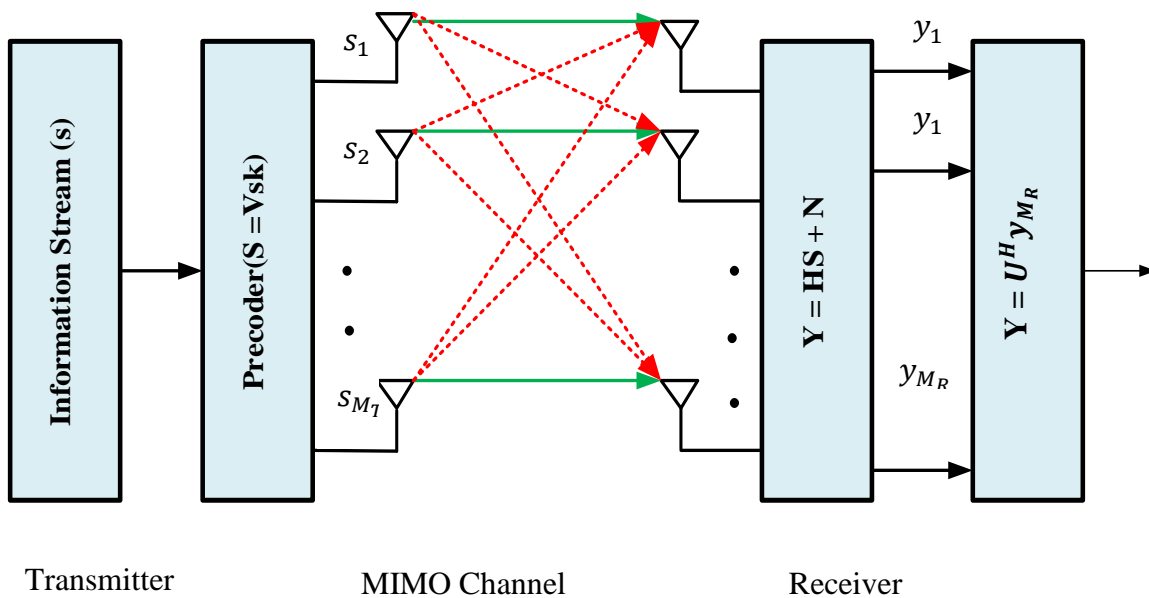
#### 4.6.2 Issues and challenges of Massive MIMO

- Pilot contamination: Since each terminal will be allocated orthogonal pilot sequence in the uplink and it is limited by quotient of coherence time interval to the duration of the channel delay spread, there is possibility of using up all the available orthogonal pilot sequence. In a bid to serve more terminals, pilot reuse policy is implemented; the adverse effect of pilots sequence reuse is called pilot contamination. Pilot contamination occurs when a terminal device acquires a channel estimation that is corrupted by a linear combination with other terminals with the same pilot sequence. The corrupted channel develops to interference targeted towards the terminal device that have the same pilot sequence and the growth of the interference is proportional to the increase to the number of service antennas (Larsson et al 2014).
- Propagation Model: The assumption in massive MIMO research that with increment in the number of antennas that each terminal device channels are spatially uncorrelated and channels becomes pairwise orthogonal. In addition to adoption of i.i.d Rayleigh fading model to analyze massive MIMO, it has been observed experimentally that actual antenna correlation is extremely bigger than i.i.d Rayleigh assumption. This means that experimental findings undermine the theoretical orthogonality of channel vectors resulting from increment in MIMO (Abu-Ella 2014). This is a propagation model challenge and can be hopefully resolved as more research work is done in that direction.

- Hardware impairment and cost: Designing and constructing inexpensive and energy efficient analog-to-digital converter (A/D), digital-to-analog converter (D/A), RF chains and up/down converter must be a requirement in massive MIMO. The low-cost may lead to huge hardware inadequacies that may also contribute to high thermal or quantization noise. Phase noise may likely degrade the system performance if free-running oscillators or cheap phase locked loop is utilized in the system. An intelligent and careful design of transmission physical layer/receiver algorithms has the possibility of solving the phase noise problem in future (Larsson et al 2014).

## 5. System Model and Simulation

The system model is a MIMO (Multiple-Input Multiple-Output) in a wireless interference communication link with a number of antennas at the base station and limited number of antenna at the terminal device due to cost and processing but for the sake of simulation as represented in **Figure 21**. It consists of  $M_T$  transmit antenna and  $M_R$  receive antennas with channel matrix or fading coefficient of  $h_{i,k}$  ( $H$ ) representing the complex transmission path of  $k$ th transmit antenna to the  $i$ th receive antenna.  $H$  is  $M_T \times M_R$  channel matrix and it is assumed to be independent identical distributed (i.i.d) zero mean complex Gaussian random variable. The transmitted symbol is  $S \in \mathbb{C}^{M_T \times k}$  and the received signal is  $Y \in \mathbb{C}^{M_R \times i}$ .



