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5G OVER-THE-AIR TESTING ENHANCEMENT FOR MULTI-USER MIMO

Master of Science Thesis
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ABSTRACT

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In this thesis work, the research is mainly carried out with the assistance of Nokia OTAVA Lab. The study focuses on designing, implementing, and testing Multiuser-Multiple input Multiple output (MU-MIMO) in a closed environment. The confined environment refers to the specialized RF chambers used for over-the-air testing and validation. The research will include the ideas to increase the current capabilities of the sea containers to equip them for MU-MIMO scenarios.

The existing working environment has a specific limitation as spacing is a crucial factor between the user equipment (UE) and the radio unit. This setup is applicable only for a single UE testing. The research aims to eliminate or provide a solution for implementing multiple user scenarios. With the existing working setup, 4 layers in the downlink can be achieved, whereas with this research, the OTA-Sea containers shall be capable of more than 4 layers in the downlink direction. With the evolving 5^{th} generation mobile technology (5G), enhanced feature testing there is always room to upgrade the system capacity. It is a challenging task at hand to analyze and improve 5G over the air communication. As the developing technology is using a combination of advanced techniques, such as MIMO and Beamforming. With this study endeavour, it is planned to provide solutions to current issues with a view toward future improvements. It will focus on highlighting the existing limitations of the test environments and the suitability in case of capacity enhancements with the expected outcomes.

Generally, the existing test setup is working for single user (SU) cases, and the aim is to introduce MU-MIMO by designing the setup for it. It will include the required separation which is based on the calculated distance and angular dimensions. Following the deployment of the new proposal, the setup will be tested several times to observe any performance degradation. The analysis has been made based on the existing configurations, i.e., all the major KPI's for a single user has been compared with the deployed MU-MIMO strategies. The expectation from the research work is to double the throughput gain by optimizing the relevant factors determining the 5G network performance in contrast with having a single user in the coverage.

Keywords: Over-the-Air (OTA), SU-MIMO, MU-MIMO, Beamforming, SRS, DL layers

The originality of this thesis has been checked using the Turnitin Originality Check service.

PREFACE

First and foremost, I would like to express my sincere gratitude and thanks to Almighty Allah (SWT), the Most Merciful and Gracious, for endowing me with the capacity to begin and complete this work. I pray to Almighty Allah that the work I have completed and the skill set I have acquired at Tampere University & Nokia Solutions will be employed to benefit society.

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Muhammad Zaid Bin Zafar

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LIST OF SYMBOLS AND ABBREVIATIONS

1G	First Generation of Cellular Communication
2G	Second Generation of Cellular Communication
3G	Third Generation of Cellular Communication
3GPP	3rd Generation Partnership Project
4G	Fourth Generation of Cellular Communication
5G	Fifth Generation of Cellular Communication
5GCN	5G Core Network
6G	Sixth Generation of Cellular Communication
AF	Array Factor
AF	Application Function
AI	Artificial Intelligence
AMC	Adaptive Modulation & Coding Schemes
AMF	Access and Mobility Management Function
AMPS	Advanced mobile phone services
AUC	Authentication Centre
B	Bandwidth
BER	Bit Error Rate
BF	Beamforming
BF	Beamforming
BLAST	Bell Lab Layered Space-Time
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
C	Capacity
CDMA	Code Division Multiple Access
cmW	Centimetre Wave
CQI	Channel Quality Indicator
CS	Circuit Switching
CS*	Coordinate Set
CSFB	Circuit Switched Fallback
CSIR	Channel State Information Receiver
CSI-RS	Channel State Information-Reference Signal
CSIT	Channel State Information Transmitter
CU	Centralized Unit
DL	Downlink
DPC	Dirty Paper Coding
DSTBC	Differential Space-Time Block Coding
DU	Distributed Unit
EDGE	Enhanced Data Rates for GSM Evolution
EGC	Equal Gain Combining
EIR	Equipment Identity Register
eMBB	Enhanced Mobile Broadband
ENDC	E-UTRAN New Radio-Dual Connectivity
EPC	Evolved Packet Core
EUTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transformation
FR1	Frequency Range 1
FR2	Frequency Range 2
GGSN	Gateway GPRS Support Node
GHz	Giga Hertz

GMSC	Gateway Mobile Switching Centre
GoB	Grid of Beams
GPRS	General Packet Radio Service
GSM	Global Systems for Mobile Communications
H	Channel
HARQ	Hybrid Automatic Repeat Request
HBF	Holographic Beamforming
HLR	Home Location Register
HPBW	Half Power beam Width
HSDPA	High-Speed Downlink Packet Access
HSS	Home Subscriber Server
HSUPA	High-Speed Uplink Packet Access
IFFT	Inverse Fourier Transformation
IoB	Internet of Bodies
IoE	Internet of Everything
IoN	Internet of Nano-Things
IoT	Internet of Things
ISI	Inter-Symbol Interference
ISP	Internet Service Provider
K	Multiple Antennas
KPI	Key Performance Indicator
LDC	Linear Dispersion Codes
LOS	Line of Sight
LR	Lattice Reduction Aided
M	Antenna Array Elements
M(r)	Number of Rx Antennas
M(t)	Number of Tx Antennas
MF	Matched Filter
Mhz	Mega Hertz
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
mMIMO	Massive MIMO
MMSE	Minimum Mean Square Error
mMTC	Massive Machine Type Communications
mmW	Millimetre Wave
MRC	Maximal Ratio Combining
MR-DC	Multi-RAT Dual Connectivity
MSC	Mobile Switching Centre
MTSO	Mobile Telephone Switching Office
MU-MIMO	Multiuser MIMO
N	Noise
NE	Network Elements
NFV	Network Function Virtualization
NGN	Next Generation Networks
NOMA	Non- Orthogonal Frequency Division Multiple Access
NR	New Radio
NSA	Non-Standalone
OFDMA	Orthogonal Frequency Division Multiple Access
OSS	Operation & Support System
OTA	Over-the-air
PCF	Policy Control Function
PCRF	Policy & Charging Rules Function
PDN	Packet Data Network
PGW	Packet Gateway
PMI	Precoding Matrix Indicator

PrB	Physical Resource Block
PS	Packet Switching
PSTN	Public Switched Telephone Network.
PTP	Point to Point MIMO
QoS	Quality of Service
QOSTBC	Quasi-Orthogonal Space-time Block Code
RAN	Radio Access Network
RAT	Radio Access Technologies
RB	Resource Block
RF	Radio Frequency
RI	Rank Indicator
RNC	Radio Network Controller
RQ	Research Questions
Rx	Receiver
RZF	Regularized Zero-forcing
S/N	Signal to Noise ratio
SA	Standalone
SC	Selection Combining
SDA	Software Defined Antennas
SDN	Software Defined Network
SGSN	Serving GPRS Support Node
SGW	Serving Gateway
SINR	Signal to Interference & Noise ratio
SMF	Session Management Function
SNR	Signal to Noise Ratio
SDMA	Space Division Multiple Access
SRS	Sounding Reference Signal
SSB	Synchronization Signal Block
STBC	Space Time Block Code
STC	Space Time Code
STTC	Space-Time Trellis Code
SU-MIMO	Single User MIMO
SVD	Singular Vector Decomposition
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TH	Tomlinson-Harashima
Thz	Tera-Hertz
Tx	Transmitter
UDM	Unified Data Management
UE	User Equipment
UL	Uplink
UM-MIMO	Ultra-Massive MIMO
UMTS	Universal Mobile Telecommunication Systems
UPF	User plane function
URLLC	Ultra-Reliable Low Latency Communications
UTRAN	Universal Terrestrial Radio Access Network
VLR	Visitor Location Register
VP	Vector Perturbation
ZF	Zero-forcing

1. INTRODUCTION

A vast majority of today's mobile customers demand high data rates and more reliable services. The next generation of wireless communication comes up with technology that offers and promises to meet the increasing demands. [1] The fifth generation (5G) is here to survive on a rapidly expanding planet and to meet expectations. 5G is an advanced wireless technology that provides extreme broadband and ultra-robust, low latency connectivity and massive networking to empower a programmable world. It will improve and transform our individual lives, economy, and society with various applications and services. The new radio (NR) frequency range has been divided into two large categories by 3rd Generation Partnership project (3GPP) for high data rates and the large bandwidth required by users. One of these frequencies is Sub 6 GHz which lies in the lower bands. In contrast, the other frequency range is known as millimetre wave, which lies in the higher bands. The range of frequencies for Sub 6 GHz is from 450Mhz-6000Mhz, whereas the frequency range for millimetre-wave is from 24250 Mhz-52600Mhz. Based on the frequency range, Sub 6 GHz is also called FR1, while the millimetre wave is FR2. For both frequency ranges, the channel bandwidth and subcarrier spacing is flexible. [2] The FR1 is mainly used for broad coverage due to its large cell size. In FR2, the cell size is small compared to FR1, as this range lies in the higher bands, causing the shrinking of the coverage area. The FR2 has a relatively large bandwidth utilized to maximize a network's capacity. Hence, with lower frequency bands, enhanced coverage can be achieved, and the higher bands can boost the overall power and throughput of the network. [3]

Beamforming and massive MIMO are considered as fundamental techniques along with advanced concepts of 5G. To meet the high data rates and demand for dense connectivity, beamforming and MU-MIMO works in parallel to meet this target. The beamforming utilizes the electromagnetic signals more effectively to improve the accuracy and reliability of 5G NR. It incorporates massive MIMO to increase data rates and enormous connectivity of 5G users. [4] Massive MIMO and MU-MIMO are types of MIMO communication. MIMO refers to Multiple input and Multiple output systems. A typical MIMO system uses two or more antenna elements on both Tx and Rx sides. Using diversity and multiplexing techniques, it can send multiple data streams simultaneously. MU-MIMO uses the same concept to send data streams to multiple users simultaneously. Beamforming is used with MU-MIMO concurrently to get a better user experience. [5] Massive MIMO, on the other hand, is a more advanced technique to enhance network capacity specifically. Massive MIMO consists of hundreds of antenna elements in a radio, thus supporting the legacy MU-MIMO and improving the overall spectral efficiency. The techniques mentioned earlier are beneficial in this thesis work. Due to the Sea container's intricate design only single UE installation is supported. The objective is to determine the smallest distance and angles between the UEs and radio unit, avoiding interference to support our broad range of multiple users. mMIMO radio units will be used with over-the-air beamforming to implement MU-MIMO scenarios in this specialized environment. This work will help future test cases related to 5G over the air-beamforming and MU-MIMO scenarios.

1.1 Overview

This thesis research work focuses on the latest wireless technology (5G NR) by using some of the core concepts of 5G to improve and develop a new testing solution. The work scope concentrates on the 5G testing enhancements in a closed environment. The confined environment refers to a compact box. The compact box is a specialized RF chamber with a radio unit on one end and a receiving device, i.e., UE, on the other. The RF chamber is an effective mechanism for performing complex 5G over-the-air testing. It has some adjustable dimensions that can be optimized according to the testing scenarios. This setting provides a prediction of comprehensive view in the field scenarios, mostly line of sight (LOS). This isolated environment has been more frequently used up to this point for single-user testing. The research work will include the re-designing of this over-the-air RF chamber to increase its testing capability for MU-MIMO implementation. It will include the calculations related to the new UE antenna position and separation between them, installation of the new hardware, integration, and commissioning of the environment, enabling the MU-MIMO feature with SRS based beamforming. In this thesis work, the calculations will involve observing different positions for UE so that they can pair without any interference to get up to 8 DL layers. The current setup can achieve only 4 DL layers with a single UE. After the proposed changes, the setup can reach to implement a solution that can test multi-users at the same time, also ensuring that after the new implementation, the UE pairing, RANK, DL layers, channel quality, SINR, MCS, Prb count, Block error rate, and gain should be stable and lies in the theoretical brackets. The new setup is proposed without using a fader; the attenuation of different polarities will be adjusted through the attenuator box manually. With the help of mentioned improvements, the test environment will be capable of getting more gain and can increase MU-MIMO testing effectively.

1.2 Problem statement

The overall IT architecture becomes much more complex with the increase in technological advancements. If we talk about 5G, it has potential to revolutionize the world with its advantages. But on the other hand, it has also changed the way of thinking about wireless communication. With the development of this technology, the network elements and the functionality of wireless architecture will be replaced entirely. Therefore, changing the existing scenario with the new features and applications is always challenging with the evolving technology. New technology must develop over time after it is introduced to the market because the field environment is entirely different from the ideal indoor environment. The indoor environment is itself confined and ideal compared to the field scenarios because of the small space and resources. In real-time communication, many hidden impairments block the way and restrict the desired results. Because of this, there is always an opportunity for advancement until the technology is fully developed and proven.

Comparably, the Nokia OTAVA Lab contributes to this advanced technology with its unique testing strategies. The test environments allow us to simulate real-time field scenarios. We can optimize the network performance and end-user experience using a complex beamforming algorithm. As described earlier, one of the test environments is a specialized RF chamber, which allows us to integrate and test different standardized use cases. Our thesis mainly focuses on developing these test lines more efficiently to enhance testing potential. Considering the user end of these chambers, the UE antennas are installed based on separation for a single user. Due to the compact size of the test line, it is not convenient to add more UEs to it. Hence the existing setup restricts from implementing MU-MIMO use cases as it concerns the separation, mobility, and number of UEs. Simultaneously the 5G technology is developing and improving continuously, which involves more critical testing. Therefore, the issue is whether these RF chambers are suitable for MU-MIMO testing and to discuss the handling of complex testing using multiple UEs. The thesis work addresses the problem by adopting a new strategy for it. Arrangements are made considering the limitations described above. The detailed analysis and observations are made in later chapters.

1.3 Objective

The primary purpose of this thesis is to provide a flexible platform that can be used in research and development (R&D) environment for the ease of 5G testing. OTAVA Lab has all the advanced types of equipment and environment for 5G end-to-end system integration and testing. This research aims to improve and provide a new 5G beamforming testing approach. This thesis work will overcome the issues for enabling MU-MIMO testing scenarios and gives a new way to measure and analyse 5G features. The major objective of this research is to find out an effective solution to enhance the testing capability and communication capacity in the existing environment. After achieving the desired locations for multiple users, there should be reasonable answers to various research questions. Depending upon the expected results on different coordinate sets, the following are the research questions (RQs) that will form the core of the entire thesis project:

RQ1: What are the possibilities of deploying multiple users in the existing setup, and what are the challenges involved?

