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**THROUGHPUT OPTIMIZATION AND ENERGY ENHANCEMENT IN
MASSIVE MIMO SYSTEMS**

Master's thesis for degree of Master of Science in Technology submitted for
inspection in Vaasa, 11 November, 2016

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ABBREVIATIONS

1G/2G/3G/4G/5G	First /Second /Third /Fourth /Fifth Generation
3GPP	Third Generation Partnership Project
AMPS	Analog Advance Mobile Phone
AWGN	Additive White Gaussian Noise
BS	Base Station
CDMA	Code Division Multiple Access
CDF	Cumulative Distribution Function
CEPT	European Conference of Postal Telecommunication
CSI	Channel State Information
CSIR	CSI Receiver
CSIT	CSI Transmitter
EPC	Evolve Packet Core
EE	Energy Efficiency
ETSI	European Telecommunication Standards Institute
eNB	Evolve Node B
FDMA	Frequency Division Multiple Access
FDD	Frequency Division Duplex
GSM	Global System for Mobile Communications

GPRS	General Packet Radio Service
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
HSPA	High Speed Packet Access
IoT	Internet of Things
IEEE	Institute of Electrical and Electronic Engineers
ITU	International Telecommunication Union
KPIs	Key Performance Indices
LTE	Long Term Evolution
MIMO	Multiple-Input-Multiple-Output
MRC	Maximum Ratio Combining
MMSE	Minimum Mean Squared Error
M2M	Machine-to-Machine
MU-MIMO	Multi-User MIMO
mMW	Millimeter Wave
NMT	Nordic Mobile Telephone
OFDMA	Orthogonal FDMA
PDC	Personal Digital Cellular
PC	Pilot Contamination

PDF	Probability Density Function
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
SNR	Signal to Noise Ratio
SISO	Single Input Single Output
STC	Space Time Coding
SE	Spectral Efficiency
SU-MIMO	Single-User MIMO
TACS	Total Access Systems
TDMA	Time Division Multiple Access
TDD	Time Division Duplex
UMTS	Universal Mobile Telecommunication Systems
UE	User Equipment
VNI	Visual Networking Index
WCDMA	Wideband Code Division Multiple Access
ZF	Zero Forcing

SYMBOLS

S_x and S_y	Integral of random variable X and Y,
$f(y)$	Denotes the probability density function (PDF)
N	Noise
S	Signal
C	Capacity
H	Channel matrix
h_{ij}	Channel gain from the <i>i</i> th receiver to <i>j</i> th transmitter
H^T	Hermitian transpose
I	Identity matrix
Σ	Matrix of singular values
E_x	Transmitted Signal energy
r	The rank of a matrix
U	Othonormal Unitary matrix
\mathbf{R}_{ss}	Covariance matrix

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ABSTRACT

For the last few decades mobile technologies have undergone enormous transformation. Mobile broadband for cellular networks has been exponentially evolving with time and in order to meet the future expectation for this high demand newer and better technologies have to be invented. The enormous success of smart electronics such as tablets, smart phones and other hand held devices that use the Internet have generated a lot of Internet traffic therefore, diving LTE to its limit.

LTE (4G) which is a high speed wireless communication standard for mobile phones and data terminals is a significant upgrade of GSM and UMTS network technologies. The Technology has downlink peak rates of 300Mbits/s and Uplink peak rates of 75Mbits/s with transfer latency rate of less than 5ms. Power Consumption level for LTE is of significant concern as well as the energy consumption in cellular networks. To solve the limitations in LTE, one great candidate is 5G radio standard. 5G relies heavily on massive MIMO to achieve its targets.

This thesis looked into significance of Multi-antenna (Massive MIMO) at the BS as a solution for energy efficiency, increased data rates and the reduction of latency rates in wireless broadband communication. And the simulation results proved that Massive MIMO has better performance compared to conventional MIMO.

KEYWORDS: Massive MIMO, 5G, Energy efficiency, Throughput Optimization

1 INTRODUCTION

For the last few decades, data traffic for mobile communication has increased exponentially. As technology keeps on maturing the demand for better wireless technologies that can support a high data throughput will be needed. According to Cisco Visual Networking Index (VNI) for global Mobile data Traffic forecast updates as of 2015, the overall global Mobile Data Traffic is expected to grow to a tune of 30.6 Exabyte per month by the year 2020 as shown in Figure 1. This exponential growth in data traffic is attributed to the increase in number of wireless devices that are accessing cellular networks worldwide. Currently more than 8 billion devices are connected and with the introduction of new technologies, more and more devices will be expected to be connected by the year 2020 as shown in Figure 2. All this newly connected devices will generate more data traffic thus a wireless Internet with higher bandwidth is required.

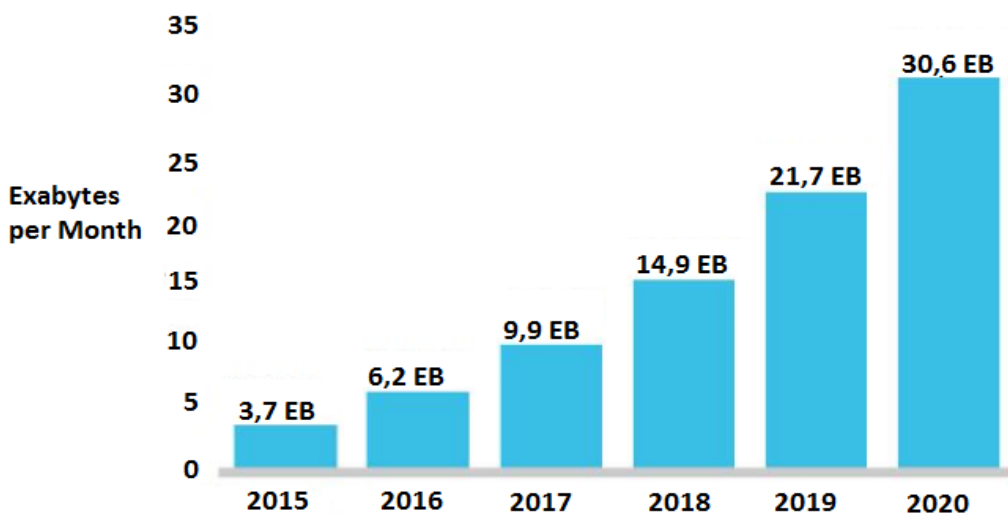


Figure 1. Cisco Forecasts 30.6 Exabyte's per Month of Mobile traffic by 2020 (Cisco VNI Mobile, 2016).

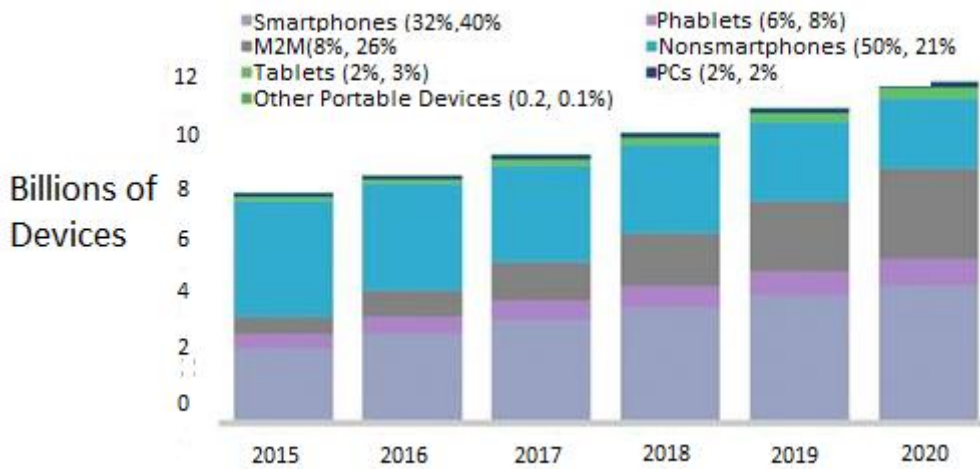


Figure 2. Global Mobile Devices and Connections Growth 2020 (Cisco VNI Mobile, 2016).

Motivated by this unprecedented growth in the number of connected devices and the approaching limits of 4G technologies, companies and universities have embarked on intensive research for the next technology that will support this expansive growth of mobile traffic and connected devices. Currently 4G technology is almost stretched to the limit and in order to meet these demands, 5G has been proposed. 5G technology is expected to support high data rates, low latency and economize the limited available space spectrum. The technology is also expected to support mobility at speeds ranging from 300 to 500km/h. (5G vision whitepaper, Samsung 2015.)

The high data rate and high capacity expected from 5G will be addressed by use of millimeter wave (mmW) systems (spectrum frequencies of between 6GHz to 300GHz), this is because wavelengths of 6GHz and below has been fully utilized. IoT expects 5G system to be able to support upto 10^6 simultaneously connected

devices per square kilometer. More of 5G specifications and expectations will be discussed in the chapter 2.

The thesis has five chapters. Chapter 1 contains the introduction. The second Chapter deals with the history and evolution stages of cellular wireless technology. In Chapter 3, the prospect of Massive MIMO is discusses. The experiments and their results are shown in Chapter 4. Chapter 5 contains the conclusion and future works.

2 THEORY AND BACKGROUND INFORMATION

2.1 Evolution of the Wireless Mobile Technology

From the onset of wireless communication technology back in 1895 when Marconi invented the first radio telegraph, the technology has been developing rapidly as shown in Figure 3. The figure shows various evolutions stages that the cellular technology has undergone. Wireless data rates have increased dramatically as well, from kilobytes per second to current rates which are in megabytes per seconds. With the high demand of wireless internet, further research and new technologies has to be put in place in order to support the high data rates that are needed.

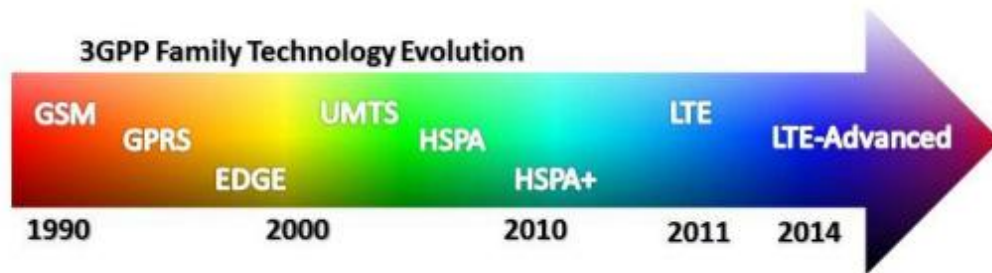


Figure 3. 3GPP Family Technology Evolution (Saraswat, Jain, Kaushik & Charu 2013).

The first generation (1G) circuit switched cellular technology was introduced in early 1980s and it was based solely on analog transmission. 1G supported only voice communication and depended entirely on Frequency Division Multiple Access (FDMA); the technology was limited in capacity and supported data rates

of 20-30 kbps and it also lacked standardization. (Osseiran, Monserrat & Mohr 2012: 3.)

Though it supported handover and roaming, the technology was only limited within countries and therefore lacked in interoperability between different systems and across different countries. Different regions of the world had different standards such as Nordic Mobile Telephone (NMT) for the Nordic countries, Analog advance Mobile Phone (AMPS) for America and Total Access System (TACS) for United Kingdom. First generation analog channel was prone to static noise interference and had no protection from eavesdropping. The technology also pioneered and applied the use of cells. The use of cells enabled frequency reuse without any serious interference between cell users. (Osseiran et al. 2012.)

The second generation mobile network also known as 2G wireless mobile networks replaced the 1G, 2G was developed by European Conference of Postal Telecommunication Administration (CEPT) was based on low band digital data signaling and it was best known as Global System for Mobile communications (GSM). GSM operates in frequency spectrum of 25MHz in 900MHz band and offers data rates in the range of 10-50 kbps. GSM technology depends in hybrid form of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). The technology also allows multiple users to access a group of radio frequency bands for both data and voice, therefore being able to eliminate signal interference. Some of the GSM standards include CDMA 1(IS-95) and D-AMPS (IS-136) for America, Personal Digital Cellular (PDC) for Japan and Global System for Mobile Communication (GSM) for Europe (Osseiran et al. 2012).

Universal Mobile Telecommunication System (UMTS) adopted by European Telecommunication Standards Institute (ETSI) as 3G technology followed the 2G technology. America endorsed the same 3G technology as Wideband Code Division Multiple Access (WCDMA). The 3G technology was developed under the third Generation Partnership Project (3GPP). This technology supported both voice and data video calling, with data rates of 384 kbps to 30 Mbps, depending on the standard. The International Mobile Telecommunication union (ITU) under the supervision of the International Mobile Telecommunication program fixed the minimum data rate of 3G to 114kbs. High Speed Packet Access (HSPA) in Radio Access Network (RAN) included both High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA). (Osseiran et al. 2013.) Figure 4 show 3G release 5 architecture for UMTS.

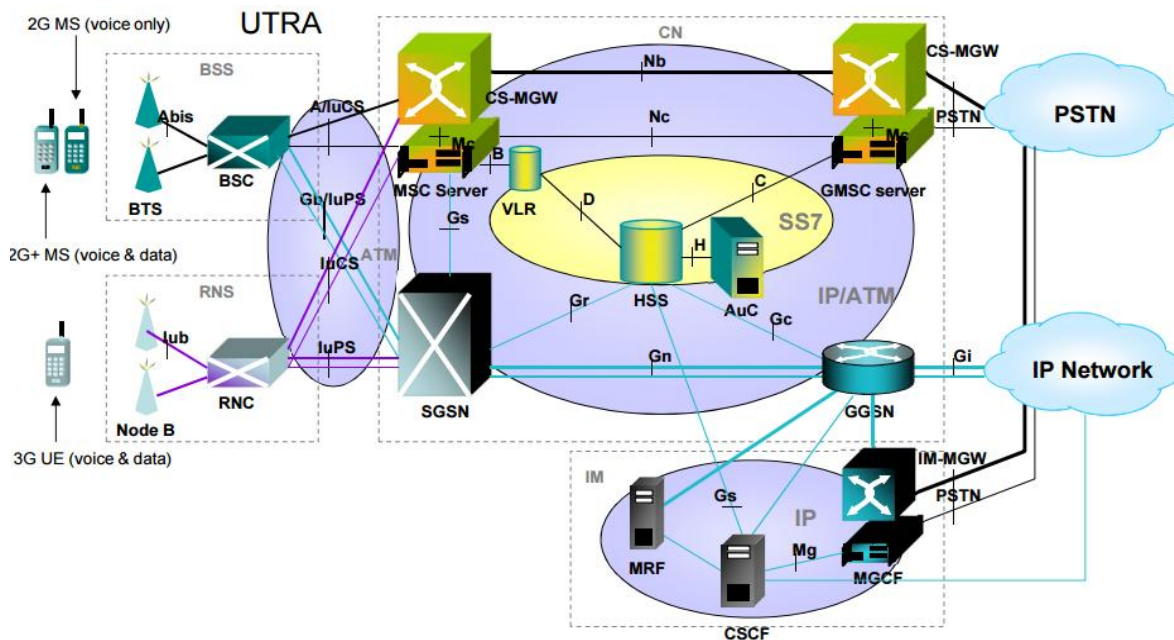


Figure 4. 3G Release 5 Architecture (GSM /UMTS). (Conningtech 2008).