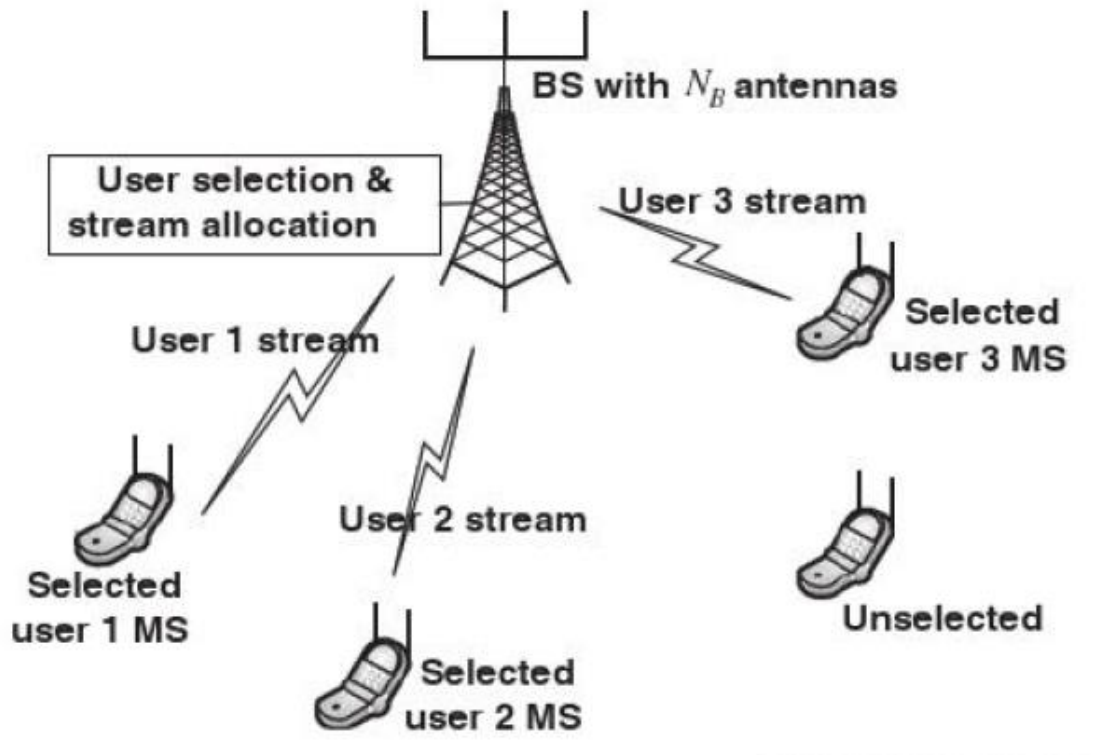
**Figure 21.** Wireless Interference MIMO communication link

### 5.1 Multi-User Detection using ordered or Non-ordered SIC

High capacity is possible in a point-to-point single user MIMO system through spatial multiplexing with additional gain of spatial diversity but in real life wireless communication system has to do with multi users who have to contest for available radio



resources like time, power, frequency and spatial streams as depicted in **Figure 22**. If we assume  $K$  independent users,  $N_B$  number of antennas at the single base station and  $N_M$  antennas at the mobile station, then the total arrangement of the antennas will be  $(K.N_M) \times N_B$  in the downlink and  $N_B \times (K.N_M)$  in the uplink (Choi et al.2012:395). The downlink is referred to as broadcasting channel or one-to-many and the uplink is Multiple Access Channel (MAC) alternatively known as many-to-one. This account for additional degree of freedom in multi-user MIMO systems compared to single user.



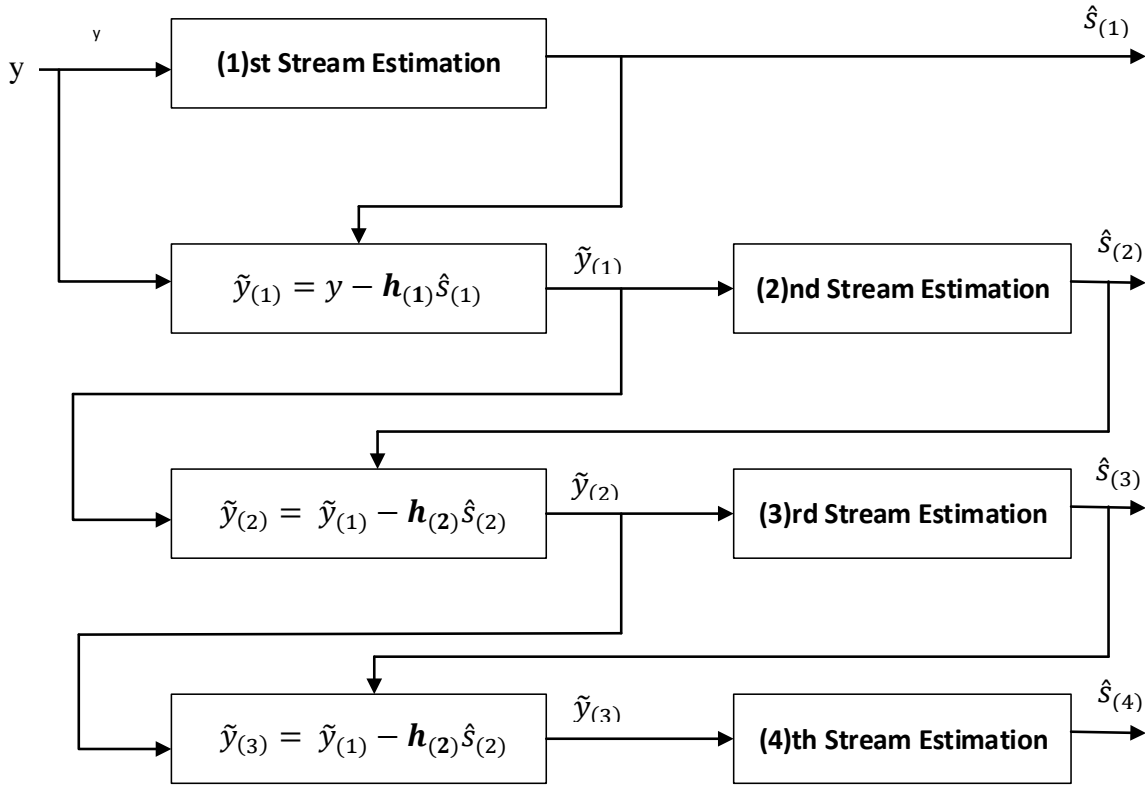
**Figure 22.** Multiple User Communication in MIMO,  $K = 4$ (Choi et al.2012:396)

The fundamental of SIC as discussed in Chapter four is iterative, that is the effect of each data stream decoded in one layer is subtracted from the original signal before the next layer is processed. It is called Non-ordered SIC when decoding is done in no particular order especially when transmission rate is lower compared to the system capacity or long codewords implemented, otherwise it is referred to as Ordered SIC. Erroneous decision is

likely to happen in each stage of SIC due to fading and randomness of the channel, Ordering is implemented to avoid error propagation in practical system. The post-processing ordering can be based on SINR, SNR or Column norm (Brown, De Carvalho & Kryitsi 2012:101).