Initially, there were no expectations from a sea container to administer more than one UE. Given its small size, it can handle only a far-field scenario as the UE antennas are connected very close, causing interference with each other. One approach is to arrange new test line with the desired coordinates. Another is to calculate the separation for multiple users and utilize the existing test line. Having utilized second approach, it aims to install the UE antennas with the calculated partition and test the MU-MIMO scenario in near, mid, and far-field to set side-by-side results. One of the significant benefits is that existing resources can be utilized more effectively to save costs by enhance the current sea container's capability to equip it with modern testing requirements.

RQ2: Having installed multiple UEs, how does it affect the network performance overall? With the proposed separation, does it allow MU-MIMO to withhold other KPIs?

In the thesis, several experiments have been conducted to collect critical KPI data and showcase the impact of MU-MIMO on overall 5G end-to-end system performance. The measured results are then compared with the theoretical calculations. MU-MIMO is expected to increase the overall throughput compared to SU-MIMO, retaining the major KPIs. Several antenna positions have been tested and are being discussed to observe the performance of 5G. The analysis of this research question is made based on these observations, and as a result, the overall network performance is improved, keeping the major KPIs stable. With MU-MIMO functionality, the expected gain is achieved by adding a second user which is realized by careful calculating the horizontal and vertical separations in the chamber.

RQ3: What would be the possibilities to enhance the test-line capability for future use cases in accordance with number of UEs?

One of this thesis goal is to check the limitations of the sea container. After that, there is a need to make theoretical calculations to check how many UE's can adjusted in the chamber while maintaining the theoretical minimum separation between the antennas. Therefore, using the suggested solution and calculations, simultaneously two UEs can be installed and adjusted while considering the dimensions of antenna separation. Having two UEs at the same time results into 4 layers each, contributing the number of layers twice than that of existing setup.

1.4 Thesis Structure

The structure of this thesis is described as follows. After the introduction, the second chapter will briefly describe radio access technologies and detailed architectures for wireless systems. Later, multiple antenna systems are characterized by considering their core concept and explaining different approaches, including diversity and multiplexing ideas, by following the MIMO classification and precoding methods. The concept behind 5G beamforming is covered in the fourth chapter of this thesis work. The distinct conceptualization behind antenna element spacing and the types of antenna beamforming, explaining the notions behind beam steering and switching technique, is spelled out. The thesis work focuses on MU-MIMO enhancements, which are carried out using MIMO and SRS based beamforming techniques. The main idea behind SRS-based beamforming comes after this part. Chapter 5 of this thesis explains the methodological phases of this research work, backed by a flow diagram and a detailed explanation of the methodology with visual illustrations. The overall implemented system model is defined in the sixth chapter; it gives a view of the system understanding and different approaches used for real-time testing. The results are covered in the 7th Chapter, where initially the used 5G soft configuration is defined. Later on, the major KPIs including Throughput, Rank, Multi-user pairing, PrB count, Channel Quality Indicator are compared in contrast with the single user results. The last figure in this chapter illustrates the best approach to implement the MU-MIMO scenario, as there are separate coordinates on which the system is tested.

The best results and the percentage gain is discussed in the explanation. Following this chapter, a precise debate over detail description about the challenges faced during this research work is written. In the last chapter a conclusion based on the best results is made. Also, the future case studies and further improvements is also described in this section. At the end of this thesis, the bibliography for the references is mentioned.

2. WIRELESS TECHNOLOGIES

This chapter will go through a brief description of wireless technologies and their architecture. It will cover the E2E wireless system foundation and working scenarios. Initially, a short history about the wireless evolution is discussed followed by the multiple access techniques which are an integral part of any communication system. Thereafter the system architectures from very 1st generation to the 6th generation are discussed. It will include the advancements, new feature's introduction, and critical understanding of a wireless network.

2.1 History (Evolution)

The world is transforming day by day with the increased usage of technology. Seamless communication always interests people around the globe due to its complexity and applications. In recent decades our communication has depended on a wired mechanism, using a physical cable connection between the source and destination. On the other hand, Wireless technology transfers data between a source and a destination without any physical medium. These days we can see the practical implementation of the wireless network very often. Network service providers are always interested in joining the race of new technologies to give a better user experience.

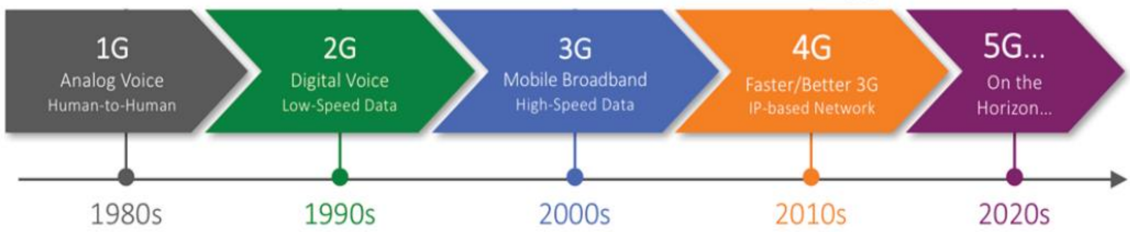


Figure 1. *Evolution of Wireless Communication* [6]

Moving from wired connectivity to wireless technologies always represents a significant revolution. Wireless technology undergoes a series of different manufacturing and developing phases, resulting in five generations of mobile technology to date. [6] These generations are named First Generation-Fifth Generation (1G-5G). Before the introduction of 1st generation (1G) mobile communication, it was inconvenient to use this technology because of the large size and cost of the devices. 1G provided access to everyone and unlocked the doors to a new era. It is an Frequency Division Multiple Access

(FDMA) based mobile technology that uses very low-frequency radio signals to deliver voice services. As this cellular technology was based on analog systems, it has poor security, reliability, and lack of capacity. As the number of mobile technology customers increased, and they are looking for enhancements and improved services. 2nd generation (2G) was introduced with the change in voice services based on a digital communication system. It also provides packet services that evolved afterward and were named GPRS and GPRS Edge. 2G is a significant change in mobile phone communication as it comes up with circuit switching and packet switching services. Packet switching was first introduced in the 2nd generation, providing a breakthrough worldwide. With the popularity of the 2nd generation, the expectations from wireless technology increased drastically. At the same time, 2G can work on a limited bandwidth range and thus can provide low data rates. 3rd generation (3G) is introduced with further improvements and a better user experience. It uses higher bandwidth than 2G, resulting in improved data rates and enhanced packet switching services. This technology has much more potential and improvements than the previous one. [6] The 4th generation (4G) evolved as a big step forward in the telecom sector as it has much more advanced features and reliable communication. It supports all the features from previous Radio Access Technologies (RATs) and provides high data rates. The advancements were made to change the whole architecture from Radio Access Network (RAN) and the core point of view. This technology is much more secure, reliable, and scalable than the past ones. Researchers have already begun to prepare for the 5th generation following the successful introduction of the 4th generation worldwide. So far, the most cutting-edge wireless technology, the 5G new radio, is set to provide massive connectivity utilizing higher bandwidths. 5G is already accepted and changed the usage more efficiently. The future applications and devices depend on the 5G network, as it provides Ultra Reliable Low Latency Communication (uRRLC), Enhanced Mobile Broadband (eMBB), and Massive Machine Type Communication (mMtc) services. 5G has a promising start of delivering data rates up to several Gigabits per second (GB/s) and has a much denser network. The dense network is capable of connecting and providing services to every single device.

2.2 Multiple Access and Duplexing Techniques

The central aim of developing upcoming wireless technologies is to operate on higher frequencies by exploring appropriate multiple access or multiplexing techniques of utmost relevance. The parallel growth of numerous access methods plays a primary role in the evolution of next-generation networks. [7] In two-way telecommunication, there are two modes of sending and receiving data. The first is a half-duplex, used for one-way communication, i.e., one user must listen when the other user is talking. The other one is called a full duplex, a technique in which users can send and receive data simultaneously. [8] Nowadays, the full-duplex mode is mainly used in cellular communication. These modes can be implemented in terms of FDD (frequency division duplex) and TDD (Time division duplex). In FDD, separate frequency bands are allocated to a user for both uplink and downlink communication, separated by a guard band. Whereas in TDD, the user utilizes the same frequency for bi-directional communication but in different time slots separated by guard period. [8]

Multiple access techniques provide available bandwidths for all the users sharing the spectrum to utilize the radio spectrum more efficiently. It will allow for efficient spectrum usage, thus increasing the overall cell coverage and capacity. As the spectrum is constrained, sharing the spectrum is a need to provide services on available bandwidth without any broken communication. [9] In radio communication, there is always a need for a method that allows multiple users to access the network by transmitting and receiving at once. [10] Based on that, several access techniques have evolved regarding cellular technology development. Multiple access refers to a new approach toward multiplexing techniques. The most common examples of various access techniques are explained below:

Frequency division multiple access (FDMA) is one of the multiplexing methods. To access a channel medium based on FDMA, the available bandwidth of the channel has been subdivided into small chunks of frequency bands. Each user is then assigned separate frequency bands for transmission. These frequency bands are uncorrelated and can be separated by using a duplexer. The Time division multiple access (TDMA) method provides access on the identical frequency to numerous users accessing the channel. It keeps the same frequency for all users but divides the radio spectrum into multiple time slots. The users are allocated recursive time slots in a frame. Code division multiple access (CDMA) is a more secure technique using the same frequency band. Even though each user uses the same bandwidth, they are all given unique codes. It takes digitalized analog signal as an input and combines it with the high-frequency chip rate signal. The code generator produces the chip rate signal with a pseudorandom sequence of numbers. The receiver, on the other hand, is fed with the code keys prior to transmission, and the designated data for a receiver is demodulated by matching the keys. A contrast between above mentioned multiple access techniques is given below: [11][12][13][14]

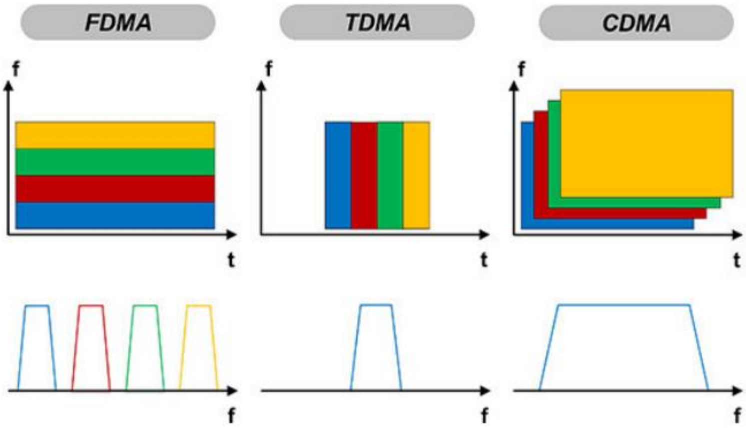


Figure 2. *Difference Between Multiple Access Techniques* [14]

As shown in Fig.2, multiple non-overlapping frequency bands exist for users throughout in FDMA. The signal is multiplied by a high carrier frequency, and different frequency parts are allocated to multiple users. In TDMA, all frequency resources are being used at a particular time. The data is transmitted vice versa, i.e., one user sends its data quickly at a given time and wait for the other user to send it. Whereas in CDMA, the users utilize all the frequency and time in parallel but are isolated from each other in terms of the specific pseudo-random sequence.

Another multiple access technique is OFDMA (Orthogonal frequency division multiple access). OFDMA is an advanced extension of FDMA as it transforms the incoming data streams of large bandwidth into smaller sub-streams of lower bandwidth (called subcarriers) using Inverse Fast Fourier Transform (IFFT). The subcarriers follow the principle of orthogonality. Orthogonality refers to the overlapping of subcarriers so that the peak of one subcarrier falls on the null of the other. The tightly spaced subcarriers absorb the same bandwidth without interference, thus revoking the guard bands (used in FDMA) by saving the bandwidth and improving the spectral efficiency. The subcarriers are organized into groups according to the services the user requires. The most compact subcarrier group is commonly known as a resource block (RB). At the receiver end, the transmitted data is recovered by applying Fast Fourier Transform (FFT). [11][13][15][7]

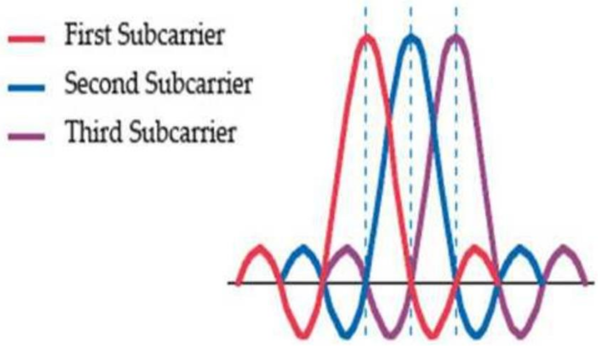


Figure 3. *Orthogonal Frequency Division Multiple Access* [16]

In Fig.3, a sinc waveform is represented in the frequency domain as we know that the Fourier transform of a rect waveform gives a sinc waveform. The sinc waveform carriers are known as subcarriers that contain the transmitted symbols. It can be seen from above that the peak of the subcarriers falls on the null points of each other. Therefore, compared to FDMA, we can pack these subcarriers very closely together to conserve bandwidth and increase the effective use of the spectrum.

Space division multiple access (SDMA) is also one of the access techniques, which exploits the space resources for enhanced capacity and transmission quality. It is used in combination with legacy access techniques i.e., FDMA, TDMA and CDMA. SDMA uses the same concept of frequency reuse method in a way, that each user is spatially separated enough to utilize same resources by limiting the interference between them. Hence, it provides the directed energy to each user accessing the channel simultaneously by using smart antennas. This technique also uses different variations to realize radio signal energy in space. [13][17] A typical illustration of SDMA approach is given below:

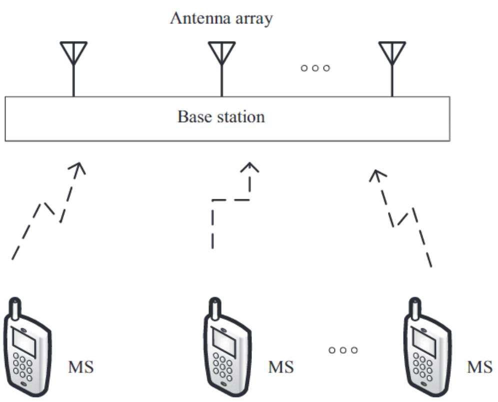


Figure 4. *Space Division Multiple access* [18]

The basic concept of SDMA is portrayed in Fig.4, where the spatially separated UEs are allocated channels of same time and frequency by the smart antennas, deployed at the base station. Each user is distant apart from each other so that there are no interfering beams within the cell coverage. [18]

2.3 System Architectures

The deployment of a network necessitates a foundation upon which a system can function. The set of protocols for a network must be standardized and accepted. Similarly, 3GPP defines the system architecture in wireless communication. All the current wireless systems are working on these standards. The wireless system architectures have some main components. The RAN and the Core are the primary sections that comprise the overall architecture. Both elements work together to form an architecture. The architecture consists of different network elements which perform system-level tasks for end-to-end communication. The network elements are optimized and evolved as the wireless legacy continues. Below are the details of standardized wireless architecture evolution.