Long Term Evolution (LTE) also known as 4G was developed by 3GPP as LTE release 8 this came after the 3G technology. The technology was expected to surpass the users' demand (which is not the case now) and it relied on Radio Access Network (RAN) of Evolve Packet Core (EPC) as shown in Figure 5. The first commercial deployment was in 2009 in northern Europe. 3GPP LTE release 8 supports high performance air interface which in turn helps provide high data throughput with low latency rate. After the deployment of the first LTE release 8, 3GPP continued researching and what came thereafter was LTE release 9 which supports the use of Multiple-Input-Multiple-Output (MIMO) transmission modes which extended the beamforming mode in release 8. MIMO transmission in release 9 helped to improve the transmission diversity therefore allowing better performance in comparison to its predecessor LTE release 8. The multiple transmission antennas at the eNB helped to achieve high peak data rates. (Firmmin 2016.)

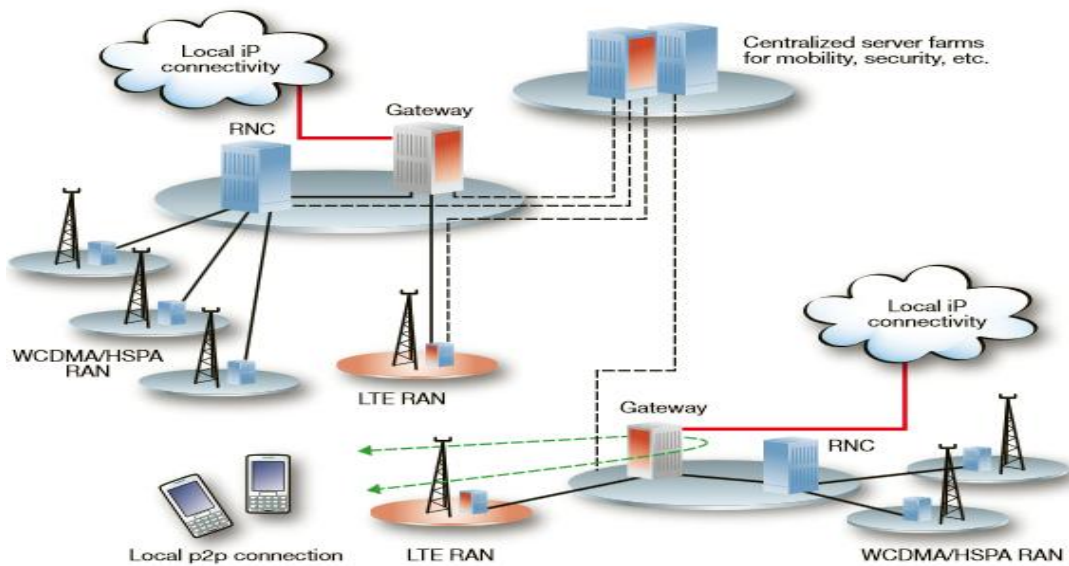


Figure 5. 4G Architecture (LTE) (Firmmin 2016).

Table 1 below shows the evolution of cellular mobile communications, the standards and data rates that it supports.

Table 1. Evolution of Cellular Mobile Communications

Wireless Systems		Standards	Data Rate
1G		AMPS, CDPD, FDMA TACS,	20-30kbps
2G Supports Voice +Data	2G	GSM	Supports only basic Voice data with data Rate of 10 kbps
		CDMA	Voice Data rate of roughly 20 kbps
	2.5G	GPRS	Develop to enable internet access(accessing best effort packet data/ cellular networks) and has a data rate of roughly 50kbps
	2.75G	EDGE	Supports Roughly 200 kbps
3G Supports Voice +Data Video Calling		WCDMA /UMTS	384kbps
		CDMA 2000	384 kbps
		HSDPA/HSUPA	3-30Mbps
		1XEVD0 Rev A,B,B,C	5-30Mbps
4G (LTE) Supports Voice, Data Video Calling, Online Gaming, Real-time Tv		Ability to operate in upto 40MHZ Radio Channels with very high spectral efficiency	100-200Mbps
5G Supports Voice, Data Video Calling, Online Gaming, Real-time Tv, Internet of Things, Big Data		Millimeter Wave, OFDMA 6GHz to 300GHz	10Gb and above

2.2 Fifth Generation Network (5G)

The unprecedented growth in amount of data traffic generated by ever growing number of connected devices have pushed the 4G technologies to its limits, leading to need of new technologies that can support high data throughput with low latency. Fifth generation (5G) is the technology expected to satisfy this needs, it is expected that 5G technologies will revolutionize our communication systems by supporting a large number of applications (upto 10^6) that demands high speed and low latency. (5G vision whitepaper, Samsung 2015.)

Compared to its predecessors 3G and 4G technologies which focused mainly on providing mobile broadband, 5G technologies will not only be limited to mobile communication but it will also provide unlimited connectivity to all kinds of smart devices through technologies such as Internet of Things (IoT), Device-to-Device (D2D) / Machine-to-Machine (M2M) communication and IP networks. The new 5G technology is expected to work in parallel with the existing 4G technology (LTE). This will enable effective utilization of the limited available spectrum resources. While 5G technologies are still under review, ITU-R identifies 3 main usages of 5G namely: Machine-to-Machine communication, ultra-reliable communication with low latency rate and enhanced mobile broadband communication as shown in Figure 6. (4G Americas 2015.)

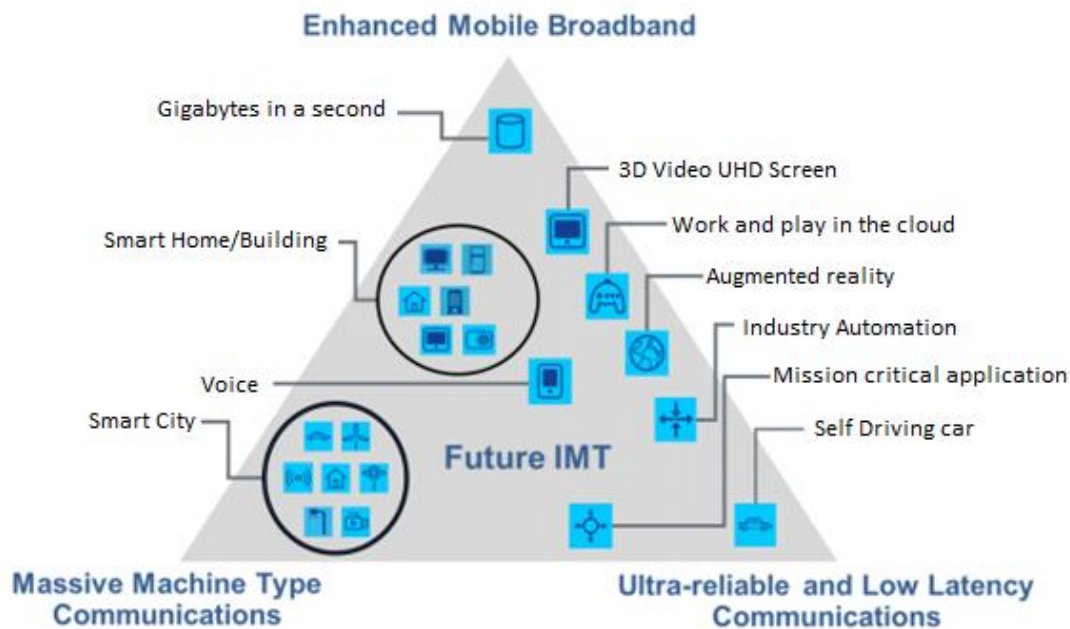


Figure 6. Usage Scenarios of 5G as suggested by ITU-R (Ferro 2016).

LTE will continue providing backward compatibility and will be part of the 5G providing wireless solution for frequency bands below 6GHz. 5G on the other hand will provide solutions for frequency bands above 6GHz that's why 5G technology is also known as millimeter wave (mmW) technology. Figure 7 shows the integration between 4G (LTE) technology and 5G technologies. The much anticipated 5G wireless technology have to meet many requirements such as being viable and profitable. Some of these requirements include: high data rates with uniformly good service and area coverage, the technology should be resilient to blockage and with the ability to penetrate through obstacles. (Jeffrey, Choi & Heath Jr. 2014.)

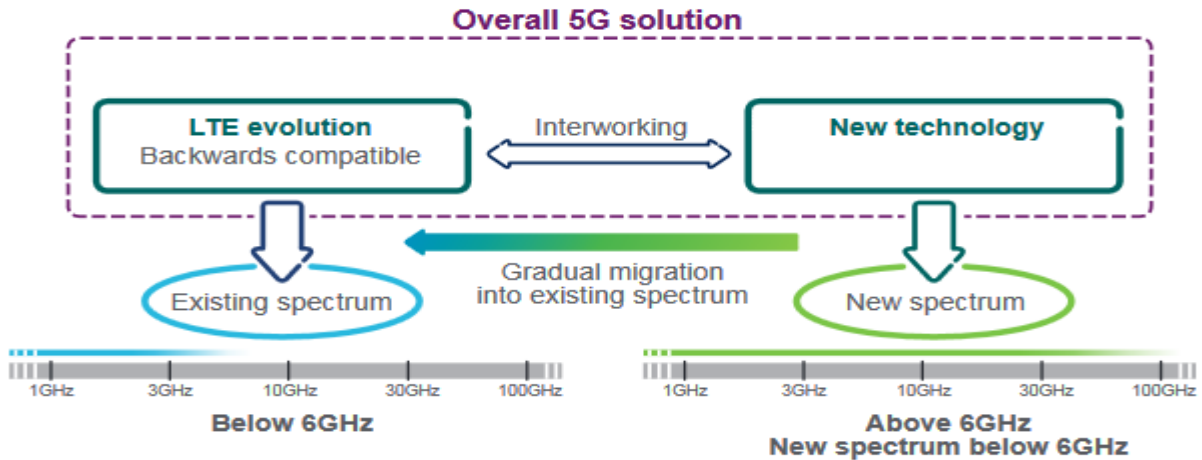


Figure 7. The overall 5G wireless access solution consisting of LTE evolution and new technology (Ericsson White paper 2016).

2.2.1 5G Application requirements

5G vision whitepaper, Samsung (2015.) expects 5G technology to revolutionize mobile communication industry. The 5G technology is expected to support immense applications that demands extremely high wireless connectivity with low latency rate. Such technologies include: super high resolution videos, Virtual Reality (VR), Augmented Reality (AR) for gaming, IoT, wearable devices, cloud computing, machine to machine communication (M2M) and many other critical applications both at the industrial level and at the commercial level as show in Table 2 below. For 5G technology to meet these expectations a proposal that consists of 7 Key Performance Indices (KPIs) has been suggested. This include a peak data rate of more than 10 Gbps, with 10 Gbps being the minimum, low latency rate of less than 5 milliseconds and less than 1 millisecond over the air

interface and spectral efficiency requirement of 10 bps as opposed to 1-3bps/Hz currently offered by 4G networks.

Table 2. Potential 5G Applications and its requirements.

Usage Scenarios	Applications Supported	5G Requirements
Enhances Mobile Broadband	<ul style="list-style-type: none"> • Virtual Reality • Augmented Reality • Tactile Internet • Cloud computing and gaming • Vehicular (all sorts of vehicles) • 3DVideos and UHD screens 	<ul style="list-style-type: none"> • Ultra-high speed Internet • Low latency rate • Short range
Ultra-reliable communication	<ul style="list-style-type: none"> • Self-driven cars • Industrial automation • Critical Mission Control applications 	<ul style="list-style-type: none"> • Ultra-High and reliable radio links • Low to ultra-low latency • Short to long range
Massive Machine-to-Machine Communications	<ul style="list-style-type: none"> • Smart homes and offices • Smart City • Sensor networks 	<ul style="list-style-type: none"> • Ultra-High reliable radio links. • High speed radio links • Short to long range • Operate in cluttered environments

2.3 MIMO

Multiple Input Multiple Output (MIMO) is a collection of signal processing techniques developed to enhance the performance of wireless communication channels or systems. The technology employs the use of multiple antenna elements both at the transmitters and at the receivers. While the signal is traversing across the wireless communication channel, the signal encounters many obstacles, therefore causing the signal to fade and also to arrive at the receiver through multiple paths, this can either causing destructive or constructive signal phase shift. The MIMO technology capitalizes on these effects. Furthermore, the technology utilizes a collection of signal processing techniques to improve the systems performance by exploiting the presence of multipath scattering (Lu et al. 2014). Figure 8 illustrates a typical MIMO system with N number of Transmitter antennas and M number of receiver antennas.