With the expected enhancement in performance in LTE and 5G in the uplink with proposed implementation of massive MIMO, the downlink can only have significant improved performance with application of optimal detection algorithm knowing the limitation in the number of antennas, compactness and cost of the user terminal. The complexity of this algorithm is of immense important since a complex algorithm will require more computational power with corresponding effect in the battery life of the mobile terminal where power consumption is a major constraint. The scenario is a little bit different in the uplink where the power consumption is not as challenging in the base station as with mobile terminal even with the green communication.

As discussed in Chapter four, linear receivers performs poorly when compared to non-linear receivers but the advantage of ordered successive interference cancellation technique (OSIC) being investigated in this thesis is that the performance can be enhanced without meaningful increment in hardware complexity. OSIC is simply a combination of linear receivers with each detected parallel data streams successively canceled or subtracted at each phase as shown in **Figure 23** and resultant decreased interference signal is used in the next phase. Zero-Forcing or MMSE algorithm can be implemented for estimation of the transmitted symbol, interference is successfully eliminated if transmitted symbol equals the estimated symbol ( $s_{(1)} = \hat{s}_{(1)}$ ) otherwise propagation error is obtained since  $s_{(1)} = \hat{s}_{(1)}$  will be used in estimation of  $\hat{s}_{(2)}$ .



**Figure 23.** Four spatial streams OSIC detection (Choi et al.2012:323)

The procedure of detection limits the performance of the OSIC since there is probability of wrong decision; four different possible post-detection ordering are discussed below.

**SINR ordering option:** Using MMSE detection algorithm, highest priority is on the signal with greatest signal-to-interference-noise-ratio (SINR) after detection based on the equation (5.0) below:

$$\text{SINR}_i = \frac{E_s |W_{i,\text{MMSE}} h_i|^2}{E_s \sum_{l \neq i} |W_{l,\text{MMSE}} h_l|^2 + \sigma_n^2 \|W_{i,\text{MMSE}}\|^2}, \quad i = 1, 2, \dots, M_T \quad (5.1)$$

$E_s$  represents the transmitted signal energy,  $h_i$  the  $i$ th column vector of the channel matrix and  $W_{i,\text{MMSE}}$  the  $i$ th row of the MMSE weight matrix.  $\sum_{j=1}^{M_T} j = \frac{M_T(M_T+1)}{2}$  is the overall values of SINR that can be computed in MMSE-OSIC (Choi et al.2012.323).

**SNR ordering option:** The interference part of equation (5.0) vanishes when ZF detection algorithm is utilized. The signal power  $|W_i h_i|^2 = 1$  and the SINR can now be represented as

$$\text{SNR}_i = \frac{E_s}{\sigma_n^2 \|W_i\|^2}, \quad i = 1, 2, \dots, M_T \quad (5.2)$$

The process of detection is the same except that SNR is used in post-detection computation instead of SINR.

**Column Norm ordering option:** The norm of the column vector can be used to decrease the computational complexity involved in SINR and SNR calculations. The received signal of successive interference cancellation can be represented as

$$y = Hs + n = h_1 s_1 + h_2 s_2 + \dots + h_{M_T} s_{M_T} + n \quad (5.3)$$

The norm  $\|h_i\|$  can be used in the detection of the signal since the received signal strength of the transmitted  $i$ th signal corresponds to the norm of the  $i$ th column in the channel matrix. The reduction in computation complexity is evident in this scheme since only calculation of norms of vector  $M_T$  is done while decreasing order of norms is used in the ordering.

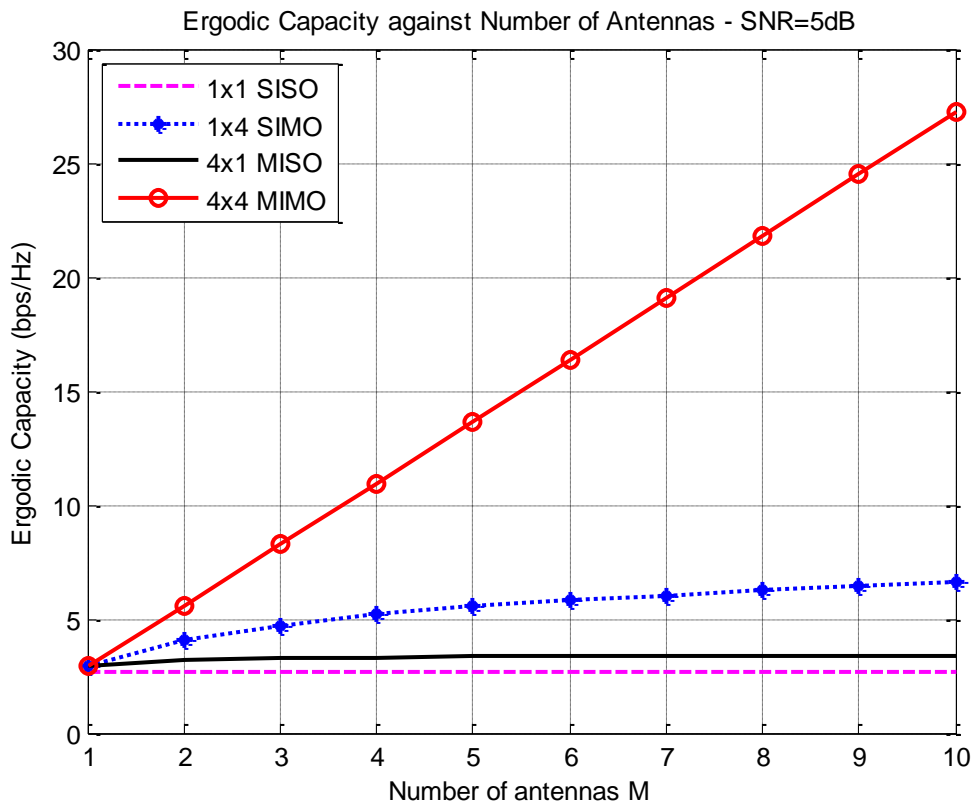
**Received signal ordering option:** This option comes with the best performance and the greatest complication because detection ordering is necessary whenever a signal is received as compared to the previous three options where ordering is done once when fixed channel is assumed.