2.3.1 1G Mobile communication

Multiple standards were followed during the initial development of the 1st Generation (1G) Mobile communication systems. Advanced mobile phone services (AMPS) & Nordic Mobile Telephone (NMT) are generally regarded as the first stage of wireless communication development. AMPS & NMT are the first communication mechanisms that work on FDMA to provide circuit-switched services, i.e. (Voice). This analog technology is known as 1G or 1st generation mobile communication. It's the first step toward replacing the traditional wired method of communication. The frequency used by this technology is 800-900 MHz, with supporting bandwidth up to 10 Mhz. It uses frequency modulation to process analog signals. [19] The detailed architecture is pasted below:

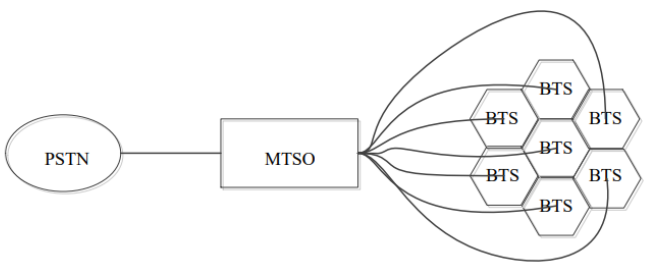


Figure 5. *1st Generation Wireless Architecture* [19]

Fig.5 shows the radio access part as the interface between Mobile Telephone Switching Office (MTSO) and Base Transceiver Station (BTS). The core part here is the Public Switched Telephone Network (PSTN). The BTS represents an acute antenna system acting as a transceiver, which can send and receive information through the same antenna panel. There is an air interface between the UE and the BTS. The traffic layout ensures that MTSO, a third party in this architecture, oversees switching and delivering resources routed from the PSTN by carrying out initial procedures. As a result of this design's in-scalability, there is a considerable risk of third-party eavesdropping, making transmission insecure. The maximum throughput with the 1G system is around 2.4kbps for CS services. [20]

2.3.2 2G Mobile communication

Global systems for mobile communications (GSM) are typically known as 2nd generation (2G) of mobile communication. The architecture of this technology is much more advanced as compared to 1G. The salient features of 2G include digital communication, time division multiple access, circuit and packet switching, and higher throughput related to 1G, GPRS, and Edge. 2G was upgraded between 2.5G and 2.7G by providing improved encrypted communication. With the initial deployment of 2G, the data rate is around 64kbps; with the evolved version of 2G (2.5G and 2.7G), we can combine circuit switching and packet switching to achieve up to 144kbps of data rate. [20,21] The detailed architecture for the 2nd generation is given below:

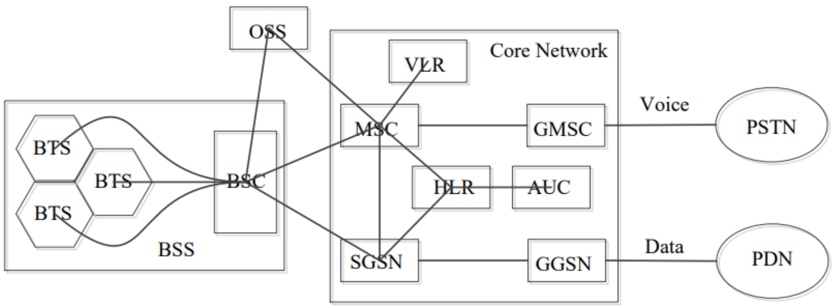


Figure 6. *2nd Generation Wireless Architecture* [19]

Fig.6 explains various changes as compared to 1G technology. The radio access part is known as BSS (Base station subsystem). The two main (Network Elements) NEs of BSS are BTS (Base transceiver station) and BSC (Base station controller). The base transceiver station (BTS) is an antenna-equipped tower. A baseband device serves as the cable endpoint for the antennas. The Base Station Controllers aggregate baseband units from several base stations. The BSC is a controller that performs various tasks. The primary responsibility of a controller is to manage and provide resources to BTSs, provide an interface between RAN and core, initialize handovers, load balancing, operation and maintenance, etc. The core part in 2G consists of several nodes. As this technology provides access to both Circuit Switching (CS) and Packet Switching (PS) services, hence the network traffic is also divided into two categories, which are explained below.

The signaling traffic is the NEs traffic in architecture before providing user service. After the completion of signaling, the network initiates the user data. Hence there are separate paths for both circuit switching and packet switching. In the core network of 2G, the main switching centre (MSC) is considered the network's central processing unit. It manages and supervises other network elements, i.e., HLR, VLR, AUC, and EIR.

The roles of these registers are used as (Home Location Register) user home location database, (Visitor Location Register) user mobility database, (Authentication Centre) user security, (Equipment Identity Register) user equipment security. Hence, in CS service, MSC works closely with these registers and generates user traffic as required after successful signaling. [19–21]

When it comes to voice services, the network will initiate the channels by completing the procedure of the mentioned NEs. The MSC will talk to PSTN for voice call requests and allocates the mandatory resources to the UE. In the case of PS, the two nodes, Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN), connected to the ISP (PDN or Internet), will schedule the user data based on request. In the initial phase of the 2nd generation, the CS architecture with digital modulation exists. Following that, in 2.5G and 2.7G, the packet services (GPRS & EDGE) were established, forwarding a step in the emerging wireless mobile technologies.

2.3.3 3G Mobile communication

The Universal Mobile Telecommunication Systems (UMTS) is considered as the 3rd generation mobile technology. This technology aims to further enhance the data rates according to increasing user demand. This technology can support both CS and PS services with enhanced mobile communication. Terrestrial networking was considered in 3G, and many network elements in 2G architecture have been substituted. e.g., the RAN was replaced by UTRAN (Universal terrestrial radio access network), BS functionalities are further improved and named as a NodeB. The Radio Network Controller (RNC) substituted the controller (BSC) in 3G. First time in wireless technology, the interface between controllers was defined in 3rd generation. Its main responsibility is to increase further the functionalities of a controller by implementing a scalable network. The bandwidth utilization in 3G was improved from several kilo hertz to 20 MHz. The multiple access technique was also replaced by CDMA to meet the increasing demand with the later developments in the 3rd generation like High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA), which provides increased data rates in both uplink and downlink direction by introducing Hybrid automatic repeat request (HARQ) and Adaptive Modulation and Coding (AMC) procedures. As compared to 2G, the throughput in 3G is approximately 2-14Mbps. [20][19] The detailed architecture for the 3rd generation is given below:

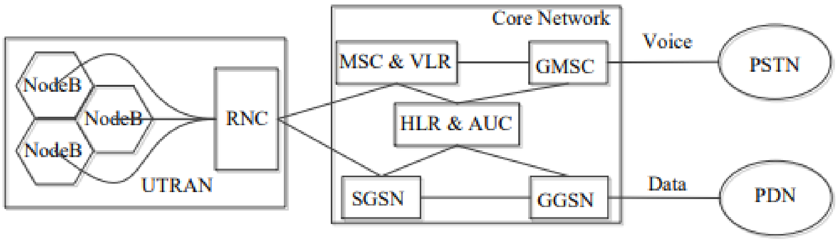


***Figure 7.** 3rd Generation Wireless Architecture* [19]

Fig.7 illustrates the 3rd generation mobile technology architecture. The main difference from the previous technology is the radio access part in the network. The core responsibilities are almost the same in the 3rd generation and follow the same pattern for both CS and PS traffic with minor changes. NodeB and RNC are considered optimized alternatives for BTS and BSC. The interfaces in 3G differ from those in 2G, and the new interface was defined as a controller-to-controller link. It helps to speed up the process and shares the load between the controllers.

2.3.4 4G Mobile communication

Long term evolution (LTE) is considered as the 4th generation (4G) in wireless mobile technology. Previously the users were getting both CS and PS services. The primary goal of this technology was to increase PS data rates. This technology was mainly evolved for high demanding data rates, improved security, enhanced capacity, mobility, and multimedia applications. From the architectural point of view, the network components are optimized and replaced with the traditional framework with advanced equipment. The idea for the 4th generation was to make the network more scalable and simpler as per 3GPP standards. The main difference between the traditional RATs is that the controller is eliminated entirely from the architecture. The BS is optimized to perform selfoptimization checks and enable controlling functions within its range. All the main functionalities were distributed between the BS and the core network. The (RAN, UTRAN) is replaced with Enhanced Universal Terrestrial Radio Access Network (E-UTRAN), and Evolved Packet Core (EPC) replaces the core network. For extreme mobile broad band services, many changes are done, e.g., OFDMA is used as a multiple access technique in 4G; as discussed previously, OFDMA can improve spectral efficiency by reducing the chances of bandwidth wastage. The data rates can be multiplied with this technique to provide higher throughput. It supports the same bandwidth range as in 3G, but bandwidth utilization is more efficient in 4G by using advanced multiple access techniques. MIMO was firstly introduced in LTE networks to combat multipath degradation and boost the network capacity and overall cell throughput. The concept of beamforming is also employed for further network capacity enhancements. These concepts are discussed briefly in later chapters. The LTE network was expected to provide throughput up to 100Mbps, while in a later version of LTE advanced, the data rates were further improved to 1Gbps. [19,20,22] The detailed architecture of the 4th generation is given below:

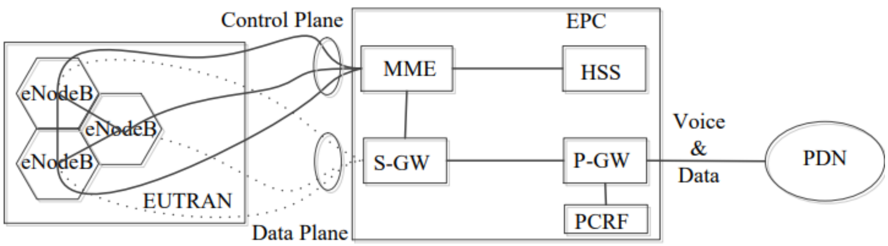


Figure 8. *4th Generation Wireless Architecture* [19]

Fig.8 describes the architecture for 4th-generation mobile technology. The radio access part which is evolved to E-UTRAN. The significant change in EUTRAN is that the NE, responsible for controlling and managing resources, is eliminated. The BS is developed to such an extent that it can handle the tasks performed by a controller. The E-NodeB now provides radio access and acts as a bridge between access and core part. This intelligent Node is optimized to the extent that it can estimate the thresholds and perform the required changes in the network. The new interface is developed in 4G networks, i.e., the X2 interface. This interface works closely with the neighbouring E-NodeB`s for load balancing and handover tasks. The new interface between RAN and EPC is known as the S1 interface. The traffic is divided into control information and data information. The control information proceeds between the NEs via the S1-C interface, whereas the data traffic is processed through the S1-U interface. In the core network of 4G, the NEs are also evolved and optimized, and their functionalities are improved. Mobility Management Entity (MME) is the central switching unit replaced by MSC from the traditional RATs. The responsibility of an MME is to process the switching between the NEs, take updates from other nodes, and perform mobility procedures, signaling, resource allocation, and management. The HSS is the similar register used in 2G and 3G as HLR. It is merged with the VLR and evolved as an upgraded register that holds the user's home database. The Serving Gateway (SGW) and Packet Gateway (PGW) are the upgraded versions of SGSN and GGSN; these nodes are linked with the internet for providing data services. Policy & Charging Rules Function (PCRF), on the other hand, performs policy checks, service charges, and Quality of service (QoS). [19]

The 4G architecture is much more scalable and flexible in terms of interoperability with other radio access technologies. LTE proposes two options for voice services; one is to design and implement an IMS server that can be integrated into core network for IP-based voice calling traffic processing, and the other is to incorporate the Circuit Switched Fallback (CSFB) mechanism for getting CS services from the supported technology. In detail, if a user wants to access CS services while connecting with the LTE network, the network will fall back to a 2G or 3G network to provide voice services. [19] One of the key benefits of the 4G architecture is that it laid the foundation of 5th generation wireless technology, which is discussed in the next section. With the further optimization of LTE salient features, it can benefit from the existing wireless architectures.