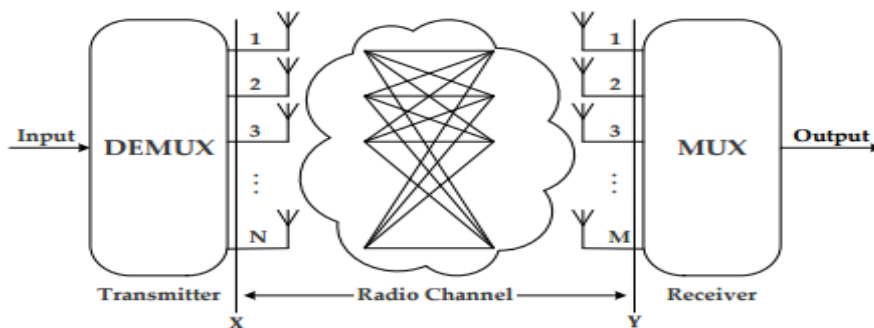


Figure 8. A typical MIMO Communication Systems and Channel with Antennas equipped with N number of Transmitters and M number of receivers (Hampton 2014).

Multipath fading is a fundamental feature of a wireless communication channel, through multipath replicas of either the same or different transmitted signals can be combined constructively or destructively to improve the Quality of Service (QoS). Without proper mitigation techniques in place, multipath can greatly affect the QoS of a signal through signal fading; multipath can also increase the power margin that is needed to serve the entire communication system, therefore increasing the total cost of the entire communication system. (Lozano & Nihar 2009.)

The signal processing techniques used by MIMO has been develop to either combat the effects of multipath scattering, or exploit it as a way of improving the performance of the wireless channel. To combat the effects of scattering and multipath, MIMO communication systems employ the use of spatial diversity techniques either at the transmitter antenna or at the receiver antenna; this improves the communication reliability of the wireless systems. And in order to exploit multipath scattering, spatial multiplexing is used to increase data throughput. So if the focus of the antenna designer is to improve the reliability of the communication channel, the spatial diversity technique will be applied in the design of the antenna. And if the focus is to maximize the data throughput, spatial multiplexing is used. (Hampton 2014.)

Figure 9 illustrates how a typical wireless transmission communication channel looks like. The signal from the base station (BS) to the mobile device can travel via different paths and this is known as multipath. Unlike the wired channels, wireless channels are extremely random in nature because of the behavior of wireless communication channels.

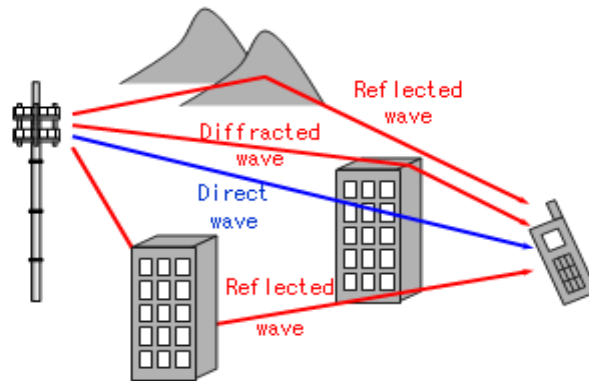


Figure 9. Typical wireless Channel scenarios (Jain 2014).

As the radio frequency (RF) transverses across the wireless transmission channel, the signal encounters a number of interferences. Some of these interferences are caused by, signals reflecting, diffraction, and scattering, these affects both the transmitted and received signal patterns, causing a number of effects. Massive MIMO techniques are designed to make use of these effects and the technology works better in a rich scattering environment. Without multipath and scattering, transmit and receive antennas are correlated thus resulting on poor performance of the MIMO system.

In a wireless communication channel the send signal arrives at the receiver antenna via two ways namely, direct and indirect path. In direct propagation also known as free space propagation the RF does not encounter any obstacles but only undergoes signal attenuation due to the distance between the transmitter and receiver. On the other hand, the signal traversing through indirect path encounters some interference causing the RF to arrive at the receiver via multiple paths, this works to the benefit of MIMO systems. The effects of various propagation

mechanisms can be seen by measuring the received RF power in relation to the distance from the transmitter, and through these measurements it can be seen clearly in Figure 10 that the signal attenuates or fades as it travel across the communication channel.

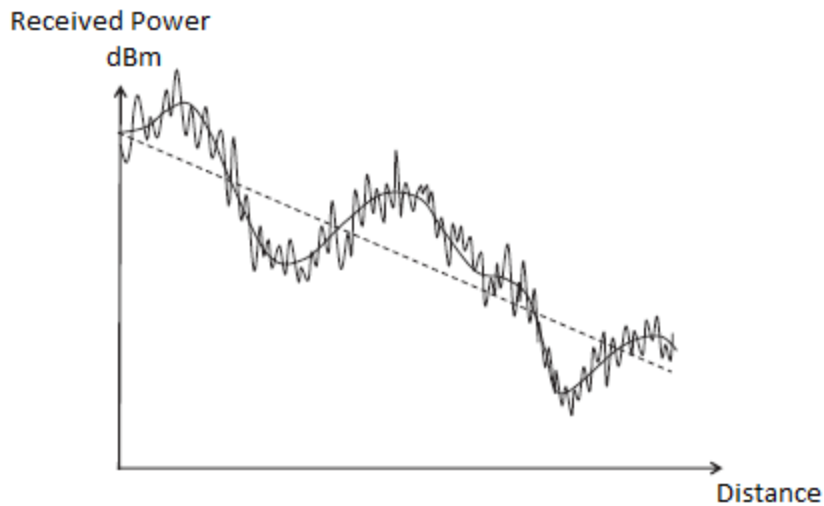


Figure 10. Path loss, multipath and shadowing (Hampton 2014).

The factor that affects the received signal can be described in three points as shown below.

- **Path loss or signal attenuation**, with this signal strength is reduced as the electromagnetic waves that carry the information transverses across the signal propagation channel. This is normally expressed in decibels (dBs) and the formula used to calculate the path loss of the signal is shown below.

$$L \text{ (dB)} = L_{\text{ref}} + 10n\text{Log} (d) \quad (1)$$

Where L_{ref} is the path loss at the reference point, n is the path loss exponent whereas d is the distance in meter, distance between the transmitter station and the receiver station.

L_{ref} is defined as:

$$L_{\text{ref}} = 20\text{log}\left(\frac{4\pi d_{\text{ref}}}{c}\right) \quad (2)$$

- **Fast fading:** In fast fading there is a sharp drop in signal strength over a very small distance; signal strength is rapidly changing. The fast wiggling curve in Figure 10 shows how the fast fading RF signal power changes with distance. The RF signal bounces over obstacles which create interference to the RF signal forcing it to arrive at the receiver via multiple paths.
- **Shadowing / Slow fading** is caused by very large obstacles such as large buildings or mountains that cause obstruction of RF signal as it travels from the sender antenna to the receiver antenna. With shadowing/slow fading there is no sharp drop in received power, the change of power is rather slower. The smoother curve presented in Figure 10 shows shadowing/slow fading RF signal power with respect to distance.

2.3.1 Spatial Diversity

MIMO communication combats the effect of multipath by transmitting the same information as multiple copies through different independent wireless communication channels. The signals are then combined at the receiver through a process called spatial diversity. Therefore the amount of signal fading experienced by each copy of the signal as it transverse across the channel will differ. This will guarantee that at least some of the signals arriving at the receiver will suffer less fading as compared to the rest of the signals. This increases the chance of receiving signals with better signal to noise ratio.

Spatial diversity can be created in two ways: Through transmit diversity or receive diversity as depicted in Figure 11 and Figure 12.

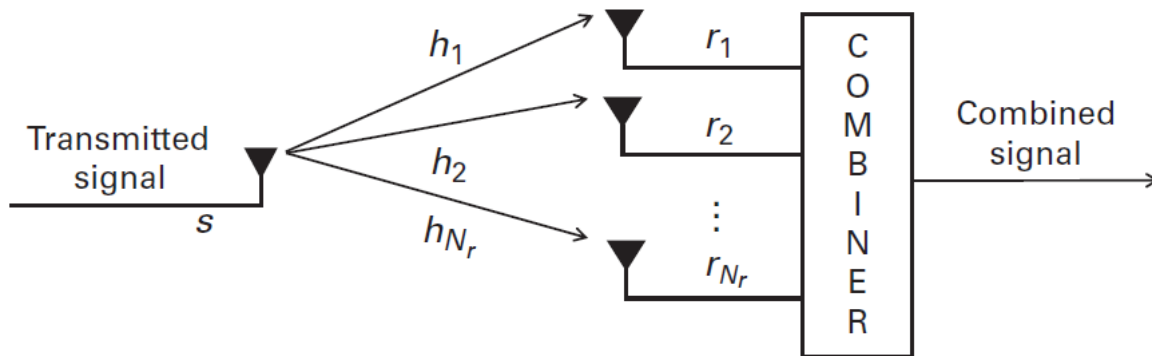


Figure 11. Transmit Diversity Combination (Hampton 2014: 10).

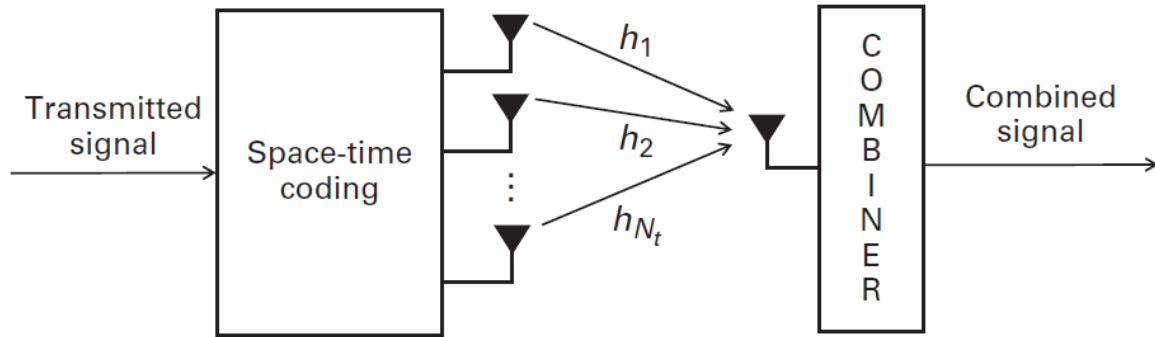


Figure 12. Receive Diversity Combination (Hampton 2014: 11).

Consider a single transmitter with m number of antenna elements and receiver with n number of antenna elements. This will eventually have mn different signal paths from the transmitter to the receiver. Since each signal fades independently, maximum diversity gain of n can therefore be achieved and the average error probability can be made to decay. Decaying in MIMO system can be expressed as $1/SNR^n$ for a higher signal to noise ratio and $1/SNR$ for the case of single antenna fading channel. Assuming that the path gain between the individual antenna pairs are identically distributed (i.i.d), independent and are Rayleigh faded. The maximum diversity gain of m transmit and n receive antennas will then be mn , this is the total number of fading gain that can be achieved with this number of transmit and receive antennas. The main aim of spatial diversity is to improve the reliability of the communication system through providing diversity gain. (Zhen & Tse 2003.) Figure 13 shows how a MIMO system used for purposes of spatial diversity looks like.

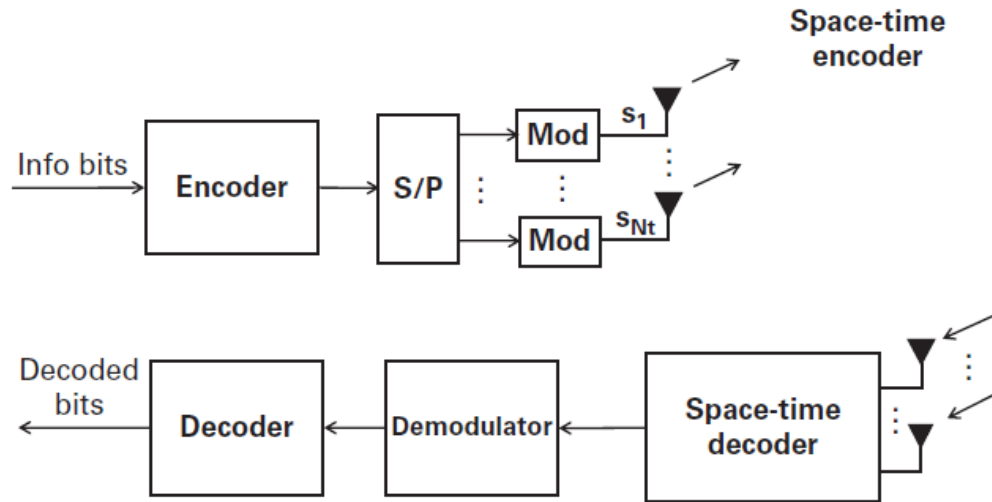


Figure 13. MIMO Systems for Spatial Diversity (Hampton 2013).

In spatial diversity information bits are first encoded and modulated using the normal error correction and modulation techniques, before undergoing space time coding (STC) and at the receiver before being transmitted across the transmission channel. The received signal first undergoes space time decoding (STC) followed by demodulation and error decoding as shown in Figure 14. In order to reduce the effect of signal fading via spatial multiplexing a number replicas of the same signals has to be generated at the transmitter and then the same replicas needs to be combined at the receiver.

There exists various ways of generating multiple replicas of the same signals for purposes of retransmitting. The first way is through a process called frequency diversity: this involves transmitting the same signal on different RF frequencies ensuring that they are evenly spaced in order to allow for independent fading. The second option is through time diversity: this involves transmitting the same signal

but at different times. The third option is polarization which involves transmitting the same signal but with different polarizations. The fourth option is spatial diversity: this involves transmitting the same signal or information via different physical paths known as multipath, and if the distance between the transmitter and the receiver is large enough, each signal will fade independently. The signal can then be combined constructively at the receiver to improve the QoS of the signal. (Hampton 2013: 8.)