## 5.2 Simulation and Analysis

The key idea of these simulations is first to validate the existing results in literatures on the concept of MIMO techniques that utilize the multipath effect hitherto considered a limitation in wireless communication to the advantage of mobile wireless communication

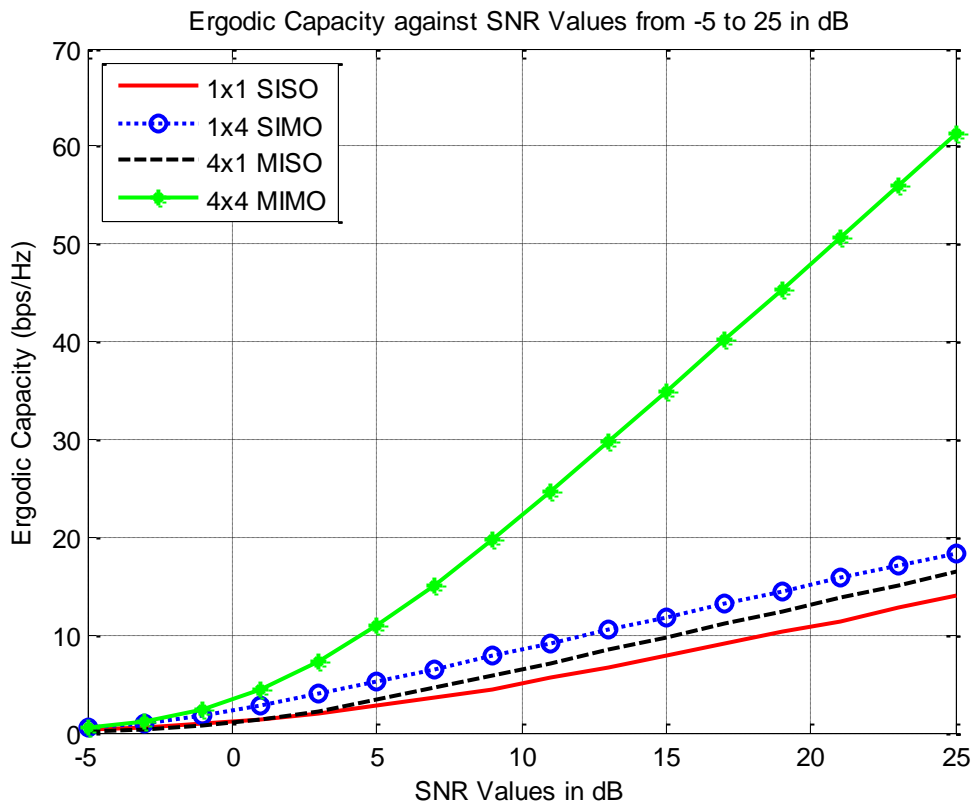
considered interference limited network in order to achieve maximum possible data rate. Independent and identical distributed Rayleigh Channel is assumed in all the simulations.

We started off with a plot of **Figure 24** depicting Ergodic capacity against number of antennas for different antenna configurations for a space time wireless communications system. It will be observed that ergodic capacity has a linear proportional increment in MIMO with increase in the number of antennas while that is not the case with SISO, SIMO or MISO. The last statement is true only where there is no power constraint but since power is restricted in a mobile wireless environment, the increment that will occur will not be linear. This is one of the reasons of the tremendous research effort on MIMO channels in the last decade trying to fully exploit the capacity increase for the new generations of wireless communications.