2.3.5 5G Mobile communication

5G is known as the 5th generation of mobile technology (NR). It is widely believed that 5G cellular networks will overcome the hidden challenges not adequately conveyed by the 4th generation. [21] To address these objectives, new technologies are being suggested and developed for 5G. The main goal of the 5G network is to provide massive worldwide internet connectivity with higher data rates, lower latency, and higher capacity by implementing an ultra-dense network. [19] Increasingly, it has been agreed that three standard services will be supported by 5G wireless systems, i.e., uRLLC, eMBB, mMTC. With the increase in traffic, the network operators are facing challenges in providing faster data rates with security of data in terms of delay and reliability. The 5G uRLLC implementation provides latency between 0.5-1ms, which is less than the 4G networks; with lower latency, it is also guaranteed to provide reliability and availability simultaneously. The uRLLC benefits many mission-critical industrial applications, including remote health, surgeries, intelligent transportation, and smart grids. [23] The eMBB service further supplements the mobile broad band traffic compared to 4G. The defining characteristics of eMBB ensure high payloads for a device with a stable connection and high reliability. [24] Whereas mMTC focuses on the low-power transmissions that need to communicate small payloads via low-power devices with flexible latency requirements. 5G provides a chance to address the essential aspects related to the massive connectivity of these devices. mMTC aims to equip the industry with wireless sensors, IoT, and various health and environment monitoring devices providing large-scale connectivity. [24] [25]

From the cellular architecture point of view, the 5G network is entirely different from the existing technologies. Demand and user expectations increase in tandem with the growing popularity of the most influential technology. The development and deployment of a potent heterogeneous infrastructure and widespread connectivity is possible only with the 5G wireless network. To overcome challenges related to 5G key features and specifications, the SDN solution is introduced by the researchers. All the network elements are placed in different clustered groups, thus managed by the centralized software-based controllers. It can make cellular architecture more scalable, flexible, improved network controlling, efficiency and QoS. [26]

During the initial development phases of 5G, the 3GPP (Release 15) (standardized body) initially proposes two modes for 5G deployment. The first mode is called non-standalone (NSA), and the second mode is known as standalone (SA). The main difference between SA and NSA is that NSA uses the existing LTE network to provide services dependent on EPC. In contrast, the SA mode has an independent 5G core, and no intermediate connectivity on existing technology is required. The below figure explains the difference between the two modes:

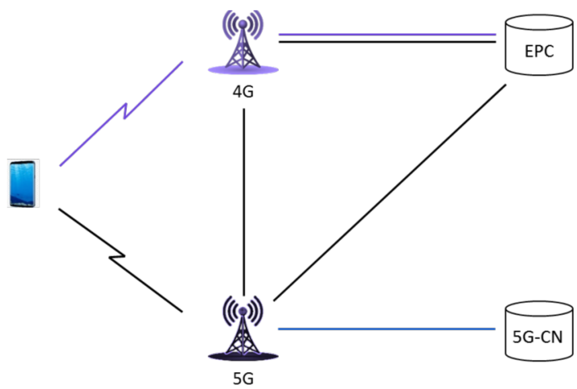


Figure 9. *Difference Between SA & NSA* [27]

In Fig.9 both 5G modes are described; in the first mode (NSA), the two nodes (4G & 5G) work closely with each for user services. The dual mode communication between two nodes has been suggested for enhanced data rates and improved mobility. In this mode, the UE has the capability to communicate with two nodes at the same time. In the SA mode, the 5G RAN is not shared with other RATs. The independent network will work like the legacy networks. The UE will camp on the gNB, and the 5CN is linked directly with the base station to manage and provide resources. [28]

The initial deployment for 5G mainly comprises NSA mode to provide extreme data rates (in other words, only 5G eMBB services are considered with this mode). The independent 5G network or SA mode is typically viewed as a complete package for the services, including eMBB, uRLLC, and mMTC. A typical SA mode is under development as it comprises several new changes, e.g., Network virtualization, Network Slicing, Core upgradation (To support and manage extreme data traffic), etc. [27]

As the technology progresses, the network operators are also investing in existing LTE networks. However, it is unlikely that 5G customers will instantly increase during the transition. Initially, the service providers are not expecting to make a significant profit or spend on implementing the 5G network at an excessive rate. [28] After the 3GPP release 15, it opens the doors for mobile operators to provide 5G services with a modest network upgrade. The objective for 3GPP rel.15 is to provide multiple scenarios for 4G and 5G connectivity with different modes.

Deployment Options	gNB	eNB	Core	Mode
Option 1	N/A	MN	EPC	SA
Option 2	MN	N/A	5GCN	SA
Option 3	SN	MN	EPC	NSA
Option 4	MN	SN	5GCN	NSA
Option 5	N/A	MN	5GCN	SA
Option 6	MN	N/A	EPC	SA
Option 7	SN	MN	5GCN	NSA

***Table 1**. 5G Deployment Option* [28]

**MN (Master Node), SN (Secondary Node), N/A (Not applicable)*

As shown in the table above, there are seven modes proposed by 3GPP for 5G deployment. The deployment option 1,2,5, and 6 refer to the 5G standalone mode, in which a single RAT is involved directly with the UE. Deployment options 3,4 and 7 are considered for 5G NSA mode. In this mode, 5G and 4G nodes work together to enable 5G services with the existing network. [28]

The concept of MR-DC proposed by 3GPP helps in the 5G initial rollout, and this solution consists of a Master and Secondary node with one or both connected to the EPC. If the LTE node behaves like a Master node and is associated with the EPC, then the Multi-RAT Dual Connectivity (MR-DC) becomes (E-UTRAN+DC), i.e., E-UTRAN New Radio-Dual Connectivity (ENDC). [29] Given LTE networks' widespread adoption and popularity, it is only reasonable for the initial 5G wireless network to be created in NSA mode using the foundations of EN-DC. If EN-DC is considered for initial deployment, then it applies to Option 3. [28] Option 3 comes with three variants suggested by 3GPP, as shown below:

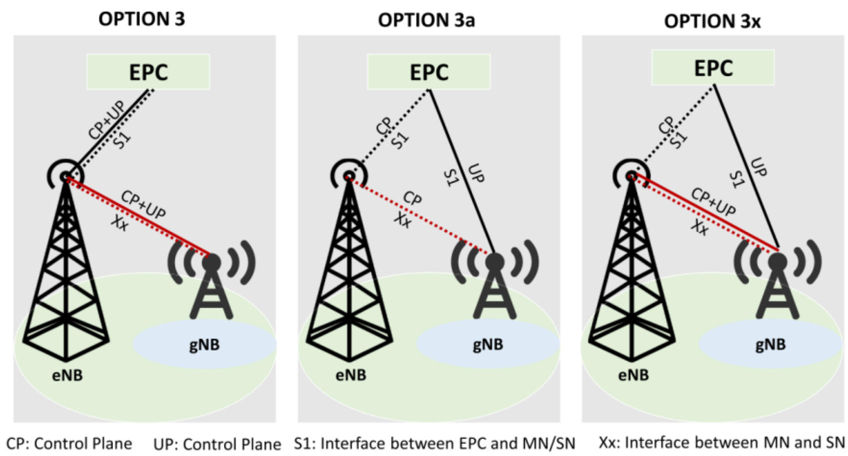


Figure 10. *NSA Option 3 Implementation modes* [28]

*Traffic splitting is the main difference between these modes.

In Fig.10, If we talk about NSA option-3 deployments, The main difference between these options is the traffic split. The 3GPP standardized the dual connectivity based on traffic split, master, and secondary node. The UE has the capability to connect with two technologies simultaneously. The NSA mode has the interworking between two RATs, i.e., eNB and gNB, with the legacy EPC as a core network.

In option 3: The anchor is placed at the LTE node, which acts as a master node. The S1-U split is configured at LTE eNB. 5G node has no direct link to the EPC. If the user requires the 5G services, the traffic will be routed from the 5G node toward the LTE node. The LTE node then routes the traffic back to the 5G node. The communication between

LTE and the 5G node is done through the X2 interface. (X2C & X2U) for control and data traffic, respectively. In this option, the eNB is overloaded by simultaneously managing the LTE and 5G data. On the other hand, the EPC needs to process user data for both technologies, thus requiring large bandwidth for required transmissions. [30,31]

In option 3a: The eNB and gNB can directly communicate with the EPC. The S1-U anchor is placed at the gNB. The signaling for 5G traffic is routed through the LTE node via the X2C interface. After signaling, the respective user traffic is transmitted to the gNB and eNB on separate interfaces with the EPC. In other words, the user traffic split happens on the EPC end. [30,31]

In option 3x: The option-3 and 3a combine to act as option 3x. The 5G node acts as a master node as the S1U anchoring and splitting happen on the gNB. It is the most popular option in initial NSA deployment. As there is no excess load on the LTE and EPC, the 5G BS checks the user type and initiates the signaling with the LTE BS. The eNB and gNB also share the user traffic on the X2U interface for load balancing. [30,31]

The cellular system architecture for 5G NR is given below:

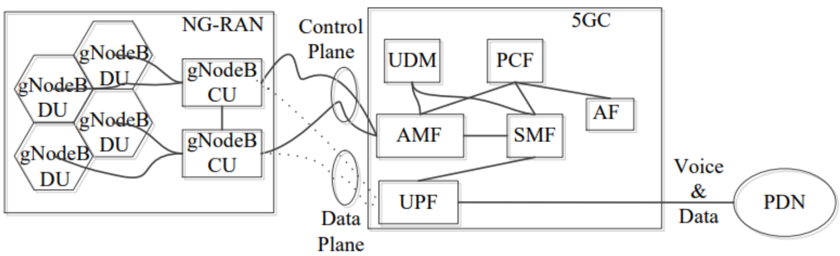


Figure 11. *5th Generation Wireless Architecture* [19]

Fig.11 explains the cellular architecture for the 5th generation. The 5G architecture is shifted to the Software Defined Network (SDN) approach, as discussed earlier. There are many significant differences compared to legacy wireless technologies. The NG-RAN now replaces the access part which was typically known as EUTRAN in LTE. [19] As part of the 5th generation, there are distinct possibilities for RAN, e.g. (V-RAN, Centralized RAN, Cloud RAN). Keeping behind the traditional RAN, the 5th generation SDN network offers a flexible solution with different arrangements. As illustrated in the figure, the BS and Baseband Unit (BBU) are further categorized into two units. Based on layer splitting, gNB-CU and gNB-DU are placed in the NG-RAN part. The splitting is suggested as a novel, adaptable, effective, and environment friendly RAN architecture. [32] The core network is replaced by 5GC compared to the EPC in 4G networks. In the core network, the MME is substituted by the Access and Mobility Management Function (AMF) with service upgradation. On the other hand, the Session Management Function (SMF) is responsible for session arrangement, suitable User plane function (UPF) choice, and allocating IP addresses to the users. Policy Control Function (PCF) is used to regulate policy implementation and checks. The UPF provides the data services linked with the PDN, i.e., the Internet. The Application Function (AF) is an application function that works closely with the PCF and focuses on policy structures. The Unified Data Management (UDM) handles the user's subscription packages and registrations. [19]

The multiple access techniques used in the traditional RATs are known as OMA. 5G is expected to utilize NOMA technologies. [19] The number of dependent devices increases as the 5G network becomes more densely populated. Hence, the previous orthogonal multiple access techniques may yield extremely high overhead, and un-wanted high latency. [33] Initially, OMA (OFDMA) is used for the 5G deployment, but this technique supports a limited number of users. The main reason for limited users supported by OMA is that the present networks are constrained by the number of orthogonal RBs available, which in turn restricts the spectral efficiency and capacity of the existing network. Different NOMA algorithms are suggested to accommodate massive and drastically diverse users. Although NOMA is a successor of previous MA techniques, the fundamental idea of this multiplexing technique is to accommodate maximum users in each RB. [34] In the recent study, three main types of NOMA techniques including Power Domain, NOMA Multiplexing and Code Domain have been proposed. [34]

Continuation of increased data rates is constant from the legacy wireless technologies, i.e., 3G & 4G. It will play an essential role as a driving force in the enhancements and evolution of the network. [35] The 5G network is expected to provide extreme data rates with enabling technologies, i.e., Network Function Virtualization (NFV), Massive MIMO, Beamforming, SDN, Network Slicing, etc. The cmW in 5G utilizes the spectrum below 6GHZ, while the above spectrum is considered for future usage. So initially, there are a lot of expectations from 5G in terms of broadband as compared to 4G; the 5G network targets to improve data rates by 100 times. With the ideal circumstances, the 5G network targets extreme data rates in both UL and DL directions as compared to previous RAT, i.e., 10Gbps and 20Gbps, respectively. [36]

2.3.6 6G Mobile communication

The 6th generation of mobile communication is yet to come. At the moment, this technology is still in the research phase. The initial set of specifications and applications that will be covered in this generation have been proposed by numerous researchers. The technology is meant to be deployed by the end of 2030. [37] The guesses about the data rates for 6G lie between 100Gbps-1Tb, supporting trillions of connected devices in the network. This can be achieved by using ultra-high frequency/Visible light and efficient spatial resource utilization. All the previous wireless technologies use frequencies lower than the 0.1 terahertz range; extremely high data rates are achievable above this range. Hence the 6th generation is the first ever wireless technology that will work on this frequency range and sometimes tends to enable a combination of higher frequencies for these requirements, e.g., THz frequency band, mmWave frequency band, and 1-3 GHz frequency band. Another practical reason for this frequency band is that the existing spectrum is full, and there is no availability for further frequency allocation. [38] [39] In the 5th generation, many enhanced features and use cases have been proposed, including Artificial Intelligence, machine-type communication, automated transportation, etc. Nevertheless, these innovations were incorporated only partially, but after a decade, 5G will lag to support the massive amount of data generated by these devices and applications. [38,39]

The main reason for enhancing frequency range in this technology is that in the future, researchers are looking to merge cellular networks to enable space-to-ground communication, which requires extremely high data rates (internet), thus, allowing the higher frequencies that can make it possible. Before that, in 5G, we are using massive MIMO radios with hundreds of antenna elements. In the 6th generation, researchers are looking for a new MIMO technique, i.e., UM-MIMO, to design an antenna with thousands of array elements, to enable THz communication. [38] In recent research, many new techniques have been suggested for upcoming 6G technology; HBF is a new concept that uses the SDA approach to implement very sharp and more focused beams transmitted from a holographic optical antenna. The radio waves will enter from the antenna’s rear side and disperse from the fore-end. The small-patched antenna elements will direct and modify the beam patterns. [39] On the other hand, artificial intelligence and machine learning techniques were partially introduced by the 5th generation. Still, they are expected to be fully functional in the 6th generation covering most of the latency-dependent applications. [39]

The development and necessity of 6G technology will be driven by the extraordinary demands posed by the latest innovative applications anticipated for the next decade that would not be possible with the traditional legacy wireless technologies. [40] The 6th generation features, and applications will enable the future world to experience extraordinary side-by-side services, i.e., underwater deep-sea communication, ground-to-space communication, IoE, IoB, IoN, AI-enabled devices, extremely high throughput, blockchain, 3-D networking, big data and many more. [37,39]

The cellular architecture has no suitable proposed framework for the 6th generation. Scientists believe that initially, 6G will be the expansion of the 5th generation from the cellular architecture point of view, supporting the existing 5G applications. It will also be integrated to support interoperability with the previous RATs. [37]

3. MULTIPLE INPUT MULTIPLE OUTPUT ANTENNA SYSTEMS

Throughout the past two decades, academics and industry have developed a keen interest in evolving multiple antenna systems for communication systems. These systems are being used for multi purposes, including improved gains in terms of diversity, multiplexing, and antenna beamforming. A significant increase in bit rate, reduced error, and improved SNR can be achieved using multiple antenna systems. [41]

3.1 MIMO Approaches

Multiple input and output systems are proposed in modern wireless communication to combat the degradation caused by multipath propagation on a transmission channel. The idea behind multiple input multiple output systems is that they will use the existing bandwidth and transmit power resources to boost the channel capacity. MIMO refers to multiple antenna arrays installed on both transmitter and receiver ends to utilize multipath for sending and receiving additional information. [42] A signal propagates through a transmission medium degrades upon receiving due to channel impairments and fading effects. [43] A typical multiple input and output system consists of different antenna combinations; the most used models are given below:

Figure 12. *Types of MIMO Communication.*

The capacity of a wireless channel is given by Shannon's capacity theorem. The multiple antenna techniques always lie between the theorem boundaries to operate. [44]

Single Input Single Output (SISO) antenna systems is a model that uses one antenna on the Tx side and one on the receiver side. There is only one spatial stream between them. This model is simplified in terms of implementation, using a single path between Tx and Rx, and there is no need for enhanced diversity processing in SISO. Due to the limited number of antennas in this mode, the impairments, including interference and fading, will affect the performance gain of the system. [45,46] The channel capacity of a SISO model is given as:

$$C = Blog_2(1 + {}^{S}/_{N}) \quad \text{(i)}$$

The above equation (i) explains a typical equation for calculating the capacity of a SISO model. The capacity (C) is equal to the product of bandwidth (B) with the logarithmic value of signal to noise value (S/N). [42]

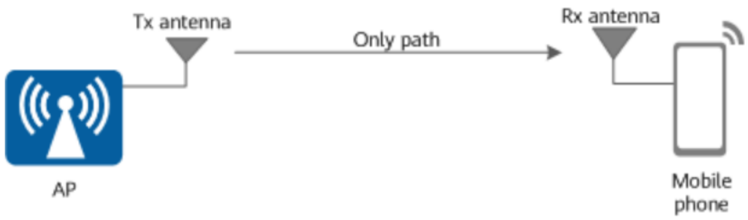


Figure 13. *Single Input-Output System* [46]

Fig.13 represents a simple SISO model implementation with a single antenna for transmission and receiving separated by the channel with a single spatial path between them.