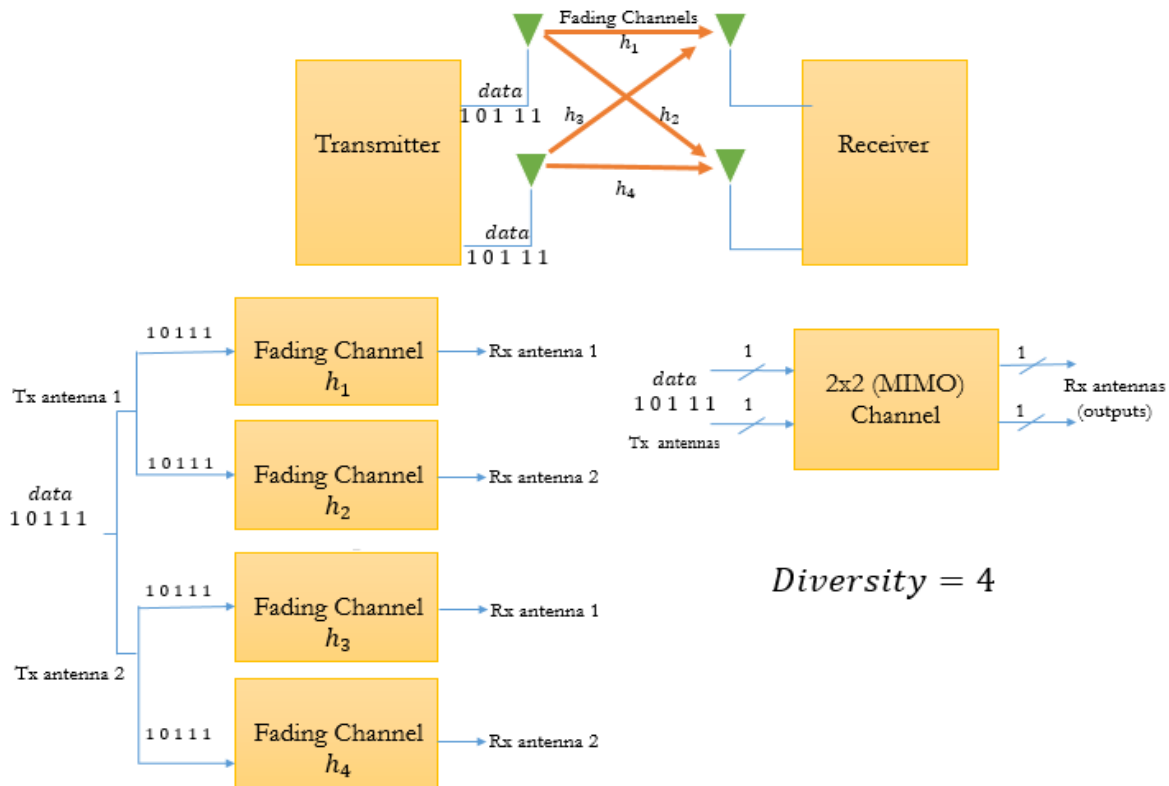


Figure 14. Multiple-Input-Multiple-Output with Diversity (Mathuranathan 2014).

There exists various ways of combining different replicas of the same signals at the receiver. Some of these methods include: use of selective combining which

involves comparing all the received signals and then selecting the one with the highest QoS. The second technique is known as equal gain combining, this involves adding all the replicas together. The third and most common option is called maximum ratio combining (MRC) which involves first scaling each replica in proportion to signal-to-noise ratio and then adding all the replicas.

2.3.2 Spatial Multiplexing

Multiple transmit and multiple receive antennas can be used to provide extra spatial dimensions for communication in suitable channel fading conditions to provide a degree of freedom gain. According to Hampton (2014) additional degree of freedom in wireless communication can be exploited through the use of spatial multiplexing. Spatial Multiplexing can increase the system's capacity without necessarily increasing the required bandwidth this depends on the amount of the antennas at the base station (BS). Figure 15 shows MIMO system used for purposes of spatial multiplexing.

Multipath is one of the fundamental features in wireless technology that massive MIMO focuses on. In wireless communication systems, there are two classes of MIMO communications, single user MIMO (SU-MIMO) and multi user MIMO (MU-MIMO). In SU- MIMO there is only one transmitting node and one receiving node but the receiving node has multiple numbers of antennas. More will be discussed in the coming chapters.

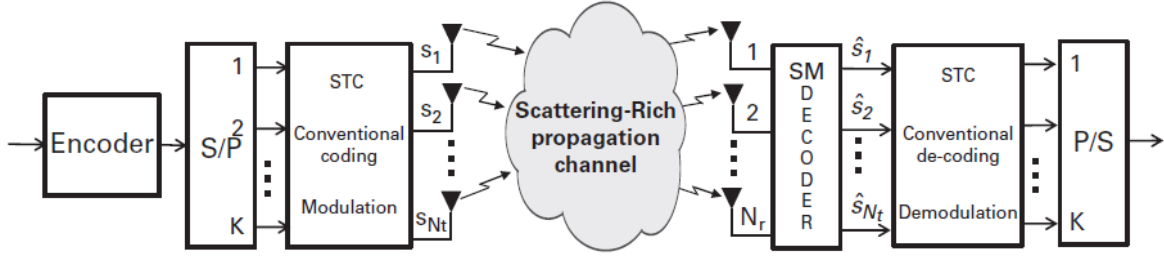


Figure 15. Basic Components of a MIMO communication system that performs spatial multiplexing (Hampton 2014: 163).

As discussed earlier in Chapter 2.3, spatial multiplexing involves the transmitting in independent streams of data through a multipath transmission channels without necessarily increasing the bandwidth of the system. Given N_t number of transmit antennas and N_r number of receive antennas with spatial multiplexing receivers the system can achieve a spatial rate equal to $N_t N_r$ as shown in Equation (3).

$$N_{stream} = \min(N_t, N_r) \quad (3)$$

From the equation we can see clearly that given N_t by N_r MIMO system the throughput of the system increases linearly as the number of antennas increases. As exhibited in Figure 8 in Chapter 2.3 the capacity of $N \times N$ MIMO system N multiplied by the capacity of the SISO system as show in Equation (4).

$$C_{MIMO}(N) = N C_{SISO} \quad (4)$$

Figure 15 shows a typical transmitting and receiving antenna. This kind of antenna is for spatial multiplexing purposes. When the transmitted bits arrive at the encoder the bits undergoes the error control coding that is performed by the encoder block. After the error check the encoded bits will move into serial parallel

converter which then splits the input stream of bits into K parallel streams. The K parallel stream will then move to the next block. (See Figure 15). The role of this block is to map the K received streams of data into N_i . The N_i streams will then be fed into the transmitting antennas in order to be converted into electrical signals and to be propagated. At the transmitter end various techniques can be employed which may include space-time coding, extra conventional error coding, modulation and other techniques depending on the used spatial multiplexing scheme. (Hampton 2014.)

At the receiver end the received signal at each antenna comprises the sum of all the transmitted signals for all the transmitting antennas. And since the spatial multiplexing involves the transmitting distinct signals for purposes of increasing the overall throughput of the system, distinct data streams are received at the receiver. Due to this the receiver is able to distinguish between the data streams and is therefore capable of de-multiplexing the received stream through SM decoder. The SM decoder performs some signal processing techniques to the received data streams in order to generate the estimate of the transmitted data streams.

2.4 MIMO Capacity

Shannon capacity limits sets the maximum data rate that a system is capable of achieving, only under an ideal scenario, assuming that the MIMO channel has small or no probability error and also no constraints in terms of delay complexity or signal interference. As Foschini (1996), Telatar (1999), Winters (1987) predicted that in MIMO systems a remarkable capacity growth can be achieved when multiple antennas are used, and the transmission channel exhibits rich scattering effects that can be accurately tracked. To understand more on MIMO capacity a comprehensive summary of MIMO capacity for both Single-user and Multi-user systems under different scenarios will be dealt with. First is the background information on both the Shannon capacity and Mutual information.

2.4.1 Shannon Capacity and Mutual Information

In 1948 Claude Shannon pioneered information theory on channel capacity using mathematical theory of communication. The theorem considered the use of mutual information between the input and the output channel. Shannon went ahead to define the capacity as the mutual information that is maximized over all the possible input distributions. The significance of these mathematical theorems was to prove that it is possible to achieve a data rate which is asymptotically close to the capacity with negligible probability of error. (Shannon 1948.)

For a time invariant, memory less single user channel with random input of X and output Y the channels mutual information can be defined as:

$$I(X; Y) = \int_{S_x, S_y} \text{Log}\left(\frac{f(y|x)}{f(y)}\right) dF(x, y) \quad (5)$$

Where S_x and S_y is the integral of random variable X and Y , $f(y)$ denotes the probability density function (PDF) of Y . $F(x, y)$ is the cumulative distribution function (CDF) of X, Y , \log is to base 2 and the units of the mutual information are in bits per channel use. All the same random variables can be represented in terms of differential entropy. Entropy is the average information content in any source with probabilistic output, and in this case the channel output and the conditional output in terms in entropy can be expressed as:

$$I(X; Y) = H(Y) - H(Y|X) \quad (6)$$

Where $I(X; Y)$ is the mutual information,

$$H(X) = - \int_{S_y} f(y) \log f(y) dy \quad (7)$$

And

$$H(Y|X) = - \int_{S_x, S_y} f(x, y) \log f(y|x) dx dy \quad (8)$$

Shannon (1948) continued to prove that the channel capacity equals the mutual information of the channel that is maximized over all the possible input distributions.

$$C = \max_{f(x)} I(X; Y) = \max_{f(x)} \int_{S_x, S_y} f(x, y) \log\left(\frac{f(x, y)}{f(x)f(y)}\right) \quad (9)$$

Time varying channel capacity can be defined in different ways, depending on the amount of Channel State Information (CSI). CSI refers to knowledge about the communication channel, this knowledge/ information is used to define how a

signal propagates from the transmitting antenna to receiving antenna. The information can also be used to regulate how power is distributed among the antenna elements. CSI is equivalent to knowledge about the channel matrix \mathbf{H} . Depending on the amount of Channel State Information (CSI) at hand, MIMO capacity can be estimated based on that information. (Hampton 2014.)

The first situation is when the receiver has some knowledge about the channel also known as Receiver Channel State Information (CSIR). The second scenario is when only the transmitter has the knowledge about the channel and this is known as Transmitter Channel State Information (CSIT). The third and last situation is when both the receiver and transmitter have the knowledge of the channel (CSIT and CSIR) also known as perfect CSIT and CSIR.

With perfect CSI adaptive power transmission technique such as beamforming can be applied for purposes of power efficiency as we will see in the chapter 4. This is in relation to the instantaneous channel state and through this, effective power utilization can be achieved without compromising the Quality of Service (QoS) as well as the overall data throughput of the system. In this situation Ergodic capacity which is the maximum mutual information is achieved through adoptive transmission policy and averaged over all available channel states. Ergodic capacity is an ideal capacity metric used in channels that keeps varying all the time, and can be achieved through the use of adoptive transmission policy as stated previously, (Hampton 2014: 42).

Another definition for channel capacity in a perfect CSI situation is the outage capacity. With outage capacity a fixed data rate in all non-outage channel states is required especially for applications that have a delay constrain and its data rates

cannot rely in channel variations. The average outage capacity is smaller than that of ergodic capacity; this is because of additional constraints that are associated with it. The two channel capacity measurement options differ, that is: the outage capacity is more appropriate capacity metric for slowly varying channels as opposed to ergodic capacity metric which is more appropriate capacity metric for channels that changes quickly.

CSIT transmission is based on channel distribution instead of instantaneous channel state. And therefore the channel coefficients are assumed to be Gaussian; here channel distribution is specified by both covariance matrices and channel mean. In CSIR a fixed transmission rates is maintained and in return the CSIR information is optimized. Therefore ergodic capacity can be defined as the rate that is achieved based on averaging over all the existing channel states, and hence relevant for channels that keep varying at a higher rate. The transmitter can then send at a rate that will not be supported by all the existing channels and when the channel is poor the receiver will then declare an outage and therefore the information/data is lost. Outage under CSIR is quite different from outage under perfect CSIR and CSIT. CSIR outage can occur when the transmitted data is lost due to inability of the receiver to decode the received data. In perfect CSIR and CSIT there is no outage since there is no data lost. (Hampton 2014.)

2.4.2 Classes of MIMO communication systems

There are exists two classes of MIMO communication systems that are used in wireless communication systems today. These classes include Single User MIMO (SU-MIMO) which is also the conventional MIMO. With SU-MIMO there exists one transmitting node with multiple antenna elements and there exists only one receiving node. The second class of MIMO communication system is the Multi User MIMO, in MU-MIMO there exist multiple users each with a single mobile cellular equipment equipped with single antenna and all these users are communicating with a single base station (BS) equipped with multiple antenna elements. The BS sees the signals transmitted from the cellular users as if they are from single transmitting equipment equipped with multiple antennas.

In the next subsequent chapters we will look into the two existing classes of MIMO communication systems, both the SU-MIMO and MU-MIMO, more emphasis on MU-MIMO this is because MU-MIMO is more practically applied in our present cellular systems.

2.4.3 Channel matrix decomposition

As we noted initially that an ideal MIMO radio channel assumes a Rayleigh fading environment. This provides enough separation between the transmit and the receive antennas and hence enabling independent fading between the signals. According to Molisch et al. (2002) the entries of an ideal \mathbf{H} matrix forms an identical and independent distributed complex Gaussian variables with both real and imaginary parts.

Assuming that the \mathbf{H} is known to both the receiver and the transmitter then any $\mathbf{H} \in \mathbb{C}^{M \times N}$ can then be characterized by applying Singular Value Decomposition (SVD) of the form.

$$\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^* \quad (10)$$

Where

\mathbf{U} is m by m unitary matrix,

$\mathbf{\Sigma}$ is the diagonal m by n matrix with only positive real numbers on the diagonal, and

\mathbf{V}^* is conjugate transpose of n by n unitary matrix \mathbf{V}

From the Equation (10) above, the diagonal elements of $\mathbf{\Sigma}$ are non-negative square roots of the eigenvalues of $\mathbf{H}\mathbf{H}^H$, and \mathbf{U} are the eigenvectors of $\mathbf{H}\mathbf{H}^H$, whereas \mathbf{V} are the eigenvectors of $\mathbf{H}^H\mathbf{H}$. Equation (10) can then be re-written as:

$$\mathbf{Y} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^* \mathbf{X} + \mathbf{N} \quad (11)$$

2.4.4 MIMO capacity Model

Even though most wireless systems nowadays support Multi-User MIMO (MU-MIMO) technology, Single-User MIMO (SU-MIMO) is still in use. Whereas it is hard to analyze the MU-MIMO capacity without the knowledge of the channel, the case is not the same for SU-MIMO. In this chapter the focus will be on capacity limits for MIMO systems in general. MU-MIMO capacity will be discussed in the next chapter SU-MIMO is not discussed.