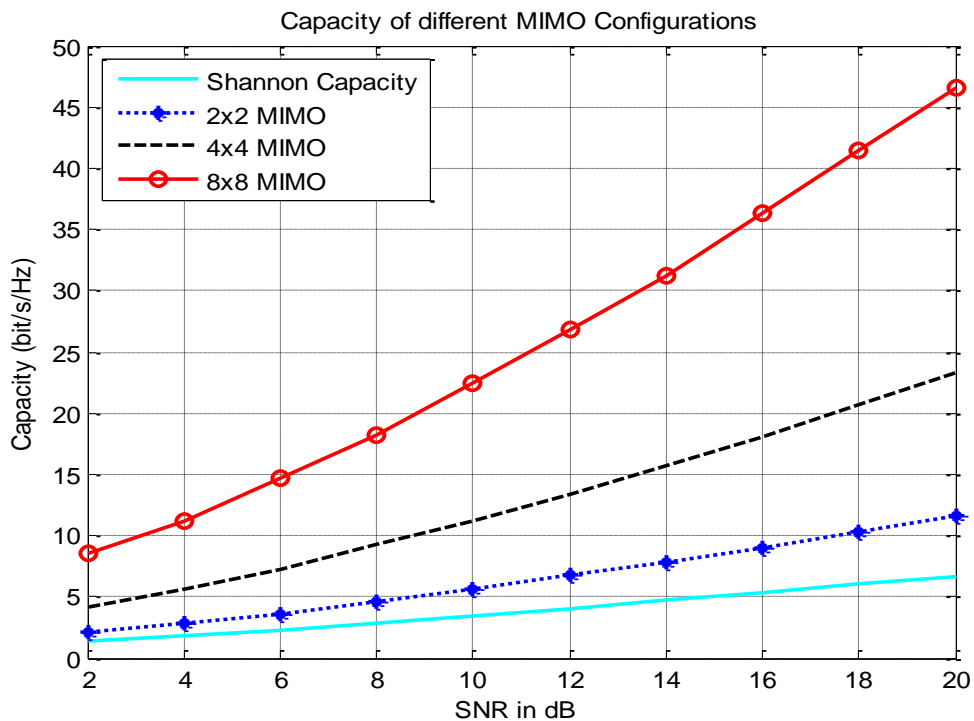
**Figure 24.** Ergodic capacity Vs different ST antenna configuration at 5dB.

**Figure 25** is the comparison of ergodic capacity with different antenna configurations in ST wireless communication environment at different transmit power (SNR). Again, it shows similar characteristics with **Figure 24** and also the superiority of MIMO channels compared to SISO, SIMO and MISO Channels. The ergodic capacity is the mean data rate and it increases with increase in transmit power (SNR), in addition with number of transmit/receive antennas as anticipated. It is noticed from **Figure 25** that capacity changes from 12bps/Hz for SISO, 14bps/Hz for MISO, 16bps/Hz for SIMO and 48bps for MIMO at SNR = 20dB, representing about 67% capacity gain by just increase in the number of antenna from traditional SISO without any further increment in power .



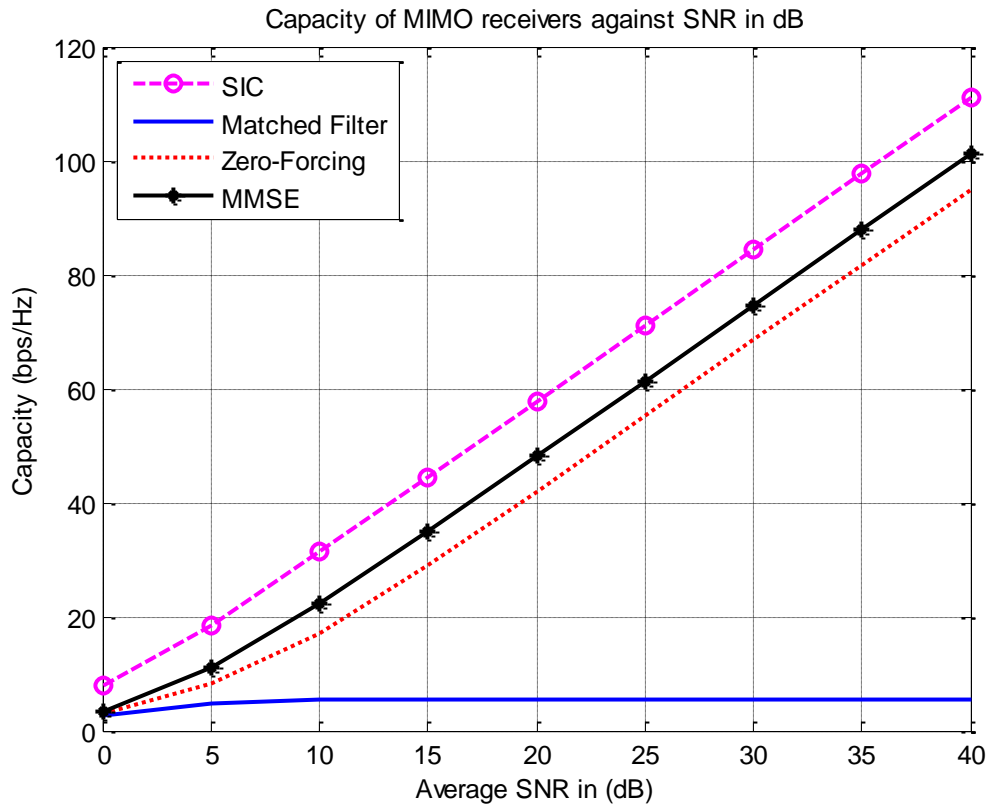
**Figure 25.** Ergodic capacity for different antenna configurations at varying SNR values.

Channel capacity is highest data rate possible through an ST wireless communication link without error. **Figure 26** is the representation of such capacity for different MIMO channels configurations, highlighting the benefit of using more antennas especially with the advent of massive MIMO techniques at the base station or the access point. The ergodic capacity of the frequency-selective Rayleigh fading channel is the same as frequency flat Rayleigh fading channels with no correlation else the former is consistently lower than that of the frequency flat fading in physical channels (Xiao and Zheng., 2003:346) but the emphasis here is not on the difference between the two type of fading channels but rather of the behavior of the different MIMO channel configuration capacity against the increase in the number of antennas. As can be observed from **Figure 26**, the Shannon capacity at SNR of 10dB is approximately 4bps, 6bps for 2x2, 12bps for 4x4 and 24bps for 8x8, representing 50% increment from Shannon capacity to the first MIMO configuration and 100% for one MIMO antenna configuration to the other.