Single Input Multi Output (SIMO) are traditional system models for which diversity at the receiver is mainly used. A transmitter will send data streams on two spatially separated paths improving the overall system reliability. If the transmitted signal is degraded from one path, the receiver will get a duplicate copy of the signal from the other path to reconstruct the required data. [46] This model is also simple in terms of implementation, but on the other hand, it involves the receiver complexity to process the separate path for incoming data. Two methods are suggested to estimate the best results in SIMO; the first one is called switched diversity (The receiver will switch the antenna based on the strongest received signal), and the second one is called MRC maximum ratio combining (The receiver will receive the signal from both antennas and combine them to obtain a better signal). [45] The channel capacity of a SIMO system is given below:

$$C = log_2(1 + \frac{Ex}{N_0} N_R) \quad \text{(ii)}$$

The above equation (ii) illustrates the capacity of a SIMO channel, the capacity of the channel has a direct relation with the increasing antennas at reciever end. The term $\frac{Ex}{N_0}$ represents the transmitted energy and noise power density respectively i.e., (SNR). The scaling factor of SNR is the number of antennas used at the reciever side. [47]

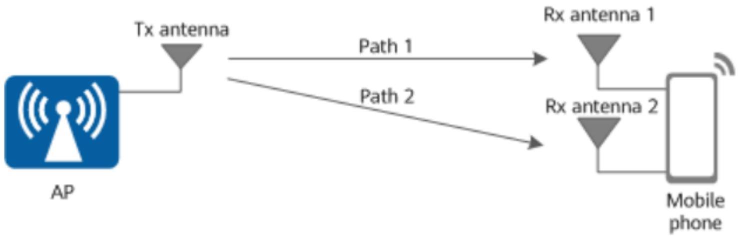


Figure 14. *Single Input Multi-Output System* [46]

Fig.14 represents a traditional SIMO system, and an additional antenna is added on the Rx end to get more than one data stream sent by Tx. It will improve the system's overall reliability by implementing diversity on the receiver side. There are fewer chances of data loss in SIMO as compared to SISO.

Multiple Input Single Output (MISO), on the other hand, is an opposite model compared to SIMO. It uses two antennas on the transmitter side instead of a receiver. Hence it is also known as transmitting diversity. The same signal is transmitted from two antennas on the channel, and the receiver combines two signal copies to get the best-estimated result. The benefit of using this model is that the maximum processing is now done on the Tx side. The end-user has to receive the signal and combine it properly. This technique is useful in cellular communication because the UE has a compact size, space, and low processing compared to the base stations. [45,46]

The overall channel capacity and model of a MISO system are given below:

$$C = log_2(1 + \frac{Ex}{N_0} N_T) \qquad \text{(iii)}$$

The equation (iii) gives the idea to calculate capacity of a MISO system, the model uses more antennas at Tx end by increasing the capacity of the system logarithmically. The SNR scaling factor is realized as the number of antennas used at Tx end. i.e., N_T. [47]

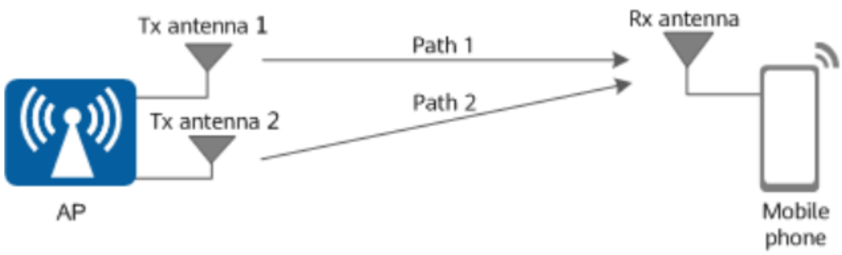


Figure 15. *Multi-Input Single Output System* [46]

In Fig.15, a MISO system is given, in which two separate antennas are being used at the transmitter side sending the same signal. On the Rx side,sss it will receive the signals from two distinct paths and combine them. The performance of a MISO model is similar to the SIMO system.

Multiple Input Multiple Output (MIMO) consists of multiple antennas on both Tx and receiver sides. It benefits a communication system in terms of reliability, enhanced capacity, and quality. A typical MIMO system consists of more than one antenna on both the transmitter and receiver end. Thus, it enables multiple spatially separated data streams to propagate through the channel. It can send multiple streams of signals on different paths; hence on the receiver end, these data streams are separated and reconstructed. Generally, a MIMO model is used for single-user communication; therefore, it is also known as SU-MIMO. Different techniques for multiple users are derived from legacy MIMO technology, explained in the following sections. [42,46] The capacity of a MIMO system and the model is given below:

$$C = max_{T_{r(Rxx)=N_T}} log_2 \det\left(I_{N_R} + \frac{E_x}{N_T N_0} H R_{xx} H^H\right) bps/Hz \qquad \text{(iv)}$$

The capcity of a MIMO system is represented in equation (iv), which is equal to maximizing the given mutual information over al possible distributions.The logarithmic term is the mutual information, which is equal to the summation of identity matrix $I_{N_R}$of noise components at dependent Rx branches and the product of signal energy over transmitting antennas & noise $\frac{E_x}{N_T N_0}$, deterministic channel matrix H, covariance matrix of the source symbol x i.e., R_{xx}, hermitian matrix of channel H^H. [47]

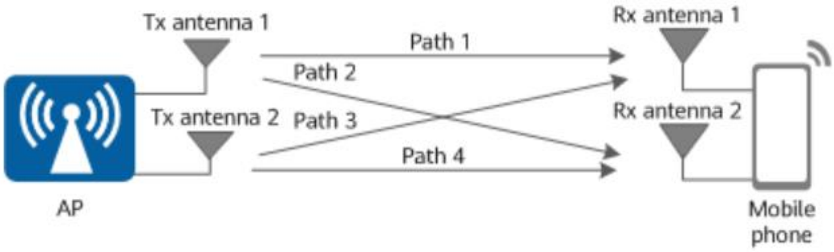


Figure 16. *Multi-Input Multi-Output System* [46]

Fig.16 shows a MIMO system model in which multiple antennas are deployed on both ends. More than one spatial path is available on the channel. Both Tx and Rx antennas can send or receive various data streams. The performance of a MIMO model is much greater than the previous multiple antenna techniques.

3.2 Multiplexing

In a wireless channel, when a signal propagates, certain channel effects (fading, refraction, diffraction, reflection) cause the original signal to deteriorate. These problems can cause information loss and severe degradation in service quality, gain, and error performance. Multipath propagation creates challenges in meeting these objectives. With the limited bandwidth resources, we have to compromise on the efficiency of a wireless network. Traditionally in the previous multiple antenna techniques, only frequency and time domain methods were used closely with the channel coding models. Hence the unexploited space domain can be utilized to meet the growing demands of the subscribers. [41] MIMO communication benefits the transmission by enhancing link robustness, efficiency, and coverage of a wireless system using various technological modes, including spatial diversity, spatial multiplexing, and antenna beamforming. [48] The modes of MIMO implementation can be used individually in different combinations. Spatial diversity and multiplexing will be covered in this section, while antenna beamforming will be covered in the next section. The classic MIMO formats are given below:

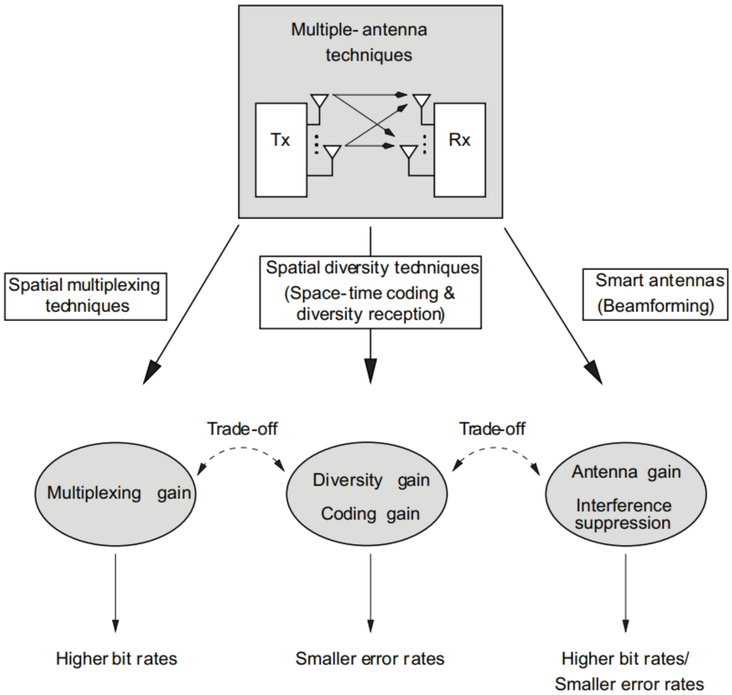


Figure 17. *MIMO Techniques* [41]

3.2.1 Spatial Multiplexing:

The spatial multiplexing technique enhances data speeds while using fewer resources. This technique separates the parallel data streams and transmits them through each antenna from the base station. If the scattering in the wireless channel is ample, then spatial multiplexing creates separated channels in the allotted bandwidth resources. Different receiver types can be used to decode incoming data streams; one of them is the linear receiver, i.e., (ZF & MMSE) the other one is the non-linear receiver (SIC & ML) which is more suitable in terms of error performance. Still, it has to process complex computations and comes at a higher cost. [49,50] At the receiver end, the decoder estimates the channel information by constructing a channel matrix [H]; the incoming data stream is then multiplied by the inverse of the channel matrix to recover the desired information. The equation for receiving and decoding the incoming bits is given below [42] [44]:

$$R = Hx + n \tag{v}$$

$$X = (H)^{-1}.R \tag{vi}$$

Equation (v) illustrates the basic understanding of the receiving signal in MIMO communication. The variable R is equal to the product of channel matrix H & complex numbers consists of transmitting vector x. Whereas n represents the channel noise during transmission. The estimation of the incoming signal at the reciever end is given by the equation (vi). The recieved signal R i.e., equation (v) is multiplied by the inverse of the the channel matrix H to evaluate the recieved signal. After multiplication the resultant vector is the actually the summation of the actual transmitted signal x with the product of $(H)^{-1}$ matrix (calculated by using SVD method) and noise n. Supposing the mimimum noise on the channel which results in approximate the best estimation of the recieved signal. [51]

Spatial multiplexing concerns the high bit rates to optimize the spectral efficiency with parallel data streams by increasing the amount of bits per symbol that can be transmitted in a given bandwidth at a certain coherence. [52] In other words, the basic principle of this method is to send separate symbols over M(t) by utilizing time and space dimensions. The incoming data is further divided at Tx into n separate data streams. These streams are transmitted via separate antennas following multipath along the channel to arrive at the Rx. The channel's various spatial dimensions are used to convey various data streams. The different separated paths have spatial identification when arriving at the Rx antenna. The Rx antenna uses unique identification to separate the desired symbols. Hence, the channel's capacity is enhanced by the number of antennas used at both the Tx and Rx end. Typically, in spatial multiplexing number of antennas at the Rx end is usually increased in number or equal to the Tx antennas. [53] During serial processing in spatial multiplexing, the incoming data is decomposed into smaller encoded bits and thus mapped onto all transmitting antennas M(t). The codewords [x1, ..., xT] are created by the interim encoding of the bits through a serial encoder, and these code words are demultiplexed and mapped onto various antennas by estimating the constellations. Serial encoding involves increased complexity due to the length of the code words. In recent research, a promising technique for spatial multiplexing has been proposed, which is named BLAST. The BLAST technique is most commonly used to improve the system's performance in terms of data rates. It involves separate data streams using a parallel encoder; the encoder with a block length acts as a SISO model to interleave and map the individual data stream to the transmitting antenna. The output data stream is a combination of overall input after encoding and creates a codeword transmitted after multiplexing over the channel. Due to parallel data processing, it is also known as V-BLAST. [53] [54] We need an equalizer to reduce inter-symbol interference because noise-corrupted data streams conflict with one another at the Rx end. As mentioned earlier, linear and non-linear receivers can be deployed for this purpose. Zero-forcing equalizer is used by V-BLAST for detection in spatial multiplexing because of its low complexity and simple design. The primary goal of the ZF equalizer is to eliminate inter-symbol interference. Spatial multiplexing can be deployed by having knowledge or no prior information about the channel condition. [53] [52] [55]

The BLAST architecture for Spatial Multiplexing is given below:

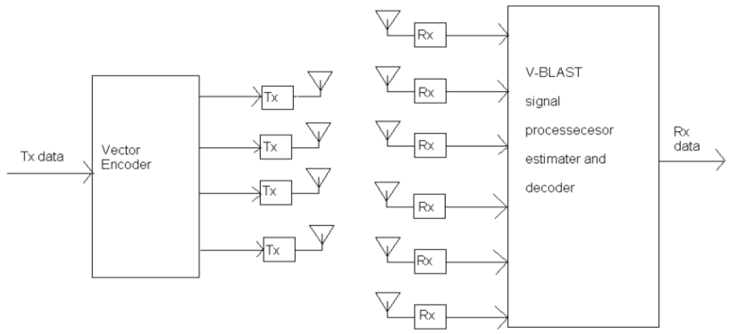


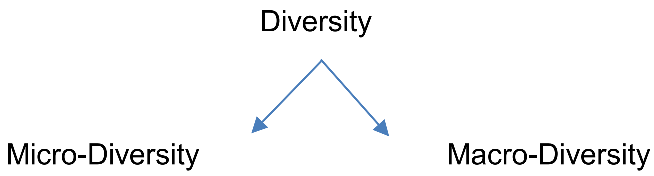
Figure 18. *Spatial Multiplexing implementation with BLAST* [55]

Fig.18 represents a more straightforward method to achieve spatial multiplexing in MIMO. The architecture includes a vector encoder that maps the parallel data streams to corresponding antennas, and the receiver estimates the incoming data streams by eliminating ISI.