In MIMO technology the transmitter is equipped with N_t number of antennas and the receiver N_r antennas. To calculate the capacity to MIMO systems a system model has to be derived. This is the mathematical equation describing the relationship between transmitted and received signals. In this case the signal is assumed to be a narrow band signal, meaning the bandwidth of the communication signal is narrow compared to the coherence bandwidth of the main channel. In our systems model we defined N as the number of antennas at the transmitter and M as the number of antennas at the receiver. When signal \mathbf{s} is modulated and transmitted from $n=1, \dots, N$ transmitters to receiver's $m=1, \dots, M$, the received signal can be expressed as

$$r_i = \sum_{j=1}^{N_t} h_{ij} s_j + z_i, \quad i=1, 2, 3, \dots, N_r. \quad (12)$$

The matrix form for this equation is

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{z} \quad (13)$$

Where

$$\mathbf{r} = [r_1, r_2, r_3, \dots, r_{N_r}]^T; \quad (14)$$

$$\mathbf{s} = [s_1, s_2, s_3, \dots, s_{N_t}]^T; \quad (15)$$

$$\mathbf{z} = [z_1, z_2, z_3, \dots, z_{N_r}]^T \quad (16)$$

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ h_{21} & h_{22} & \dots & h_{2N_t} \\ \vdots & \vdots & \vdots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \dots & h_{N_r,N_t} \end{bmatrix} \quad (17)$$

\mathbf{H} is the channel gain with h_{ij} representing the transmit gain from antenna j to the receiver antenna i , considering that there are M antennas at the transmitters and N antennas at the receiver. \mathbf{Z} is the additive white Gaussian noise (AWGN) with zero mean and variance. In relation to Equation (6) and Equation (9) the capacity of MIMO system can be derived. By replacing X with \mathbf{s} and Y with \mathbf{r} the following equation can be derived:-

$$C_{MIMO} = \max_{p_{\mathbf{s}}(s_1, \dots, s_M)} \{H(\mathbf{r}) - H(\mathbf{r} | \mathbf{s})\} \quad (18)$$

Where maximization is done over multivariate distribution $p_{\mathbf{s}}(\mathbf{s})$. Simplifying Equation (18) with (13), MIMO capacity will then be:

$$C_{MIMO} = \max_{P_{\mathbf{s}}(s_1, \dots, s_{N_t})} \{H(\mathbf{r}) - H(\mathbf{z})\} \quad (19)$$

Assuming that \mathbf{z} is independent identically distributed (iid) real Gaussian random variable with mean μ and variance σ^2 :-

$$H(\mathbf{z}) = \frac{N_r}{2} \log_2(2\pi e) + \frac{1}{2} \log_2 |\sigma^2 \mathbf{I}_{N_r}| \quad (20)$$

And

$$\max\{H(\mathbf{r})\} = \frac{N_r}{2} \log_2(2\pi e) + \frac{1}{2} \log_2 |\mathbf{H}\mathbf{R}_{ss}\mathbf{H}^T + \sigma^2 \mathbf{I}_{N_r}| \text{ Bits} \quad (21)$$

Where \mathbf{I}_{N_r} is the identity matrix, \mathbf{H} is the channel matrix, \mathbf{H}^T is the transpose of the channel matrix, and \mathbf{R}_{ss} is the covariance matrix of \mathbf{s} . The final capacity for real signals will then be:

$$C_{real} = \max\{H(\mathbf{r}) - H(\mathbf{z})\} \quad (22)$$

Substituting Equation (20) and Equation (21) with Equation (22) the final capacity for real signal in MIMO systems will be:

$$C_{real} = \frac{1}{2} \log_2 \left[\frac{|\mathbf{H}\mathbf{R}_{ss}\mathbf{H}^T + \sigma^2\mathbf{I}_{N_r}|}{\sigma^2|\mathbf{I}|} \right] \quad (23)$$

Using this two matrices properties

The determinant of any identity matrix is 1

If A and B denote two matrices with the same dimensions with a denoting

any scalar. Then $\frac{1}{a}|\mathbf{A} + \mathbf{B}| = \left| \frac{\mathbf{A}}{a} + \frac{\mathbf{B}}{a} \right|$

Then the channel capacity of the real signal in MIMO system will be:

$$C_{real} = W \log_2 \left[\mathbf{I} + \frac{1}{\sigma^2} \mathbf{H}\mathbf{R}_{ss}\mathbf{H}^T \right] \text{bits/sec} \quad (24)$$

Where W is the signal bandwidth

According to Hampton (2014:39) a complex signal has minor difference with the real signal. The capacity of a complex signal is twice the capacity of real signal this is due to the fact that complex signals have both real and imaginary parts that are able to transmit independent information. The transpose matrix in real signal is replaced with \mathbf{H}^H (Hermitian) in complex signal. Hence the final capacity for complex signal will be:-

$$C_{complex} = 2W \log_2 \left[\mathbf{I} + \frac{1}{\sigma^2} \mathbf{H}\mathbf{R}_{ss}\mathbf{H}^H \right] \text{bits/sec} \quad (25)$$

2.5 Imperfect CSI (Open Loop)

In CSIR the receiver but not the transmitter has the knowledge about the transmission channel. And because of this, there is no predefined way of transmitting the signal; this in return has some implications on the amount of energy used as well as the correlation and dependencies between the transmitter and the receiver. Because of lack of knowledge about the communication channel the transmitting antennas N_t uses equal power across all the antennas and are independent and uncorrelated to each other. Considering the initial MIMO system equation.

$$\mathbf{r} = \sqrt{\rho} \mathbf{H}' \mathbf{s} + \mathbf{z} \quad (26)$$

Where \mathbf{r} is $N_r \times 1$ received signal vector, \mathbf{H}' is $N_r \times N_t$ normalized random channel matrix. While \mathbf{s} is $N_t \times 1$ transmit signal while \mathbf{z} is $N_r \times 1$ noise signal vector and ρ is the signal-to-noise power ratio at the receiver. Following normalization of the CSIR, MIMO channel capacity can then be represented with the following formula.

$$C = \log_2 \left| \mathbf{I}_{N_r} \frac{\rho}{N_t} \mathbf{H} \mathbf{H}^H \right| \quad (27)$$

Where ρ represent signal-to-noise ratio, $\mathbf{H} \mathbf{H}^H$ is the Hermitian matrix of the normalized channel matrix. The formula above only applies on CSIR condition. A much higher capacity of the MIMO system can be achieved in the situation of a perfect CSI condition; this is when both CSIT and CSIR are known.

The Hermitian matrix $\mathbf{H} \mathbf{H}^H$ can then be expressed as a product of 3 matrices by use of Eigen decomposition as follows.

$$\mathbf{H}\mathbf{H}^H = \mathbf{U}_{N_r} \mathbf{D}_{N_r} \mathbf{U}_{N_r}^H \quad (28)$$

Where

$$\mathbf{D} = \text{diag}\{\lambda_1, \lambda_2, \dots, \lambda_r, 0, \dots, 0\}, r(\mathbf{H}\mathbf{H}^H) = \text{Channel Rank}$$

Simplifying Equation 28 with Equation 27, as shown in Hampton (2014) the channel capacity of MIMO system under CSIR will then be:

$$C = \sum_{i=1}^r \log_2 \left(1 + \frac{\rho}{N_t} \lambda_i \right) \quad (29)$$

Where r is the channel rank and therefore Equation (29) clearly shows the importance of having a bigger channel rank and this can be achieved through having many transmitting antennas. Channel rank is a way of characterizing how large is the multipath in MIMO channel.

2.6 Perfect CSI (Closed Loop)

In perfect CSI (Closed Loop) channel state can be effectively tracked and therefore the statistical channel model at the transmitter is based on accurate Channel Distribution Information (CDI) received by the transmitter from the receiver through the feedback. The distribution model for the estimation of the channel will then be based on the information received from receiver. Figure 16 below illustrates a typical scenario of a communication channel for the case of perfect CSI. Parameter θ defines the channel distribution and channel realization at different time instant and are identically distributed and independent. The channel statistics keeps on changing over time, this is because of the nature of the wireless

communication channels and also the mobility of the transmitter or receiver, due to this variance in the channel, θ will also be time varying. The feedback channel in this case will be assumed to be noise free, which is not the case in real situation. With this assumption the CDIT to be deterministic function of the CDIR therefore optimal codes can then be constructed directly from the inputs.

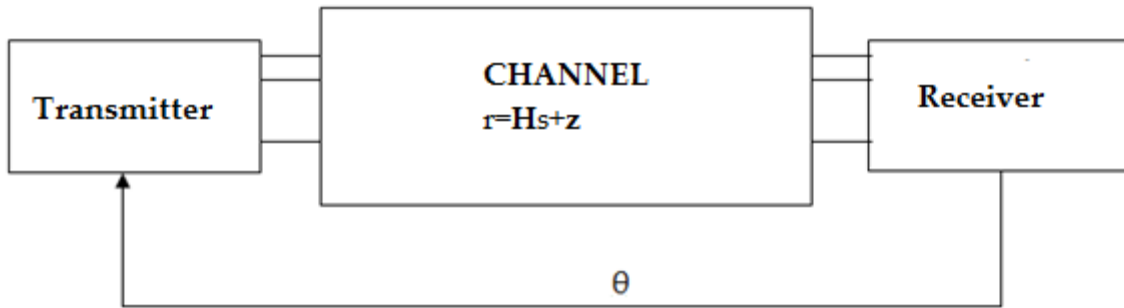


Figure 16. MIMO Channel with Perfect CSI.

In this situation the transmitter has perfect knowledge of the underlying CSI power allocation and therefore the right channel metric will be used to improve the channel capacity unlike the imperfect CSI.

Due to the feedback capability, both the transmitter and the receiver have the knowledge of the \mathbf{H} creating what is known as perfect CSI. In such scenarios when the transmitter knows the \mathbf{H} (channel matrix) the optimal strategy is not to distribute transmit power equally like in the case of imperfect CSI.

3 MASSIVE MIMO

Massive MIMO offers greater advantage in comparison to conventional MIMO. By using large number of antennas in a MIMO system, a degree of freedom in spatial domain is created, therefore better performance is achieved. Argument based on random matrix theory Lu et al.(2014) has demonstrated that the effects of uncorrelated noise and small scale fading are eliminated; transmission energy also decreases as the number of antennas elements increases. The use of simple match-filter (MF) pre-coding/detection techniques has also given massive MIMO an advantage. Other advantages of massive MIMO include:

- **Increased capacity and reliability of a wireless system:** As the number of antennas elements increases, also the number of the number of multipath increases as well. This leads to a much greater level of data transfer within the same period of time. The signals can be combined constructively at the receiver to increase the data throughput of the system.
- **Hardening against intentional jamming:** larger diversity due to massive number of antennas offers more complexity on how the system works. Due to this, large numbers of multipath are created by this large number of antennas, therefore making it complex, tedious and resource consuming for jammers to compromise the system.

- **Improves Spectral and energy efficiency:** In comparison to its predecessor conventional MIMO, Massive MIMO can reduce the energy consumption

Practical use of Massive MIMO is in area of cellular communication where Multiuser Multiple-input-Multiple-output (MU-MIMO) technology is applied, this is where base station (BS) is equipped with multiple antennas to serve a set of single antenna users in a given cell and all the users share the same multiplexing gain. Through information theory, results have shown that the capacity of MIMO systems increases linearly as the number of transmit and receive antennas increases. Communication between the base station (BS) and the mobile users is achieved by making the channel orthogonal to allow the BS to communicate with individual users in different time frequencies. Such technology allows the use of expensive equipment's only at the BS while the user terminals with single antennas are relatively cheap.

Because of multi-diversity the performance at the MU-MIMO systems are less affected by the interference encountered in the propagation environment compared to its counterpart point-to-point MIMO. As a result of these advantages MU-MIMO has become part of cellular systems. The Technology has been applied to some communication standards such as 802.11 (Wireless Fidelity), 802.16(WiMAX), and Long term evolution (LTE). (Quoc et. Al 2013: Vol 61 94). According to 3gpp (2016) the use of MIMO technology was first used in High Speed Packet Access (HSPA) release 6 and later integrated into 3G and subsequent technologies. The main focus of massive MIMO is to exploit the available spatial

resources that improve the performance of spectral efficiency, energy efficiency and the data throughput of the communication system.

3.1 Multi User MIMO

A cellular network comprises of mobile users otherwise known as subscribers which are allowed to move freely within an area served by a BS. A Cellular network is divided into sub-sections known as cells; each cell is served by one BS. Mobile subscribers cannot communicate directly but rather through a network. In MU-MIMO bandwidth is reserved since multiple mobile users use the same bandwidth and the base station receiver distinguishes between the individual arriving data streams with the help of spatial decoding techniques. In MU-MIMO an increment of data throughput will not be felt by individual mobile users but instead the whole system data throughput will be increased (Lu et al. 2014). As Ngo et al. (2013: 61) mentioned that in theory the system cannot achieve the optimal data throughput if several users communicate via the same frequency resources.

The challenge in MU-MIMO is inter-user interference and to mitigate this counter interference complex techniques have to be applied, such as maximum-likelihood multiuser detection, and dirty paper coding in the uplink and downlink respectively. Initially the BS was equipped with few antennas to serve multiple users in a given cell but recently BS developers have been interested in applying the use of Massive MIMO technology to serve many cellular users, therefore forming what is known as Multi-User MIMO (MU-MIMO). This is when the BS is equipped with a very large number of antennas which will then communicate with

hand held cellular system which are equipped with single antenna. Since there are many cellular systems communicating with this single BS, the BS will assume that it is communicating with another BS equipped with multiple antenna elements as well. The use of very many antennas at the BS has proven to reduce the effects of intra cell interference. (P. Vishwanath et al. 2013: 1912-1921.)