**Figure 26.** Ergodic capacity of MIMO Channels Vs Number of antennas.

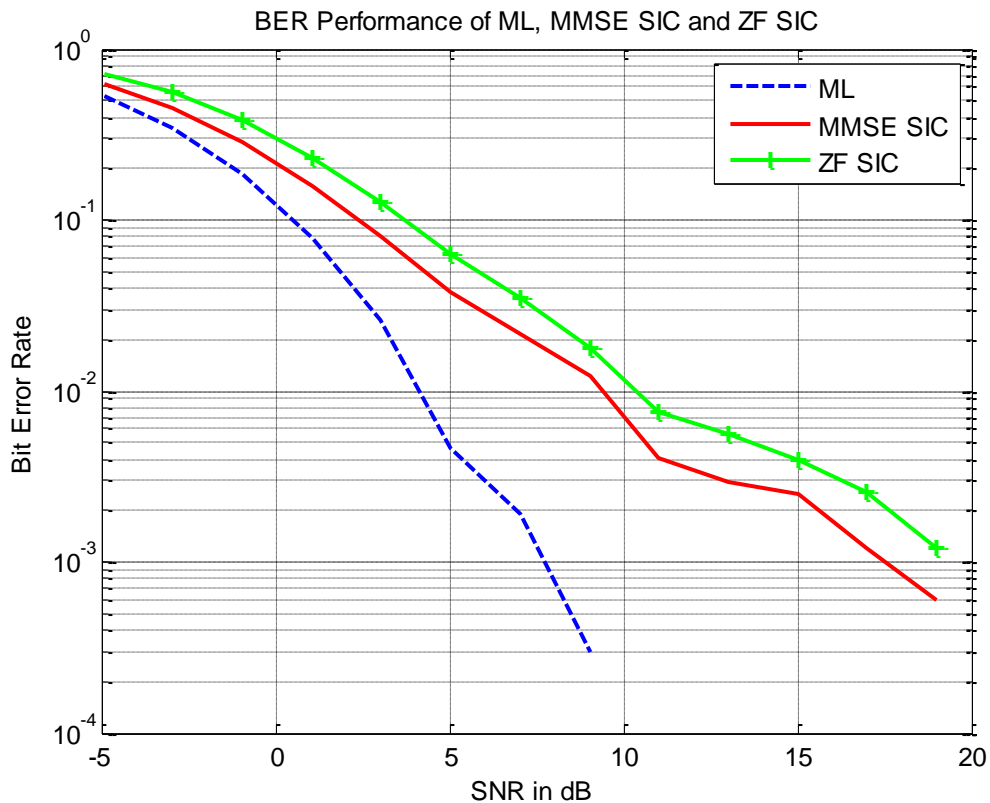
Achievable rate of different MIMO receivers is simulated in **Figure 27** for a 4 x 4 MIMO at various transmit power (SNR). Successive interference cancellation outperforms the linear receivers, though the complexity of such a receiver must be considered in any analysis. At a very low SNR (below zero), the sum rate of different receiver scheme are almost the same but increases proportionally with increase in SNR. It will be observed from **Figure 27** that achievable rate for Matched filter is 5bps/Hz, 42bps/Hz for Zero-Forcing, 48bps/Hz for MMSE and 58bps/Hz for SIC at SNR of 20dB. This achievable rate is under the assumption of independent and identical distributed Rayleigh fast fading channel.



**Figure 27.** Capacity comparison of different MIMO receivers at different SNR for  $M_T = M_R = 4$



The next figure is a comparison of different interference management MIMO receivers. It can be observed from **Figure 28** that ML detector has the optimum performance followed by MMSE SIC and ZF SIC. The challenge with ML detector is that the complexity grows exponentially with increase with the number of antenna which has limited the practical application (discussed extensively in Chapter 4). Incorporation ZF and MMSE linear receivers with non-linear Successive Interference Cancellation receiver gives rise to sub-optimal detector with very low implementation complexity compared to ML. MMSE SIC is preferred since ZF receivers enhances noise.