3.3 Diversity

Evolving next-generation mobile systems must offer reliable communication for both voice and data services. With the changes in technology, mobile devices are also designed to be compact and portable, enabling high processing to advantage different kinds of urban, rural, micro, and macro diverse environments. The future technologies are designed accordingly to provide better quality and user experience by utilizing available resources and less power. [56]

With the improved data rates, transmission reliability also plays a vital role in MIMO implementation. Diversity refers to a method in which multiple dependent copies are sent by the transmitter so that the receiver gets multiple copies of the same signal by increasing transmission reliability. The transmitted signals must be uncorrelated from each other. Diversity is a method of avoiding the possibility of deep fades and error probability in a wireless channel. The idea behind this method is to send replicas of the input signal to travel on multipath and combine at the receiver end. Diversity can be implemented using Time, Frequency, or Space. By exploiting the channel using diversity methods will help to improve the SNR and lowers the chances of error detection. [57] Categorically the diversity method is divided into two main types: [41]



Both diversity types differ from each based-on fading and shadowing effects. In fading, the received signal may be vulnerable to different multi-paths in the wireless channel, which results in signal reflection and scattering, causing the signal to lose information. The other phenomenon, shadowing can cause path blockage by an environmental obstruction in a channel. [58]

Micro diversity overcomes the issues related to channel fading; rich scattering in the environment gives rise to minor fading effects on the communication channel. Micro diversity can utilize several co-located antennas separated under a wavelength so that multiple spatially separated data streams can fade independently from each other. With this method, there is a high possibility of recovering the signal in a fading environment. The gain in micro diversity is increased by using a large number of antennas during communication, which makes it less likely for all the data streams to fade deeply at the same time [41].

Macro-Diversity deals with the medium which have obstacles between a transmitter and a receiver, such a medium is referred as the shadowing effect, in which the hindrance blocks the user on a transmission path. Macro diversity allows for the deployment of multiple antennas at the Tx and Rx side and spatially separates them on a large scale so that the base station does not overlook the user. By this method, there is a low probability for all the streams to get blocked simultaneously as of large-scale separation is deployed in the environment, which can increase the error performance of the system. [41][59]

3.3.1 Spatial Diversity

This diversity technique falls in the category of micro diversity. Spatial diversity in MIMO uses the same concept by deploying multiple antennas on Tx and Rx sides that are spatially separated to overcome multipath fading effects. By using this technique, the signal will follow multiple paths in the wireless channel to reach the destination, and the Rx can estimate the best quality signal. To achieve diversity gain and subsequently increase BER, it is possible to send and receive duplicates of the same information sequence using multiple antennas that have been suitably encoded. [48,52] The below figure represents a spatial diversity implementation in MIMO:

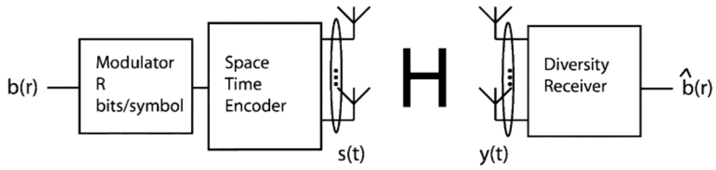


Figure 19. *Spatial Diversity* [60]

Fig.19 illustrates a MIMO model with a spatial diversity technique; the modulator maps the high-speed incoming bit rate on a constellation of bits/symbols. The modulated signal bits are spread on the transmitters by using an encoder that encodes the bits in the form of spatial codes. The same information is carried out by the individual antennas on a channel (H) and follows multiple paths to arrive at the receiver. [60] Spatial diversity is further categorized into below types:

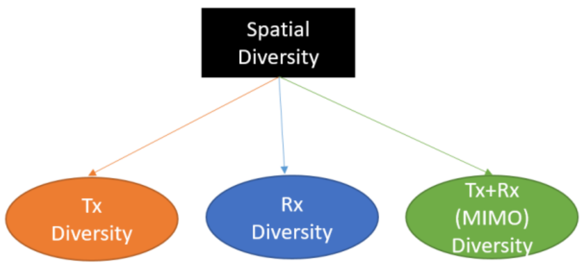


Figure 20. *Types of Spatial diversity*

The spatial diversity in MIMO can be applied by implementing above mentioned scenarios. As discussed in the previous section, Tx diversity can be used in a case where the number of antennas at the transmitter is greater than the receiver antennas. This type of configuration is mainly used in MISO systems. The Rx diversity is opposite to the Tx diversity, as the number of antennas at the receiver is more significant. This implementation is used in SIMO systems. Or a combination of both techniques can be used to get maximum benefits from a wireless channel. In theory, the best way to combat multipath channel fading is to regulate the Tx power, so channel circumstances at the Rx must be familiar on the Tx side so that the Tx can estimate and deform the signal to lessen the impact on the received signal. [56]

If we consider Rx diversity in which spatially separated antennas are deployed at the receiver end to get replicas of the signal from a transmitter, researchers have proposed various techniques to estimate the desired signal. [56] These techniques are referred to as selection and combining techniques at the receiver. E.g., MRC, EGC, and SC are the most used Rx diversity techniques. In these techniques, complex circuitry is involved at the receiver end, which is processed by complex algorithms to combine or select the independent spatial replicas of the signal. The Rx gain with these approaches is explained by the number of Rx antennas used to implement diversity scenarios. [52] The Rx diversity is considered as a traditional strategy initially. There are specific problems with this technique; due to the compact size of the user devices, it is challenging to enhance the circuitry by deploying a large number of antennas on a confined board.

Additionally, the processing of this circuitry includes powerful processing causing battery drainage, complex hardware designing, and increased hardware cost. Therefore, transmit diversity is more appealing as it involves adding more antennas at the transmitter side (BS). A BS typically has more resources and can manage multiple devices in the coverage range. Hence upgrading the BS is a more novel approach toward diversity as it offers cost reduction and efficient processing. [56] The Tx diversity technique uses a different approach to send statistically independent data streams. It employs distinct frequency and coding schemes. To generalize, the coding schemes refer to the complex channel matrices proposed by Alamouti to maximize gain in spatial diversity. [61] The key benefit of using Alamouti space-time codes is that it can reduce the receiver complexity by implementing decoding schemes using the same Rx selection & combining methods. [52] Depending on whether a transmitter has access to channel state information, it can be categorized into two modes, i.e., Closed-Loop Tx Diversity and Open-Loop Tx Diversity. The closed-loop method surpasses the open-loop diversity in terms of performance, even if the non-idealities in the channel state information are not considered. The common non-idealities involved are delayed feedback, approximation of channel, beam error estimation, etc. [62]

The difference between both open-loop and closed-loop is given below:

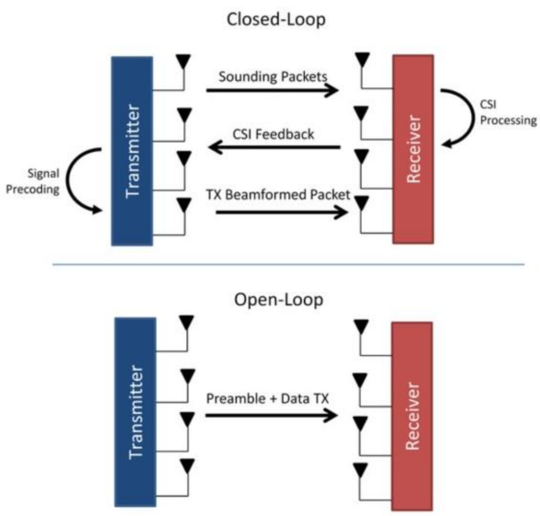


Figure 21. *Open & Closed-Loop Systems* [63]

Fig.21 defines the significant difference between the two approaches; a closed-loop system is feedback-dependent, and no pre-channel information is needed for an open-loop system. The channel state indicator is divided into CSIT and CSIR based on open-loop and closed-loop mechanisms. The closed loop mechanism manipulates the receiver's CSI feedback; the transmitter's precoder (implements complex space codes) provides uncorrelated paths for the users by achieving spatial orthogonal data streams with minimum ISI. The precoder considers the receiver's CSIT information to cancel the chances of interference between the data streams. [63]

On the other hand, the open-loop approach uses the CSIR method for data transmission. In this case, the transmitter is blind and does not have CSIT information. For channel estimation, a set of an encrypted pre-specified sequences is generated and transmitted over the channel with the data. The receiver will solve the preamble matrix given by the transmitter to analyze unfolded channel characteristics. The main advantage of using CSIR is the erasure of additional overhead for the feedback signal. i.e., no extra handshake for channel feedback. The disadvantage of this approach is that there is a possibility of ISI (inter stream interference) which the transmitted data streams can cause due to channel correlation. The transmitter, in this case, does not have any prior information about the channel to modify the data streams over the channel. [63]

Over time, various space coding techniques have evolved to effectively and efficiently utilize space-time coding to help analyze MIMO channels' capacity. Multi-antenna transmissions are made possible using STC coding. STC methodology is carried out at different time periods on several antennas in the temporal and spatial domain to establish a correlation between the signals transmitted. Tx diversity and energy gain can be achieved in spatially uncoded situations by using time and space coding to maintain the same amount of data transfer and avoid extra bandwidth resources. [64] Plenty of programming frameworks are suggested to implement STC; these all-coding matrices are based on Alamouti's space coding, i.e., STTC, STBC, DSTBC, QOSTBC, and LDC. [52]

3.4 MIMO Classification

The MIMO systems are continuously evolving to meet the developing demands for wireless technologies. Based on that, the MIMO systems are classified into three different categories, which are described below:

3.4.1 Point to Point MIMO

This system is considered the most straightforward approach to MIMO implementation. The transmitter (BS) station sends out a signal with a vector value, meaning that each component has a unique piece of data. The channel matrix is multiplied by this vector to generate the output. The output at the receiver vector matrix depends on the propagation channel, and the vector contains the transmitted symbols. The propagation channel impacts the receiver's estimation, and if the channel condition is vital, the receiver can easily estimate the transmitted symbols and separate them. [65] The detailed architecture followed in point-to-point MIMO communication is given below:

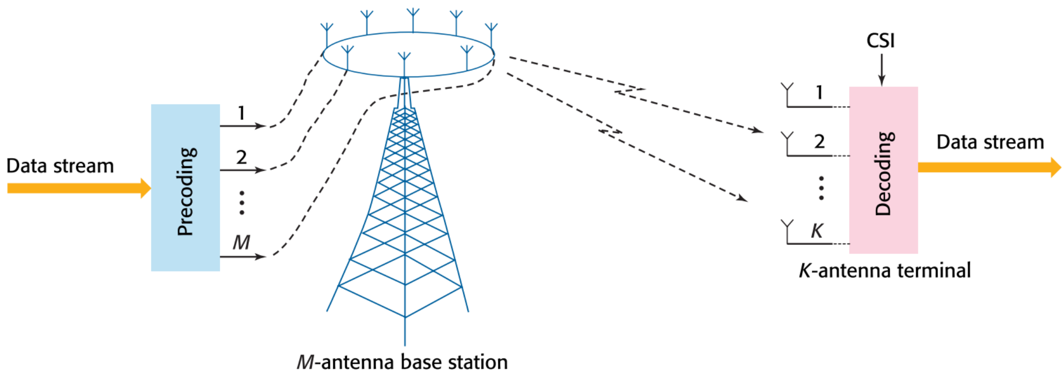


Figure 22. *Point to Point MIMO System* [65]

Fig.22 illustrates traditional point-to-point MIMO architecture; the BS consists of multiple arrays of antenna elements (M), transmitting the data over the air towards a receiver with multiple antenna (K) installed. In this process, the precoding of the signal is performed by the BS, whereas different combining and decoding techniques are used on the Rx side. In these techniques, different combinations of time and frequency multiplexing methods can be used to accommodate distinct users in each block. The wireless medium involves the transmission and reception of both Tx and Rx vector components. The propagation model between Tx and Rx decides the coefficients used to combine the received signal. The transmitted signal is estimated at the receiver end, considering it a linear combination. The spectral efficiency, in this case, determines by the SNR, i.e., higher the SNR greater the spectral efficiency. [65] As discussed in the previous section, the capacity of a wireless system depends upon Shannon's theorem; the channel capacity formulae for Point-to-Point MIMO are written below [65]:

$$C = log_2 . \det\left(I_k + \frac{\rho_d}{M} G_d^H G_d\right) \quad \text{(vii)}$$

The equation (vii) represents the capacity for a channel in the DL direction; for the UL channel same equation follows except for some replacements, i.e., $G_d = G_u$ and $\frac{\rho_d}{M} = \frac{\rho_u}{K}$. In the equation, the component I_k represents matrix with identity components, G_d gives the channel frequency response, and ρ provides the SNR with value in both UL and DL directions. [66]

3.4.2 Multi-User MIMO

The method in which a single BS can transmit multiple data streams to several spatially separated users is known as MU-MIMO. With this approach, we can attain improved efficiency and spectrum usage. Spectrum and energy efficiency are critical aspects in designing a wireless network; the capacity of a channel affects the spectrum efficiency with theoretical boundaries. These two features are highly dependable on SNR, the accuracy of channel estimations, and the correlation of propagation environment in space. [67] MU-MIMO is a successor of traditional MIMO systems in terms of maximum supported users for improved performance. It is possible with MU-MIMO to increase cell edge and spectral efficiency by sending separate spatial parallel data streams to multiple users without any degradation by boosting the spatial diversity of multiple users. [67] The detailed architecture for MU-MIMO is pasted below:

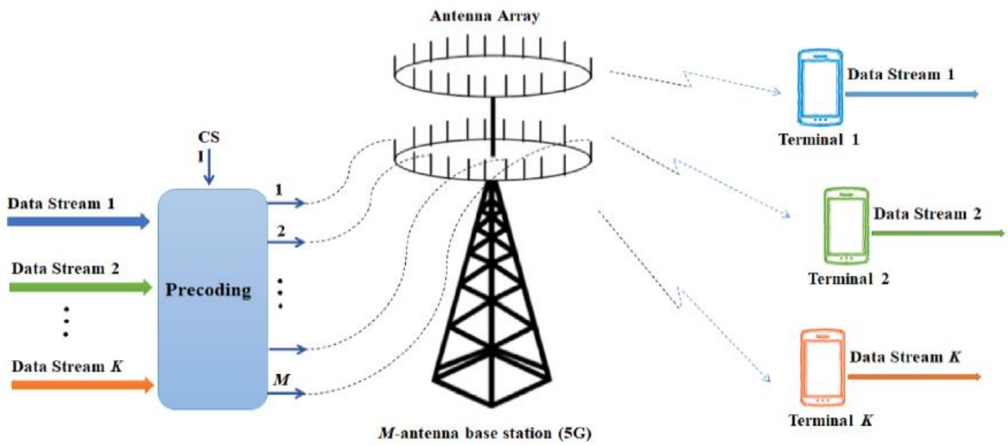


Figure 23. *Multi-User MIMO System* [68]

Fig.23 gives an overview of MU-MIMO implementation in a wireless network. The MU-MIMO can be derived from Point-to-Point MIMO systems by dividing the K-antenna module into various isolated terminal modules. In terms of complexity, the receiver terminals in MU-MIMO are simple in design containing a single antenna module as compared to Point-to-Point antenna terminals with multiple k antennae. The devices with a single antenna are separated from each other on large wavelengths, which results in coherence avoidance. With the described scenarios, MU-MIMO can improve multiplexing gains. [66] The channel capacity equation is the same for MU-MIMO and Point-To-Point MIMO systems in UL communication, whereas the equation for DL channel capacity is given below [65]:

$$C_{DL} = sup_a\{log_2\ det(I_m + \rho_d G_d D_a G_d^H)\}\ where\ a \geq 0\ \&\ 1^T a = 1 \quad \text{(viii)}$$

Here in equation (viii), $D_a \in MX1$ representing diagonal matrix elements, a &1 define the vectors with value 1. It is essential that both Tx and Rx must be aware of the downlink channels to achieve this capability. Each user connected with a transmitter must need to know about their DL channels, whereas the transmitter must know all DL channels as well as UL channel state information. The scalability in MU-MIMO is because of the additional channel state information feature. The channel state is fed to the transmitter before communication starts; the Tx plays the main role of precoding in these scenarios. The precoding part plays an important role in improving the channel performance, e.g., complex algorithms like Dirty paper help to achieve the desired performance. Still, it requires high-profile processing modules and the power to code and decode the logic. Also, it takes close estimations of the channel to perform accurate measures. The BS can get the CSI information in UL by using pilot signals, whereas, in the case of TDD implementation due to reciprocity, CSI for DL can also be attained by using UL pilot signals. [65,66]

Comparing the two technologies, MU-MIMO offers two main benefits over PTP MIMO. 1) It is slightly susceptible to the channel propagation conditions; it outperforms in LOS situations which are introduced due to the separation between users and BS array resolution based on angular dimensions. 2) Only single transceiving modules are needed. [65]

3.4.3 Massive MIMO

Massive MIMO is the upgraded version of MIMO technologies. Massive MIMO systems use antenna arrays, including hundreds of antennas serving tens of thousands of user devices simultaneously. The primary goal of mMIMO technology is to reap the same benefits as MIMO but on a much greater scale. There are many advantages to massive MIMO in terms of energy efficiency, robustness, security, and spectrum efficiency. [21] mMIMO uses the core concept of spatial multiplexing, which relies on feeding CSI to BS in both UL & DL directions. As in the previous section, the pilot signals are sent to estimate the channel condition suitable in UL communication but challenging in DL direction. The same mechanism is followed in the traditional MIMO system to check channel responsiveness. For specific reasons, it does not seem to continue in mMIMO communication; the first reason is that as the BS transmits the pilots, they essentially follow the orthogonality amidst the transmitting antenna. Hence as mMIMO involves hundreds of antennas in hardware, it automatically requires more frequency and time slots for sending DL pilot signals. The second reason is that due to increased BS antennas, the modules need to feed large number of channel condition responses requiring more UL slots to send the feedback. [21]

The architecture for mMIMO is illustrated below:

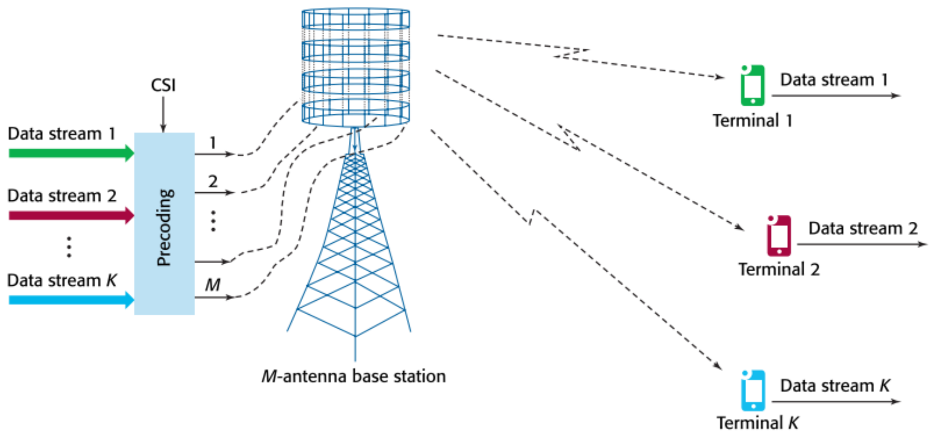


Figure 24. *Massive MIMO System* [65]

Fig.24 gives a representation of the mMIMO technique; the BS is equipped with hundreds of antennas, making it possible to connect an enormous number of users simultaneously. This technology's primary goal is to ensure that each terminal receives its individual data streams without interfering with others. This can be achieved by utilizing multiplexing approaches in which each user gets a separate path to transmit and receive information. The BS controls the information before transmission by performing complex algorithms at the precoding step; these devices take CSI as an input because the channel's frequency response should be known before transmission. After precoding, the information is then carried to each antenna element; using a large number of antennas makes the systems more flexible in terms of more directive beams and user detection. [65] mMIMO technology is here to address the fundamental drawbacks in the legacy MU-

MIMO systems through continuous improvement and development. There are three main differences between these technologies: 1) The BS is the only entity that can estimate and react to the channel response thus making users modules much cheaper than MU-MIMO. 2) As M is often substantially larger, varying in size compared to K, multiple users can be served by optimizing the power radiation at each antenna element. 3) The straightforward digital processing (Linear) close to ideal can be utilized equally in UL & DL directions. [66]

3.5 MIMO Precoding

Precoding is one of the core ideas behind MIMO communications. It involves intelligently complex algorithms to optimize network scalability. In a MIMO communication system, one of the main challenges is to make the receiver device as simple as possible because of its low processing and power consumption. For this purpose, precoding techniques are proposed, including the powerful processing at the BS to avoid complexity on the receiver end. [69] Precoding is a method that uses transmission diversity by appropriately balancing the data being sent. With this method, the communication channel's corruptive consequences will be mitigated. With different MIMO approaches, many precoding algorithms have been proposed. Precoding types, including linear and non-linear, are equally applicable for MU-MIMO and mMIMO communication. Precoding is similar to equalization in its function; however, it occurs before transmission rather than at the receiver. The standard goal of precoding methods in MU-MIMO/mMIMO is to improve SINR. [66] The types of linear and Non-Linear precoding techniques are given below:

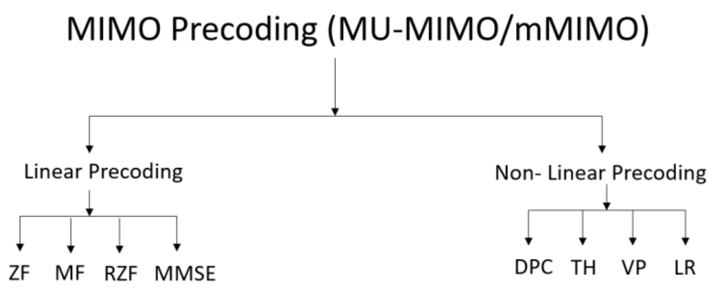


Figure 25. *MIMO Precoding Types* [66,69]

Fig.25 gives a generalized view of different precoding approaches that can be implemented in MIMO communication. Although channel state information (CSI) is a crucial element in strengthening the transmission in real-time communication, precoding is a viable option for handling CSI. Many studies have revealed that mMIMO precoders play a crucial part in handling the degraded performance by pointing the beams towards the intended locations of the receiving devices. By employing precoding algorithms in mMIMO advises the capacity and performance irrespective of infinite antenna elements and canceling the impact of fading and interference on a wireless channel. [69]

To increase the data rates at the receiver end, precoding algorithms involve sending multiple streams of data with diverse antenna elements, each of which is weighted independently and appropriately. [70] The linear precoders are developed to send information in a linear fashion. This technique is more useful when the number of antenna elements is large (mMIMO), and it includes reduced complexity and improved performance compared to other techniques. It involves computation based on CSI. Non-Linear precoding focuses more on enhanced capacity; this technique involves complex algorithms than linear precoders. It includes an algorithm that estimates the channel condition aside from CSI participation with the Rx. It gives better performance and capacity conditionally if the number of antennas at Tx is relatively small compared to the Rx antennas. This type is configuration is not applicable in mMIMO.[66,69,70]

4. ANTENNA BEAMFORMING

Beamforming is now an essential part of wireless communication systems. The ability of antennas to successfully minimize channel interference, improve SINR, and have high bit rates by boosting the antenna gains is considered antenna beamforming. [71] The antenna beamforming uses the concept of using a distinct scaling factor for each antenna to broadcast the same symbol; the receiving signal is combined coherently using separate scaling factors. It boosts the Tx/Rx diversity of a system whose SNR can be maximized by optimization of these scaling factors. [72] With the use of Massive MIMO, Beamforming is able to increase network capacity and performance significantly. As opposed to a wide area, beamforming utilizes advanced antenna technology to focus a wireless signal in a specific direction. This technique reduces cross-beam interference, enabling the deployment of larger antenna arrays. [19] The below figure illustrates the beamforming concept:

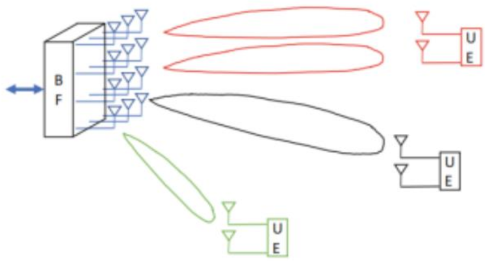


Figure 26. *Basic diagram of Antenna Beamforming* [19]

A wireless signal represents electromagnetic signals propagating with electric and magnetic components. The antenna elements which are responsible for transmitting these electromagnetic waves are sensitive to a single polarization. That is why it can be seen that different polarization techniques are being followed in antenna design. Cross-polarized antennas are commonly used as both electromagnetic components which are 90 degrees separated. In beamforming, the challenge is to make these electromagnetic waves more directive in the point of interest. These electromagnetic signals either add up or cancel out the effect with each other. More antenna elements are added to the antenna panel to achieve maximum power in a particular direction, ensuring that the signals are added constructively, boosting the gain in the desired location. [73,74]

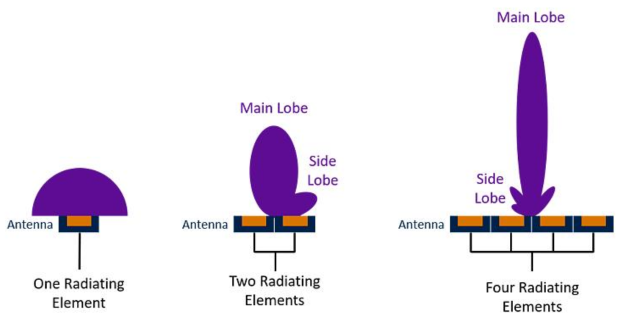


Figure 27. *Beamforming using multiple radiating antenna elements* [74]

Fig.27 explains the concept of getting more directed means by adding antenna elements and feeding them with the same signal. There is a point when a signal is propagating in the air; it has chances to add up purely or cancel out each other entirely. In between partial constructive and destructive interference also happens, generating high grating lobes or side lobes. The side lobes of a beam-formed signal might produce too much interference if antenna arrays were not correctly built. Antennas with more radiating elements tend to have a more focused main beam and weaker side lobes. Minimizing the side lobes is a challenge in wireless communication these days, as it reduces the gain of other main lobes in the same direction.

4.1 Beam Switching & Steering

Switching and steering of a beam are considered as a beam management procedure which includes intelligent handling of the beams for expected outcomes. Most of the beam-related procedures are proposed under 3GPP TR 38.802. The beam switching involves the mobility of the beam within a cell. The algorithm for beam mobility defines a threshold for beam switching. Beam switching can be achieved by L1 and L2 procedures when a user is attached to the network. [75] Beam sweeping/steering, on the other hand, can be implemented by 3GPP-defined procedures, including SSB-based Sweeping, CSI-RS-based Tx Sweeping (Refinement), and CSI-RS-based Rx Sweeping (Refinement). [75] Basic terminology in steering and switching involves the variation of phase and amplitude at the radiating elements. By adjusting these components, we can get a more directed beam for a user. An antenna's radiating elements can be used to direct a single beam in a certain direction by using the same frequency. To accommodate a variety of users, distinct frequency beams can be guided in different directions. The beam direction is estimated by above-mentioned techniques at the transmitter side. If a user is in a moving state, the best possible beam is allocated over the time the user is moving. Or the beams are switched during the user's mobility by the switching algorithms deployed. To provide the tracking granularity, the 5G BS is supposed to be substantially closer to the user. [74] A fundamental difference between beam switching and steering is given below:

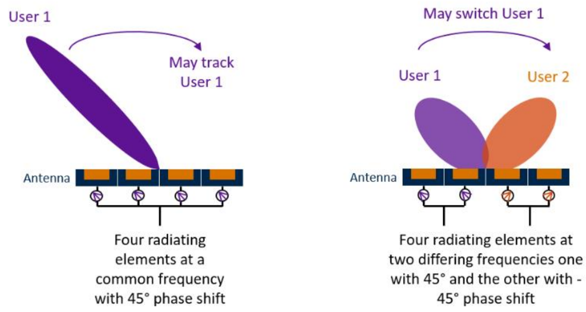


Figure 28. *Beam switching and steering* [74]

Fig.28 explains the difference between beam management; in beam steering, the same input signal is fed to each radiating element. A complex circuitry is involved before radiating elements that are responsible for changing the amplitude and phase of the signal to steer the beam in the desired location. On the other hand, a single beam can also be split into two beams accommodating parallel users in the cell range. In this process, the signals are split and fed to different antenna elements by changing the phase and magnitude of the signals separately. This approach results in the division of one powerful beam into two weaker beams.