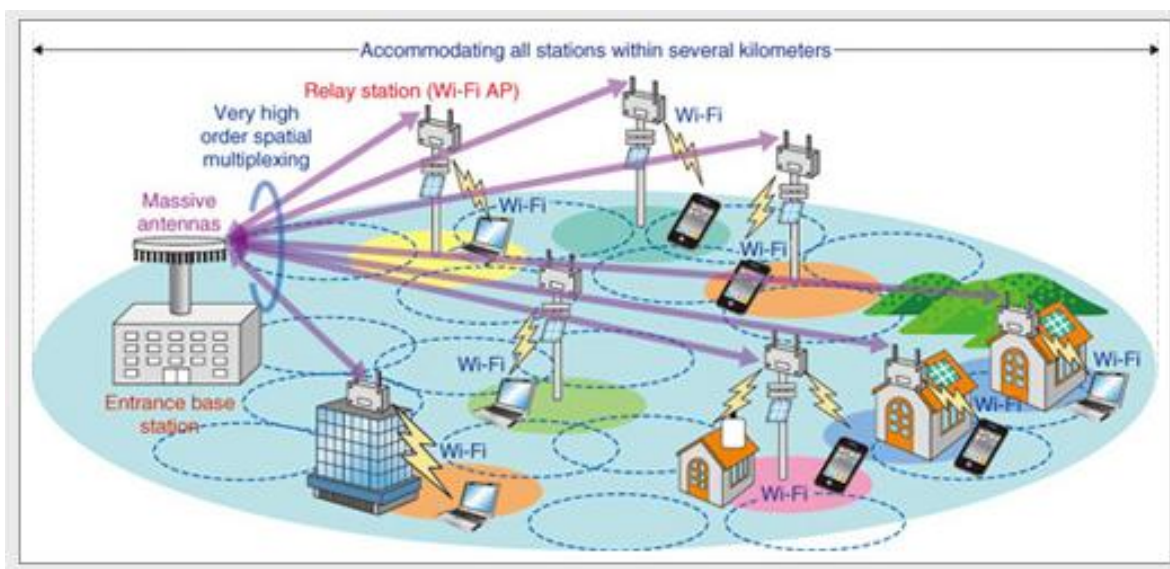


Figure 17. Massive MIMO (Nakatsugawa 2013).

Massive MIMO systems can obtain promising multiplexing gain as compared to its predecessors and have the ability to eliminate propagation interference within the communication channel. To understand the analogy of massive MIMO we will look into a MU-MIMO situation comprising of L cells each serving K number of single antenna users and has one BS with M number of antennas. Denoting the channel coefficient as follows, k -th user located in l -th cell and connected to the m -th antenna of i -th BS as $h_{i,k,l,m}$ which is the same as complex small scale fading factor

multiplied by the amplitude factor which leads to geometric attenuation and large scale fading.

$$\mathbf{h}_{i,k,l,m} = \mathbf{g}_{i,k,l,m} \sqrt{d_{i,k,l}} \quad (30)$$

Where $g_{i,k,l,m}$ represents the complex small scale fading and $\sqrt{d_{i,k,l}}$ represent the large scale fading coefficients. Small scale fading coefficient is assumed to be different for different users in the same BS while large scale fading is assumed to be the same in different antennas in the same BS. The channel matrix of the k -th user in l -th cell and i -th base station can be expressed in the following way:

$$\mathbf{H}_{i,l} = \begin{bmatrix} h_{i,1,l,1} & \cdots & h_{i,K,l,1} \\ \vdots & \ddots & \vdots \\ h_{i,1,l,N} & \cdots & h_{i,K,l,N} \end{bmatrix} = \mathbf{G}_{i,l} \sqrt{\mathbf{D}_{i,l}} \quad (31)$$

Where

$$\mathbf{G}_{i,l} = \begin{bmatrix} g_{i,1,l,1} & \cdots & g_{i,K,l,1} \\ \vdots & \ddots & \vdots \\ g_{i,1,l,N} & \cdots & g_{i,K,l,N} \end{bmatrix} \quad (32)$$

And

$$\mathbf{D}_{i,l} = \begin{bmatrix} d_{i,1,l} & & \\ & \ddots & \\ & & d_{i,K,l} \end{bmatrix} \quad (33)$$

Since the users have single antennas the assumption at the BS is that, all these multiple users communicating with the BS are treated as if they were additional single autonomous users as shown in Figure 32. For simplicity we will assume that all the users are transmitting their data using the same time frequency resources,

we will also assume that all the users have perfect Channel state information (CSI), (Lu et al. 2014).

For MU-MIMO two scenarios will be considered: the first one is the uplink communication, this is the communication from the mobile users to the BS and the second situation is the downlink communication that is, communication from the BS to the Mobile users.

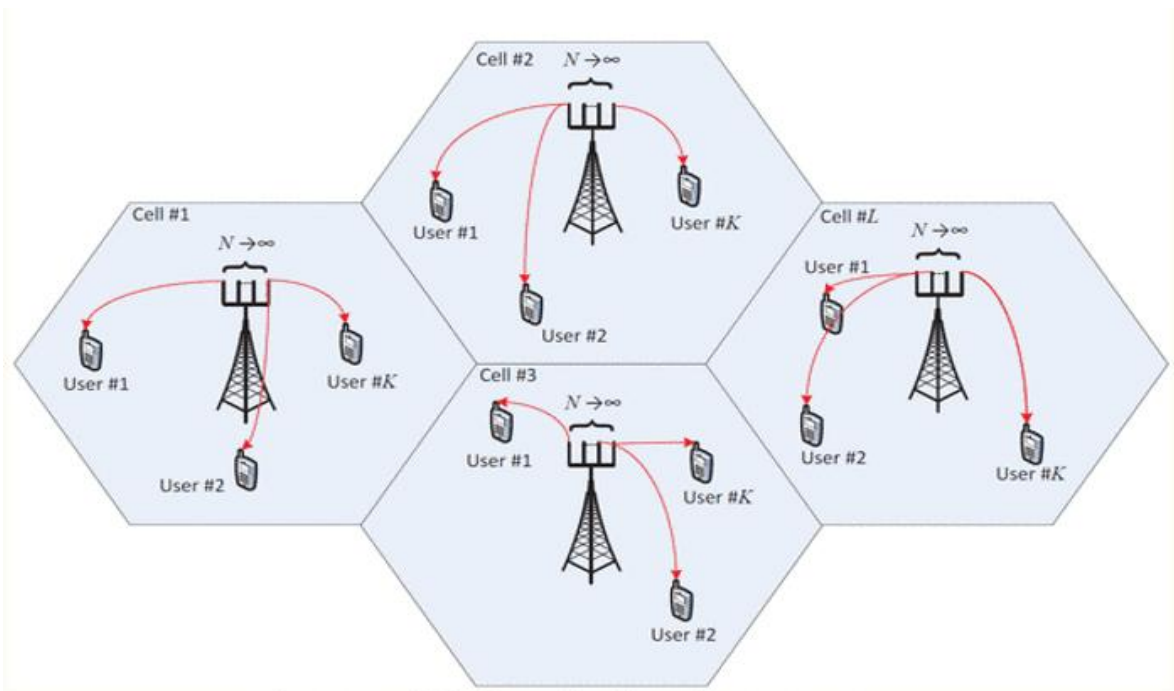


Figure 18. Multi Cell Massive MIMO System (Lakshminaravana 2014).

Lu et al. (2014) finds that as the number of antenna elements in BS tends to infinity, the amount of transmitted power is reduced by a proportional rate of $1/M$ for the case of perfect CSI and $1/\sqrt{M}$ for the case of imperfect CSI. To achieve this simple linear receiver can be used at the receiver BS and some of these receivers include:

Zero forcing (ZF) Maximum ratio Combining (MRC) and Minimum Mean Squared Error (MMSE).

In cellular network there exists two communication scenarios that have to be considered. The first is the Uplink MU-MIMO where the multiple users transmit data to the BS, the second is the downlink MU-MIMO where the BS transmits signals to multiple users. In uplink situation different users transmit data to the BS using the same channel and it is up to the BS to separate the received signals. In the downlink situation where a single BS is transmitting the signal to multiple users as exhibited in Figure 18 the challenge is inter-user interference, but with the help of Multi User Detection (MUD) techniques the problem can be sorted out.

3.1.1 Uplink MU-MIMO

Consider an uplink scenario of MU-MIMO systems with a BS equipped with N number of antennas receiving data from K single antenna users as in Figure 18. The signal received at the BS from the mobile users can be denoted in vector form as $y_u \in C^{N \times 1}$ where it has the same expression as

$$y_u = \sqrt{p_u} \sum_{k=1}^k h_k s_u + n \quad (34)$$

Which will then be:

$$y_u = \sqrt{p_u} \mathbf{H} x_u + n_u \quad (35)$$

Where $\mathbf{H}=[H_1, \dots, H_K]$

\mathbf{H}_k ($N \times 1$); $k=1, \dots, K$ which represents the mobile users U_k , $k=1, \dots, K$ with single antenna element. Where x_u represents the uplink channel matrix and $n_u \in^{M \times 1}$ is the zero mean noise vector with complex Gaussian distribution and identity covariance matrix independent of $H(N \times K)$ and ρ_u is the average signal to noise ratio (SNR). From the received signal vector y_u together with the knowledge of Channel State Information (CSI), the BS will coherently detect the signal transmitted by k -th user: x_k^u is the k -th element of $x_u = [x_1^u \dots x_k^u]^T$ with $E[|x_k^u|^2] = 1$. Assuming that small scale fading coefficients for different users are independent then the column channel vectors from different users will be asymptotically orthogonal as the number of antennas at the base station grows to infinity (Hien et al. 2013).

Based in results (23) the overall achievable rates for all users will be:

$$\begin{aligned} C &= \log_2 \det(\mathbf{I} + p_u \mathbf{H}^H \mathbf{H}) \\ &\approx \log_2 \det(\mathbf{I} + N p_u \mathbf{D}) \end{aligned} \quad (36)$$

So with simple match filter (MF) processing at the BS the achievable capacity will be:

$$= \sum_{k=1}^K \log_2 \left(1 + N p_u d_k \right) \frac{\text{bits}}{\text{Hz}} \quad (37)$$

Where

K is the number of users, N is the number of antenna elements in the BS,

p_u is the uplink transmit power and d_k is the signal fading for user k .

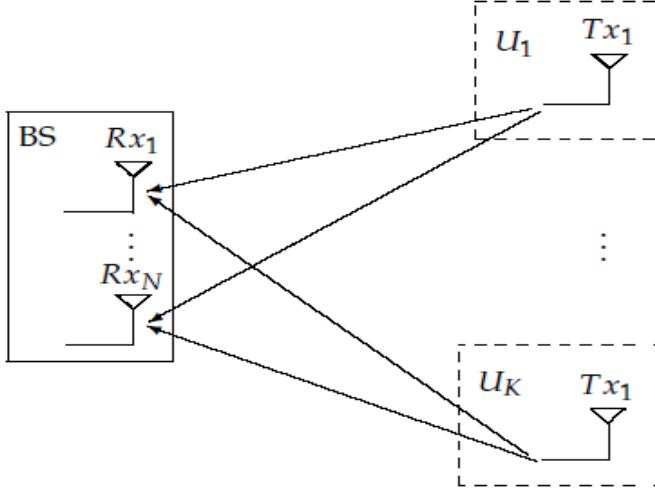


Figure 19. Up-Link MU-MIMO with N antennas at the BS and K mobile users.

3.1.2 Downlink MU-MIMO

Here we will consider the downlink of a MIMO communication system within a single cell as illustrated in Figure 18. Within a single cell, all mobile users communicate with the same BS, and they all share the same transmission medium. So the BS must be capable of separating the RF from different mobile terminals.

The receive signal vector at all K users $\mathbf{y}_d \in \mathbb{C}^{K \times 1}$ can be denoted as:

$$\mathbf{y}_d = \sqrt{p_d} \mathbf{H}^T \mathbf{x}_d + \mathbf{n}_d \quad (38)$$

Where $\mathbf{x}_d \in \mathbb{C}^{N \times 1}$ is the signal vector transmitted by the BS and $\mathbf{n}_d \in \mathbb{C}^{K \times 1}$ is the additive white noise with p_d as the transmit power for the downlink. Based on uplink pilot transmission with CSI corresponding to all users the BS can perform power allocation and therefore maximizing the transmission hence having the system capacity as:

$$\begin{aligned}
C &= \max_{\mathbf{P}} \log_2 \det(\mathbf{I}_N + \mathbf{p}_d \mathbf{H} \mathbf{P} \mathbf{H}^H) \\
&\approx \max_{\mathbf{P}} \log_2 \det(\mathbf{I}_k + \mathbf{p}_d \mathbf{N} \mathbf{P} \mathbf{D}) \frac{\text{bits}}{\text{HZ}}
\end{aligned} \tag{39}$$

Where \mathbf{P} is the positive diagonal matrix with power allocation $(p_1 \dots p_K)$ as the diagonal matrix and $\sum_{k=1}^K p_k$

Since \mathbf{P} and \mathbf{D} are both diagonal matrices then the signal from the BS to each users will be treated as originating from SISO transmission, and with this inter-user interference can be suppressed.

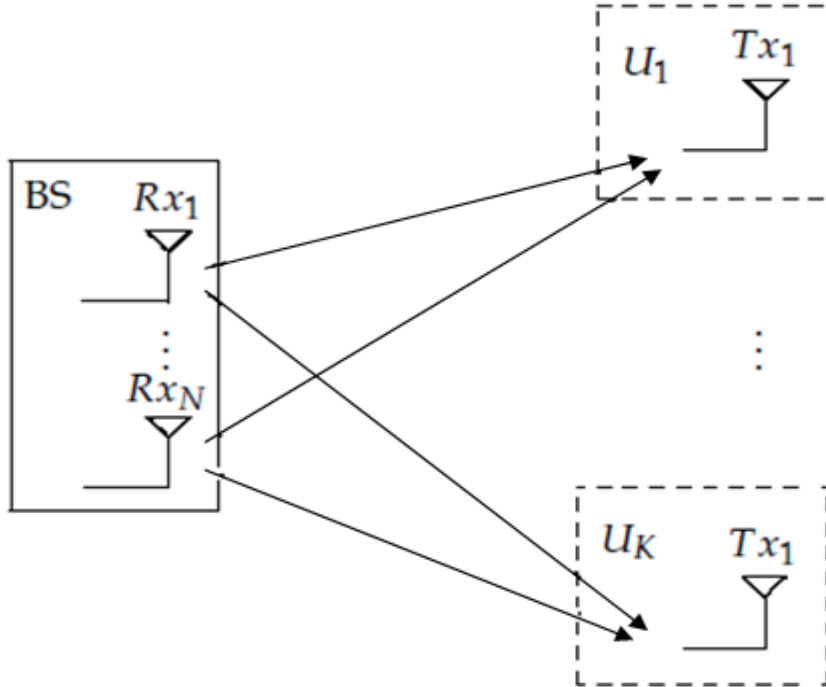


Figure 20. Down-Link MU-MIMO with N antennas at the BS and K mobile users.