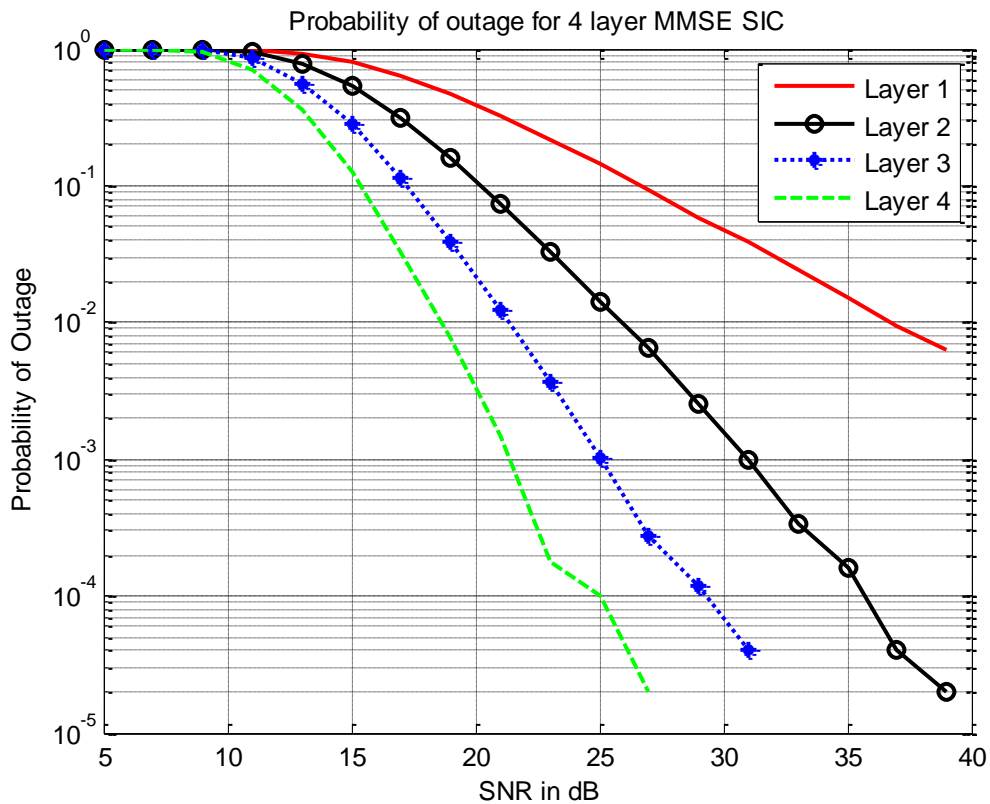


**Figure 28.** BER comparison of ML, MMSE SIC and ZF SIC Receivers,  $M_T = M_R = 4$ .

The next diagram is performance comparison of four layers non-ordered SIC which do not take into account the possibility of error propagation that may result from wrong estimation of the transmitted symbol in any of the stages. It can be observed from the

**Figure 29**, the progressive improvement as the signals are being detected in each stage and being canceled thereby increasing the diversity gain of the SIC.

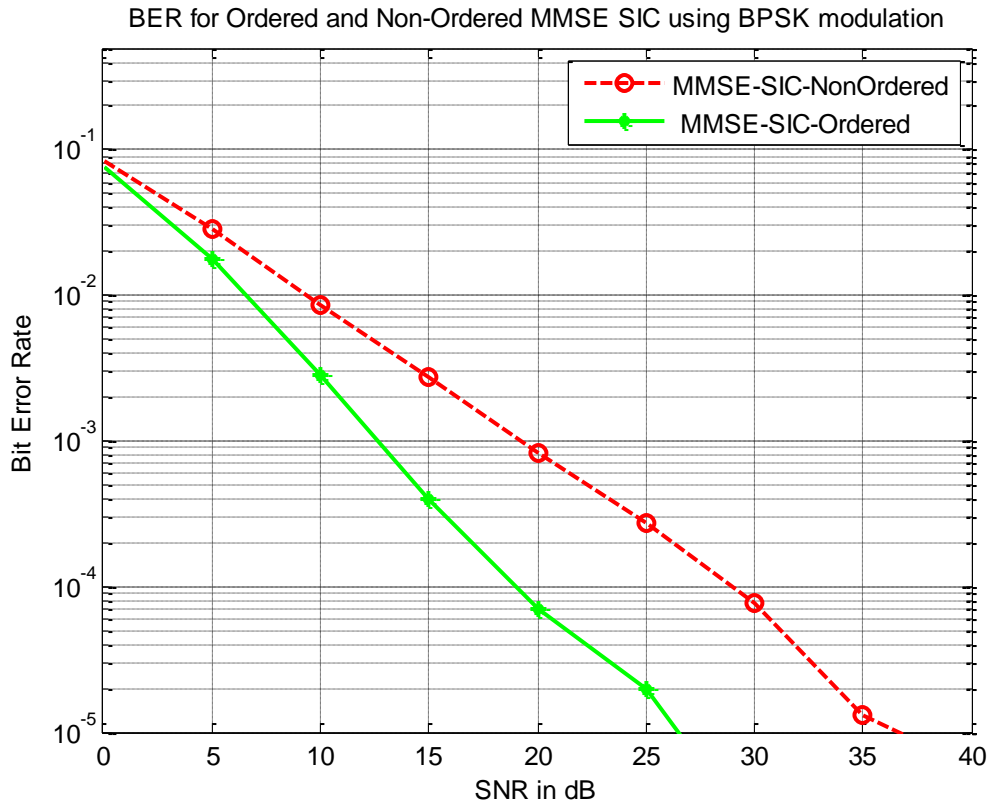
In a Multi-User Detection (MUD) environment, the contribution of the first user is removed from the received signal after detection. The process is repeated progressively until all the users are detected. The advantage of this scheme in interference management when using post SNR detection processing in OSIC is that users with highest SNR are detected first, followed by the next user with the next highest and so on, thereby making it easy to detect all the users with low SNR with minimal or no interference if there is no propagation error.



**Figure 29.** Outage probability for four stream SIC receiver,  $M_T = M_R = 4$

V-BLAST implementing OSIC processes users with highest SNR first, removes its effect, encodes and modulates for the next user until the entire users are progressively decoded.

The benefit is that users with low SNR can achieve their target with minimal or no interference compared to when it has to contend with very strong users.



**Figure 30.** Performance comparison of Non-ordered and Ordered SIC  $M_T = M_R = 2$

The efficiency of SIC can be greatly improved with slight increase in complexity and propagation error reduced when post SNR detection optimal ordering is implemented in addition. This ensures that strongest user is decoded first and subtracted from the received signal, thereby improving the performance of the whole system as can be seen from **Figure 30**. To further illustrate this point, the simulation result in **Figure 30** shows performance improvement in bit error rate performance from  $10^{-3}$  to  $10^{-4}$  at SNR of 20dB. There is always trade off in practical systems depending on the requirement of the application,

ordering may be necessary for some application that requires strict BER performance while ordinary SIC will suffice for systems with relaxed BER performance.

Every layer of ZF or MMSE can achieve a diversity gain of  $M_T - M_R + 1$  while SIC has the possibility of achieving  $M_T - M_R + K$  ( $K$  is the number of layers or stream in OSIC detector). The reduction in performance of ZF and MMSE detectors is attributed to deficit in array gain (Brown et al. 2012:108).

## 6. CONCLUSION AND FUTURE WORK

The benefit of capacity increase and spectral efficiency of MIMO technology has been limited in practical application due to the fact that wireless mobile communications network are interference-limited and that MIMO receivers are interference aware. Consequently, increasing the number of antennas by the use of MIMO system introduces corresponding increase in the number and sources of interference especially at high signal-to-noise and interference ratio (SINR).

Based on above premise, interference management in MIMO vis-à-vis cellular networks becomes a prerequisite to realizing the full advantage of this system. Interference management in LTE and beyond is a broad topic as there are many methods to manage different interferences applicable in a mobile network as identified and summarized in **Figure 5**. The method employed will depend on the type of interference of interest; it has been broadly categorized into homogenous and heterogeneous network. Some of the techniques in that figure like spread spectrum and frequency reuse are not spectral efficient hence the advent of MIMO system. Some other spectral efficient methods identified may have a high level of complexity and may sometime require knowledge of channel state information (may be difficult to obtain due to varying nature of the wireless channel).

In this thesis, our treatment has been limited for the other cell interference. Interference management in MIMO were largely discussed and investigated because MIMO has been proven in literature to be the key technological enabler for 4G and 5G networks. In fact, the discussion has progressed even further to Massive MIMO especially as we advance towards 5G roadmap. A robust Interference management in MIMO (which may be assumed to be interference management in 4G and 5G) is not only a necessity but a condition for mining full benefit of MIMO technology.

Successive interference cancellation based on V-BLAST algorithm has proven through simulation to be very attractive and efficient method to deal with this interference especially in downlink multi-user detection environment. Though simulation revealed that

Maximum Likelihood (ML) detection is optimal technique for dealing with this kind of interference compared to SIC but literature has acknowledged that the complexity of ML detector increases exponentially with increase in the number of antennas. The computational power and the consequent demand on the battery required especially for a mobile terminal in downlink makes it unattractive at this stage.

The appeal of SIC or OSIC is that it is possible for all users in MUD to achieve their respective target without any corresponding increase in the transmit power. Since the basic idea is that the signal of strongest user at the same time the strongest interferer to other users is decoded and removed first, the diversity gain is achieved while each user accomplish its target.

The major challenge with broadcast channels (BC) or downlink transmission is non-availability of simple harmonized signal detection method and therefore supplementary interference management technique will be required at the base station to effectively deal with it. In simple terms, in addition to implementing OSIC at the receivers (mobile stations), one of the following precoding transmission methods have to be adopted in the base station to have a robust interference management: Dirty paper coding (DPC), Tomlinson-Harashima precoding (THP), block diagonalization and channel inversion.

Channel inversion/regularized channel inversion in multi-user environment is a precoding technique that treats all signals as interference except the desired. It is similar to ZF precoding under the assumption of single antenna at the mobile station ( $N_M = 1$ ,  $K = N_B$ ) and number of users equals number of antennas at the base station. The noticeable difference is that received signal per mobile terminal is a scalar instead of vector as in the case of ZF.

Block diagonalization (BD) occurs when the pre-transmission processing is done for multiple users under the assumption of more than one antenna. The target is to mitigate the interference from other users or terminals in the precoding and is better suited for noisy environment compared to channel inversion. The interference cancelation can be achieved

by diagonalizing the channel matrix in such a way as to meet the total power constraint at the transmitter and the precoder matrix must be unitary.

Dirty paper coding (DPC) precoding method requires thorough channel state information at the transmitter since the probable interference is mitigated before transmission, that is for  $k$ th user signal reception,  $(k-1)$ th user signals must have been known and cancelled with during precoding at the transmitter.

Tomlison-Harashima precoding was initially developed to minimize peak or average power in decision feedback equalizer (DFE) to avoid error propagation. It is a mixture of symmetric modulo operation with DPC with full channel impulse response information (Choo et al 2012:412).

The limitation of SIC or OSIC is that it is not much effective in a power controlled network environment or in a network that employs power allocation algorithm. The reason is that when all the users have the same power or similar SNR, the algorithm will not be able to determine the order of detection. It is efficient interference management technique when the interference comes from the same network but additional scheme will be required in a heterogeneous network to sufficiently deal with interference that may arise from different network.

OSIC will be effective algorithm to manage Cell edge users that may be receiving interference from other cells from neighbor base stations. Since it is possible to decode and remove the strongest signals first, it will possible to remove the strongest interferer first which improve the performance of the cell edge users.

From the inception of the research on the topic, it became obvious that the topic "INTERFERENCE MANAGEMENT IN LTE AND BEYOND" is a broad topic. This means that all the possible interference in a wireless mobile network cannot be covered in a single thesis. It was apparent to narrow down the topic and the common guiding question was to investigate the aspect of interference management that will be useful to both LTE and future generation of networks. Through the review of literatures, it became evident that

MIMO has become and will continue to be the technology driver of the next generations of wireless networks. At the end of this study, a lot of open problems are still conspicuous and therefore form part of my future work:

- Since Massive MIMO will be a key technology in 5G network, future work may be specifically to look at practical implementation of successive interference cancellation in a massive MIMO environment. It will also be good research topic to investigate the four precoding transmission techniques mentioned earlier in a bid to find out the best scenario for practical implantation of each one, its draw back, resource requirements and strong point.
- Future generations of network are expected to be more dense, dynamic and heterogeneous. Interference management in environment with macro-cell, micro-cell and different technology like WiMAX definitely will be more challenging. A prospective research could be interference management that can dynamically adapt to such unpredictable environment.



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