3.2 Energy Efficiency of MIMO systems

As the wireless cellular network and systems evolve, the need for high spectral efficiency due to spectral scarcity and the ever growing need for high data throughput with less latency rate and minimum power consumptions have triggered the research in these areas. Ghosh, Ratasuk, Mondal, Mangalvedhe and Thomas (2010) state that mobile terminals have evolved and currently mobile terminals are equipped with large screens, bigger memory capacities and faster digital signal processors. All these needs more power and since these mobile terminals are hand held and small devices, better technologies with energy efficiency capabilities are needed.

Wireless cellular systems are evolving to support broadband data services that can offer much higher capacity rates. The high capacity rates expected of these cellular systems can be achieved, but with expense of high energy consumption. The disadvantage of this is that with high capacity rates the mobile terminal battery life reduces. In mobile terminals the uplink RF is the main consumer of battery energy in cellular systems and therefore reducing the energy consumed by the uplink RF plays an overall role of reducing the total energy consumed by the cellular system.

Massive MIMO is expected to support high spectral efficiency as well as providing a high energy efficiency solution with just simple linear transceivers. By increasing the number of antennas at the BS (M) massive MIMO is able to support high spectral efficiency (Marzetta 2010). When the number of antennas in BS tends to infinity ($M \rightarrow \infty$) inter-cell interference and multi-user interference is randomized and without the need of complicated pre-coding and coordination techniques, the

two interferences can then be averaged out and the only remaining limiting factor at this point is the problem of pilot contamination (PC). (Li, Xu, Xiong, Yang, Zhang, Chen, and Xu 2011.)

To achieve the 5G expectations, energy efficiency as the pillar of 5G technology must be met (Li et al 2011). However massive MIMO techniques improve spectral efficiency at the expense of extra radio frequency and also complicated signal processing techniques which in turn consume more power due to its complicated circuits (Cardoso and Correia 2012). To maximize the energy efficiency (EE) of the downlink multicarrier of MIMO systems, the configuration of spatial and frequency resources must be optimized. Li et al. (2011), show that in Massive MIMO systems, energy efficiency (EE) and spectral efficiency (SE) increases as long as the frequency resources are available: that is as the number of antenna elements in BS increases.

As massive MIMO technology is expected to be energy efficient, the use of large antenna array gain with large multi-user multiplexing gain and inexpensive components can significantly reduce the power consumption. In the recent years a lot of research has been carried out to ascertain the effect of a large number of antenna elements to the energy efficiency (EE) as presented in the paper written by Ngo et al. (2013). The uplink of massive MIMO has the potential of improving the energy efficiency of the communication system through the power scaling law which states as the number of antenna elements tends to infinity, the power consumption reduces.

Since amplifiers, cooling systems and associated circuits at the BS consume a lot of power, having a technology that will reduce power consumption at the BS will be of significant help, and that technology is massive MIMO. For the uplink situation the transmit power of the mobile phones reduces therefore, enabling the batteries to last longer.

3.2.1 Optimal power allocation in MIMO systems

For the optimal power allocation we will consider the perfect CSI scenario where both the transmitter and the receiver have knowledge of the channel, \mathbf{H} matrix. The practical technique used to implement spatial multiplexing in this case is Eigen beamforming. In imperfect CSI mode the power is distributed equally amongst the transmit antennas through the equal power allocation mechanism, the situation in perfect CSI scenario is not to distribute its transmitted power equally amongst the antennas nor to make cross correlation between transmitted signals zero. As stated above that as $(M \rightarrow \infty)$ the number of antenna elements in the BS tends to infinity. Most of the interference will be cancelled out. Mohammed (2014) investigated that the number of M impacts the energy efficiency of a system. Mohammed (2014) goes ahead to analyze the problem of power allocation in the uplink of MU-MIMO systems and proved that for maximum energy efficiency the user equipment (UE) must be switched off, which is not the case in a real life situation where we want the UE to work optimally.

4 EXPERIMENTAL PART

4.1 System and Channel Model

Considering a multi-cell with L number of cells, each cell has K number of users with one BS that is equipped with M antennas. For logical conclusion M and K are considered to be significantly large such that $M \gg K \gg 1$. The assumption also is that each terminal (mobile phone) is equipped with one antenna thus reducing the design costs. For channel estimation the uplink pilots are used which operates in TDD mode and therefore allowing for the downlink channel estimation through channel reciprocity. The received signal from the k^{th} user will then be expressed as:

$$y_k = h_k^T w_k s_k + \sum h_k^T w_i s_i + n_k \quad (40)$$

Where vector h_k denotes the channel from the BS to the k^{th} user, each with the size of M . Vector h_k is also assumed to be zero mean and variance Ψ_k , s_k is the signal from the k^{th} user and w_k is the pre-coding vector of k^{th} user with n_k as the noise vector.

In massive MIMO regardless of the used pre-coding schemes, the channel from each BS to the user terminal is orthogonal. Therefore the channel capacity for the k^{th} user can then be:

$$C_k = B \log_2 \left(1 + \frac{M \Psi_k P_k}{\sigma^2} \right) \quad (41)$$

Where B denotes the systems bandwidth, p_k is the used power by the k th user to transmit its data while σ^2 is the noise power.

In this thesis, we will consider Base Station (BS) equipped with M number of antenna elements and K user terminals focusing mainly on a single cell scenario as seen in Figure 21. For purposes of analysis, the optimal value of M that maximizes the use of energy is of main concern. Two situations can influence the optimal value of M , the first is under the ideal situation without the effects of pilot contamination and the second one is under the influence of pilot contamination. Depending on the situation, different optimal values can be reached.

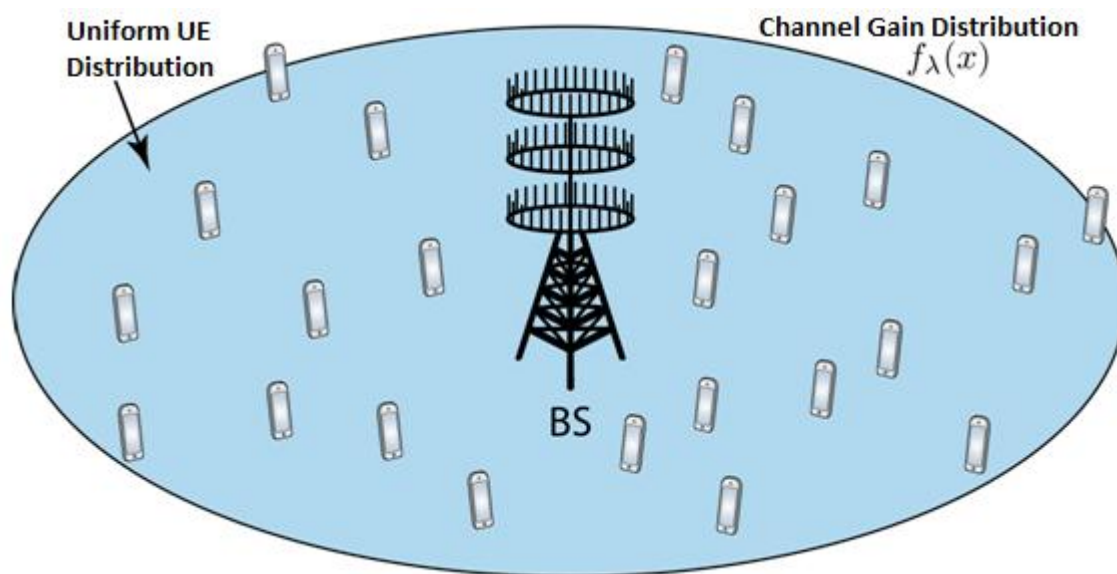


Figure 21. Single cell with one BS and K users.

4.2 Throughput in Massive MIMO Systems

Some of the modern wireless standards that have implemented the use of MIMO systems include IEEE 802.11n, LTE and WiMaX. The technology can support high data rates even under extreme conditions with signal interference, multipath effects and signal fading. Figure 22 shows the linear dependencies between the average ergodic capacities in bits/s/Hz of different number of antenna elements against the signal to noise ratio (SNR).

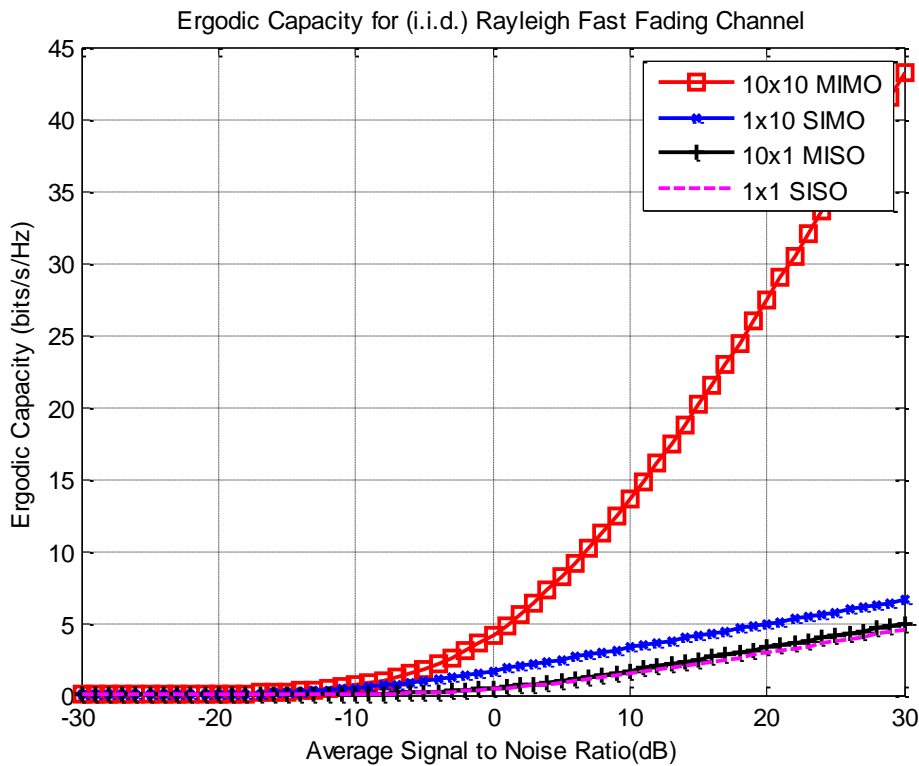


Figure 22. Ergodic Capacity in bit/s/Hz against Different signal to Noise ratio (dB).

Figure 22 clearly highlights the advantages of using more antenna elements compared to single antenna elements at the BS. Both ergodic capacities of the frequency selective relay fading and frequency flat Raleigh fading channels are the same (Xiao and Zheng, 2003). The emphasis in Figure 22 was to compare the ergodic capacities of different antenna elements against the different transmit power (SNR).

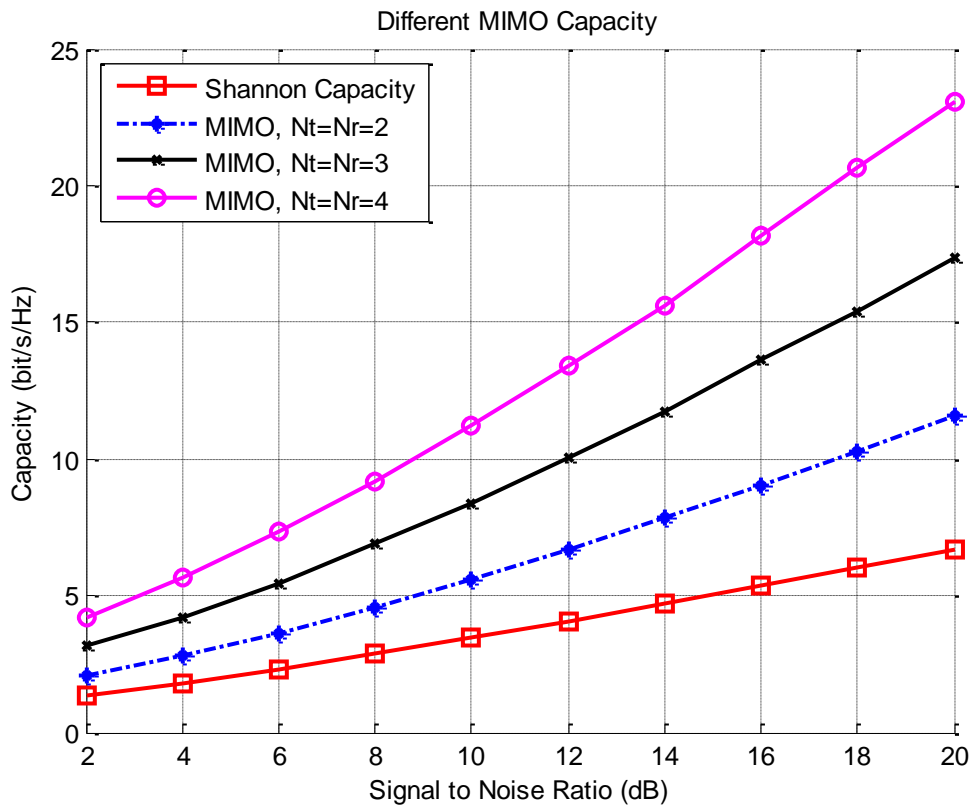


Figure 23. Ergodic capacity in (bits/s/Hz) against the Signal to noise Ratio (dB) for different number of antenna elements

Figure 23 shows that if the number of antenna elements at the transmitter increases, the ergodic capacity increases as well, take for instance Shannon capacity as signal to noise ratio (SNR) of 12dB is approximately 4bps, 5.5dB for 2 by 2 MIMO system, 10dB for 3 by 3 MIMO, and 14 dB for a 5 by 5 MIMO system.

Achievable rate of MIMO receivers for Independent and Identical distributed (i.i.d) Rayleigh fast fading channel is simulated in Figure 24.

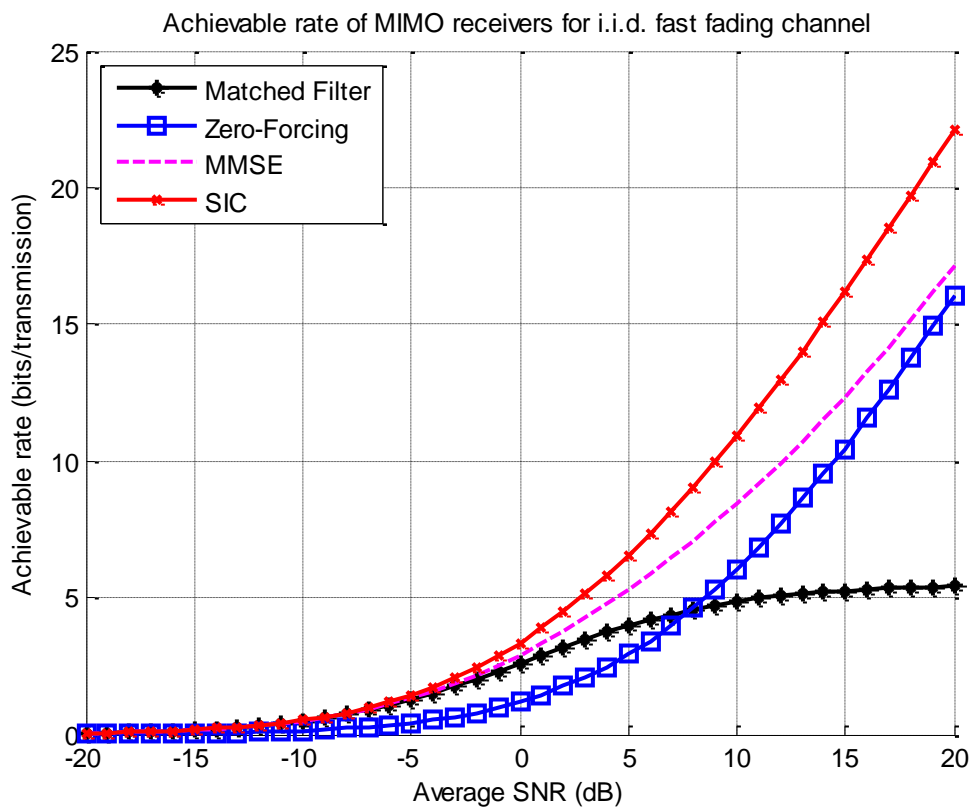


Figure 24. Capacity comparison in terms of achievable rate for different MIMO receivers at different SNR

From Figure 24, it can be clearly seen that Successive Interference cancellation (SIC) receiver performs than its counter parts namely the Match Filter (MF), Zero Forcing (ZF) and Minimum Mean Square Error (MMSE). At a very low signal to Noise ratio (SN) all the receivers are almost at par, but as the SNR increases the difference is clearly outlined. Take for instance at a SNR of 20dB MF has an achievable rate of close to 5bps/Hz, 6.5bps/Hz for ZF, 8bps/Hz for MMSE and 11bps for SIC receiver. This achievable rate (bit/Hz) is under the assumption of i.i.d Raleigh fast fading.

4.3 Energy Efficiency in Massive MIMO systems

As stated before the one of the key enhancement in 5G technology is energy efficiency of the communication system, measure in Joules/bit. As the throughput of massive MIMO increases, power consumption of the system should stay about the same. In order to achieve this several parameters has to be adjusted which may be extremely challenging. (Andrews et al. 2014). Due to the increase in network density the access network consumes more power and in that relation focus has been drawn to a number of factors to help in reducing energy consumption of the systems. Some of these factors include: Resource allocation, Network Planning, spectrum allocation among others.

Energy efficiency is defined as the ratio of average sum throughput and the total power consumption in bits/Joule. Based on ergodic achievable rates and the realistic power consumption the energy efficiency η , energy efficiency formula is defined as follows.

$$\text{energy_efficiency} = \frac{\text{Useful_output_energy(Joules)}}{\text{total_input_energy(Joules)}} = \eta = \frac{R_j}{T_{\text{Total}}} \quad (42)$$

Where

R_j is the total useful output energy served by j^{th}

BS, while P_{Total} is the total power consumed in that particular cell this include both the transmitted power and the power consumed by the BS.

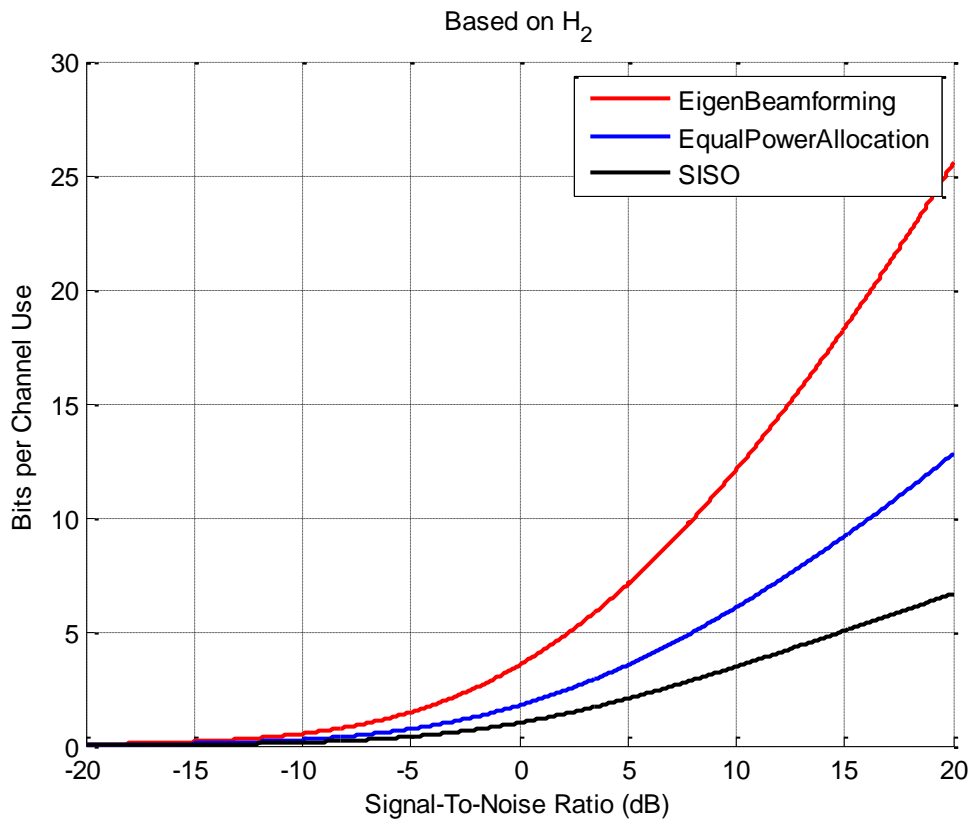


Figure 25. Comparisons of Theoretical capacity predictions of H Matrix.

Based on theoretical formulas, Figure 25 shows comparisons of antenna capacities under various assumptions namely; eigenbeamforming, equal power allocation,

and Single Input Single Output. Here we consider perfect CSI situation where both the transmitter and the receiver has knowledge of the channel. In Eigenbeamforming situation power is distributed based on water filling algorithms where high power is allocated to the antenna with high throughput while not allocating any power to non working antenna. In the situation of Equal Power allocation, power is equally divided to all available antennas, whether working or not, equal power distribution does not economize power like the eigenbeamforming and that's why from Figure 25 we can clearly see that eigenbeamforming has the best bit per channel use.

For purposes of reducing multi user interference and noise in this simulation Zero forcing (ZF) pre-coding scheme is used. The received signal vector for mobile terminals will be:

$$y = \sqrt{\frac{P_{tx} N_t}{K}} \mathbf{H} \mathbf{W} x + n \quad (43)$$

Where y represents the $K \times 1$ received vector for each terminal. x is the transmit signal and P_{tx} is total transmit power, N_t is the number of antenna elements at the BS, n is noise, \mathbf{H} is the channel matrix with \mathbf{W} being the ZF pre-coding matrix.

So in multiuser Massive MIMO systems the channel capacity will then be.

$$C \approx \lambda B K \cdot \log_2 \left(1 + \frac{P_{tx} N_t}{(I + N_o B) K} \right) \quad (44)$$

Where I is Multi-user interference, λ is the scaling factor, B is Bandwidth and $N_o B$ is the noise power.

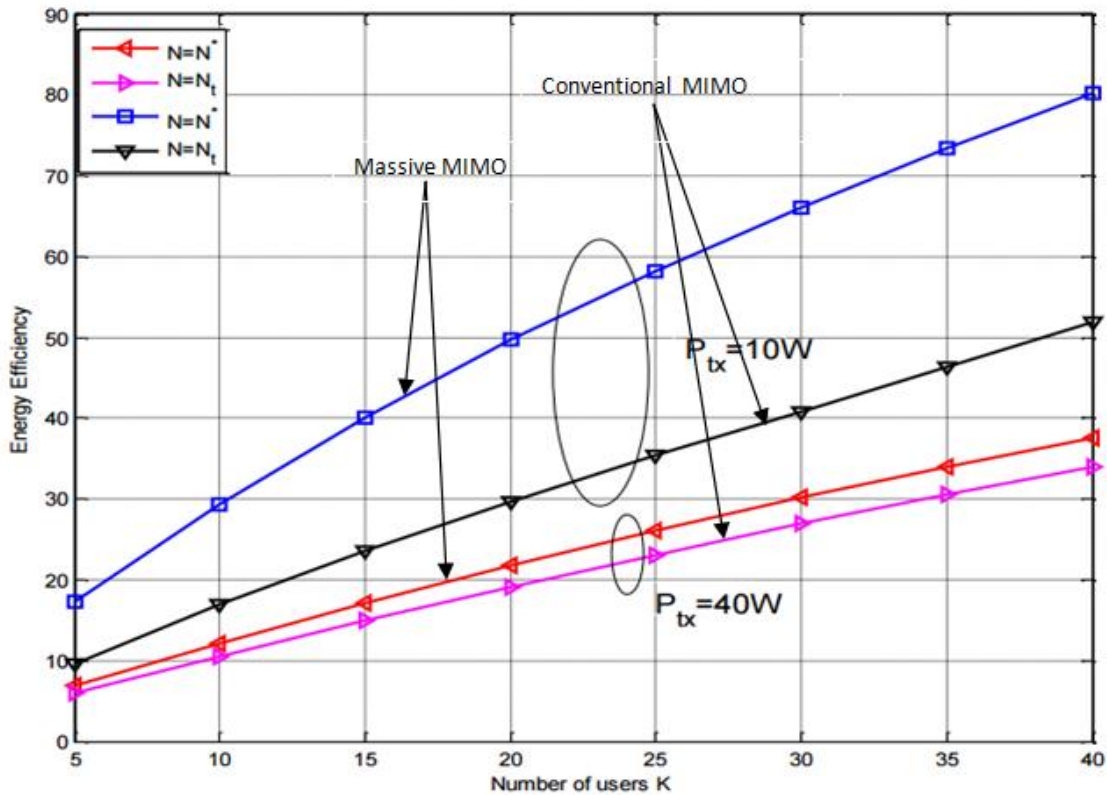


Figure 26. Energy Efficiency Improvement through Transmit Antenna Selection

Figure 26 shows a comparison of 40W and 10 W transmit power, in two scenarios. The first scenario is for massive MIMO, that is when the number of transmit antenna elements is relatively large compared to the receive antenna elements ($N=N^*$) and the second scenario is for conventional MIMO, that is when both, the transmitter and the receiver antenna contains the same number of antenna elements ($N=N_t$), maximum number of transmit antenna elements in this case is 8. The Simulation results clearly shows that the transmit antenna selection in Massive MIMO is energy efficient compared to the conventional MIMO.

5 CONCLUSION AND FUTURE WORK

The amount of data traffic for wireless devices has been increasing significantly for the last few decades. Therefore there is a need for better technologies with the ability of conserving energy but also provide faster connectivity with less or small latency rate. For the next generation of mobile wireless network it is crucial that the technology should be more efficient as compared to its predecessors. One of the technologies that have been proposed to fill in this gap is Massive MIMO which is currently under active research. In this thesis a number of issues have been addressed starting from why we need this technology by looking at the amount of data traffic currently generated and the expected amount in the near future. From the graphs it clearly shows that there is a need for this technology.

Energy consumption as well as high data rates are some of the fundamental features for current and future wireless technologies. For the last few years designers of communication networks has been focusing mainly on performance metrics such as high data rate, high data throughputs and low latency rates, the latter is still of great concern as we have seen in this thesis but now energy efficiency is emerging as one of a greater concern. The next generation wireless network (5G) focuses on energy efficiency and on high data rates by using very large antenna elements at the BS. From chapter 4 Figure 19-24 we can clearly see that increasing the number of antenna elements at the BS has significant effects to energy and data throughput.

As the innovation progresses, it is expected that by the year 2020 the number of connected devices will be more than 50 Billion. Some of these devices will provide

crucial support to human life, especially in the medical area and in the Machine-to-Machine communications. Therefore latency is a sensitive issue; for instance in driverless cars where the reaction time should be in the range of macro second in order to prevent accidents. Massive MIMO is a suitable technology for time critical application with low and high data rates. Furthermore it is energy efficient.

In this thesis we have looked into different aspects of conventional and Massive MIMO. Concentrating on their performance differences in terms of, data throughput and energy efficiency. Simulation results have shown that by equipping the BS with large number of antenna elements, energy efficiency and data throughput can be dramatically improved. However there are still some significant studies that need to be done and these can form the basis of future work.

- Since Massive MIMO is expected to be a key technology in 5G, and its main target is energy efficiency and high throughput. It will be interesting to investigate on better hardware implementation techniques that conserve energy and better interference management and modulation techniques for purposes of high data throughput.

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