4.2 Antenna Array

4.2.1 Antenna Element Spacing

In MIMO and 5G technology, antenna array plays a vital role in multipath scenarios. Antenna array features and design are critical to the success of mMIMO technology. Antenna performance characteristics, including radiation pattern, efficiency, and mutual coupling, must not be overlooked while designing compact array designs that provide high gains and performance. [76] The antenna array design is primarily concerned with the preference of an antenna element following the array's geometrical dimensions. To achieve specific performance indicators, the element excitation is determined. To calculate the overall array field, we multiply the field of a single element at a given reference point by an array factor (AF). [76] The concept of AF is used to figure out the array pattern by taking in the mentioned dimensions. The array factor depends on how the antenna elements are arranged, the spacing distance between them, phase and magnitude of the incoming signal used at each antenna element. [76] In both vertical and horizontal (elevation and azimuth) beam directions, the performance of beam patterns depends on the element spacing. When it comes to the horizontal beams, each column represents an element. In vertical beamforming, the vertically separated subarrays are considered an element. [77]

As discussed in the previous section, the number and spacing determine the antenna characteristics and performance. These two variables are the most important aspects in determining the gain and HPBW of an antenna. The spacing is considered in terms of Lambda (wavelength). [78] If we increase the element spacing, it degrades the V-HPBW by increasing the antenna gain. On the other hand, with the increased spacing, many unwanted grating lobes also tend to appear with high radiating power, which will cause the scattering of power radiated from the main lobe. [71] The most suitable antenna spacing is half of the wavelength means 0.5 Lambda, as it provides the best directivity and reduced side lobes by avoiding coherence between the beams. The minimum range for antenna spacing is defined below 0.5 lambdas. Some good performance can be expected with increased spacing, i.e., narrow and directive beams at the cost of narrow HPBW, which can cause severe degradation to these beams and overall performance. [79] Hence it demonstrates that there is a trade-off between HPBW, directivity, and grating lobes if we increase the spacing above 0.5 lambdas. [76]

4.3 Beamforming Approaches

When it comes to the above 6 GHz band, in massive MIMO communication, beamforming is becoming a need because of the varied propagation characteristics, such as a greater distance between antennas, reduced throughput due to ambient gas absorption and excessive free space path losses, the possibility of rainfall as well as nonlinear propagation. [80] Hence the beamforming can be implemented by using the below techniques.

4.3.1 Analog Beamforming

Analog beamforming was firstly introduced in practical applications in 1961 [81]. A critically handled RF switch box and various phase shifting elements were used to steer a beam. The concept of this technology is still used in various wireless systems by using more complex hardware and algorithms. The improvement in today’s circuitry enables each element's phase to be handled independently compared to the old technology. [81] The analog beamforming consists of N-transmitting antenna elements, where each element is fed with independent phase shifters and programmable attenuating modules which are responsible for processing and controlling of phase and magnitude of the signal. The transmitting antenna device can also include a power amplifier in active beamforming in contrast to a single amplifier with high power on the RF chain in passive beamforming. [80] Due to the simple design of analog beamforming, it is ineffective as compared to the other techniques. It mainly consists of low-cost phase and amplifier modules, which can process a single RF chain forming a single beam at a time. [80,82]

The architecture followed in analog beamforming is given below:

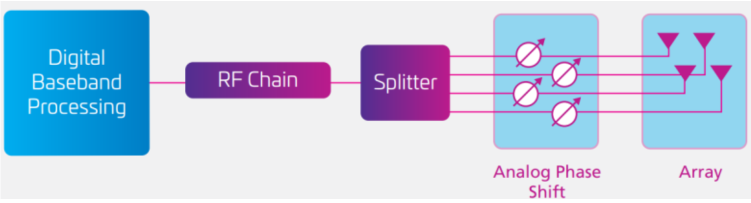


Figure 29. *Analog beamforming* [71]

Fig.29 represents the processing diagram of analog beamforming; this type of beamforming is more suitable in mmW communication in which beam directivity to a user is more important. Also, due to the dense network in mmW, fewer multipath errors are involved, making this technique more efficient. Implementing multiple data streams is a challenging task in analog beamforming. [81] The above diagram shows a single RF chain splitting before antenna elements before that phase shifters are deployed to implement phase variations in the signal. The process of amplification is also done before signal broadcasting. [4]

4.3.2 Digital Beamforming

As compared to analog beamforming, digital beamforming can theoretically support an infinite number of RF chains as long as the antenna elements are large enough. The analog beamforming is confined to a single beam irrespective of increasing antenna elements. During the digital baseband processing, if appropriate precoding is defined, it can increase the transmitting and receiving information flexibility. Since this technology can create a large number of beams with separate antenna processing, advanced multi-user MIMO approaches can take advantage of extra privileges. Maximum theoretical antenna performance can be achieved by digital beamforming compared to alternative beamforming approaches. [81] This is the underlying principle of digital beamforming, in which binary streams of digital signals are transformed into RF signals. Each array element receives a digital baseband signal that represents the transmitted signal's phase and magnitude. It is necessary to weigh these digital signals so that they combine to generate the intended beam during the beamforming process. Different algorithms are defined for this purpose to form various types of beams, i.e., multiple beams with different shapes or beams with guided nulls, etc. The enormous number of RF chains required to achieve this level of adaptability often requires high processing powers. [80]

Comparatively, the digital beamforming approach may result in higher gains and improved SINR. It can also replace the complexity of beamforming in terms of hardware and design by implementing software base intelligent algorithms in digital signal processing units. Different approaches to digital beamforming are suggested; they fall into two categories: fixed and adaptive digital beamforming. In fixed digital beamforming, the weights used at antenna arrays are predetermined and remain constant throughout the beamforming process. On the other hand, according to operational scenarios, the beam weights are dynamically modified according to the requirement in adaptive digital beamforming. Due to the adaptive and flexible selection of the beams in the algorithm, adaptive beamforming is considered to predict the performance and capacity enhancement of the system by modifying the interference null due to canceling effect. [83]

The digital beamforming follows below procedures in its architecture:

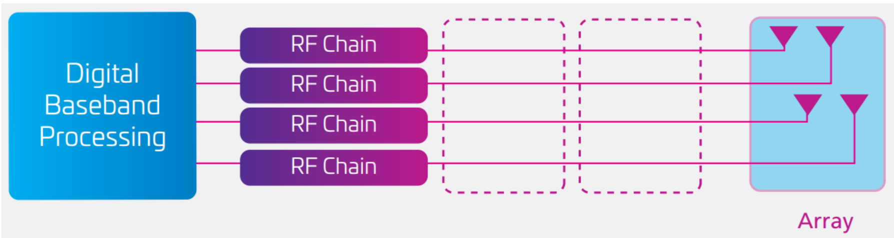


Figure 30. *Digital beamforming* [71]

Fig.30 explains the basic circuitry followed in digital beamforming; the pre-coding part is done in the baseband units. More than one RF chain with separate processing blocks is used for each antenna element. For accommodating multiple RF chains, digital beamforming involves complex processing and high-energy consumption, making it challenging for hardware and complex processing of the modules. The benefit of digital beamforming is that several antenna elements take part to form multiple beams, which are than dedicated to parallel users at the same time. This technique is more suitable in mmW communication and MU-MIMO implementation. [4] [71][73]

4.3.3 Hybrid Beamforming

In an effort to increase the performance of analog beamforming and reduce the complexity of digital beamforming, hybrid beamforming comes with combining both techniques. [80] Decreasing the amount of RF chains results in considerable decrement in the overall cost of the circuitry. The digital signal processing modules have limited options for converters, as they are less in number than the antenna elements. With fullfledged digital beamforming, fewer data streams can be maintained at a particular time. It will result in low performance and capacity gaps due to certain channel attributes. [81] Hybrid beamforming is superior in terms of reliability and efficiency as compared to previous techniques. It divides the tasks between analog and digital schemes to provide flexibility, reduced cost, extremely low block error rate, and improved performance. Hybrid beamforming includes fixed analog beamforming, pre-coded code books, preceding matrix, and analog beam weights that work closely to enhance performance at a minimal cost. Another difference with adaptive digital beamforming is that CSI is considered part of hybrid beamforming, making it a preferred technique for getting extreme data rates with several streams [83] Various optimized algorithms for hybrid beamforming have been suggested to take full advantage of analog and digital beamforming, which are categorized into two groups: Adaptive Blind and Adaptive Non-Blind. The main difference between these algorithms is that the Blind algorithm does not require any pre-statistical information for user detection. Whereas in Non-Blind algorithm requires the characteristics of a transmission channel by sending reference signals to estimate the interested user. [82]

The detailed architecture of hybrid beamforming is given below:

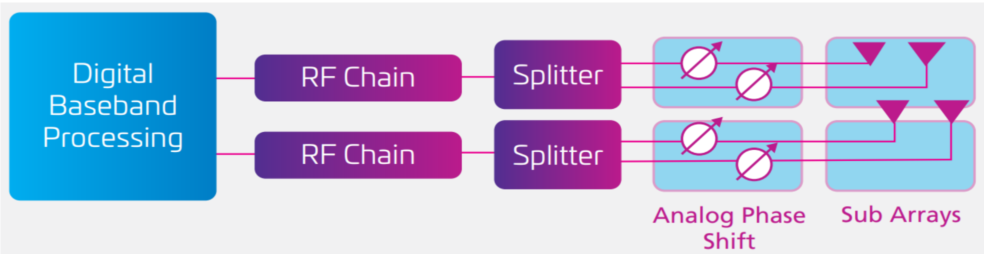


Figure 31. *Hybrid beamforming* [71]

The above figure explains the idea of hybrid beamforming, in which digital beamforming is placed at the baseband end, and analog beamforming continues in the RF modules, followed by phase shifters before sending the signal to the radiating elements. Thus, it can offer high flexibility between analog and digital BF by providing low cost and power circuitry. [4]

4.4 SRS Based Beamforming

Not long-ago extensive research and prototype development has focused on Massive MIMO as a potentially game-changing option for 5G. Compared to FDD MIMO communication, TDD-based MIMO communication offer significantly lower overhead in pilot signaling, taking advantage of channel reciprocity. Furthermore, BS handles the intensive calculations involved in channel assessment without requiring users to provide feedback on the condition of the channel. [84] In today's 5G cm-wave (Sub-6Ghz), digital beamforming is mostly used as each RF chain is processed by separate Trx units, as described in the previous section. [85] The 3GPP standardized body proposed reference signal anomaly in both UL and DL channel estimation, i.e., (SRS and CSI_RS/SSB) for managing beamforming-related tasks. The practical beamforming implementation depends on SRS-based channel assessment. This method includes the regulation of the best vectors used for pointing beams toward users. [86] The UL channel information processing is the most crucial task involved in MIMO communication; the processing requires multi-user detection and is concerned with the computation of the best precoding weights for beamforming. As discussed earlier, by exploiting the channel reciprocity in TDD, the DL channel information can be obtained from the UL channel as they both use the same frequency in this configuration. This DL information is utilized to perform critical precoding from a codebook at the BS by operating GoB to form PMI-based beams. These PMI beams are generated from a massive grid and cover an approximate user location based on the channel information. Hence the exact location detection of a UE is always challenging. SRS-based beamforming in TDD can be used in both directions using reciprocity. In the case of UL transmission, the transmission can be carried out either by a codebook-based mechanism or by a non-code book method. In a codebook mechanism, the matrix for precoding is taken from the available code book; in contrast, the UE suggests the precoding matrix based on CSI_RS in the case of a non-code book where the required matrix is not available at the BS end. In the code book method, different SRS-based signals are generated from different antenna ports of UE's; the BS calculates the channel conditions based on SRS and allocates the resources in the direction of interest. In the non-code book technique, the UE first calculates the DL_CSI_RS from the BS and transmits the SRS signals based on that by suggesting the suitable precoding matrix. The BS estimates the SRS information and assigns approximate resources to the UE. [84–87]

The difference between both methods is illustrated below:

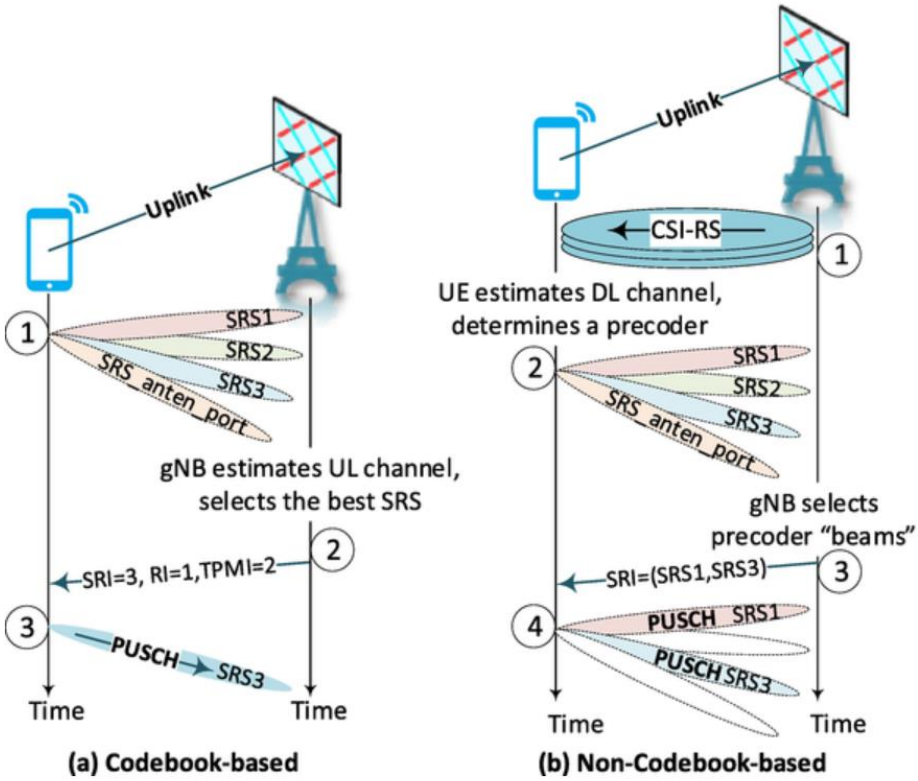


Figure 32. *Codebook and Non-Codebook based UL SRS* [87]

Fig.32 depicts the basic implementation of SRS-based beamforming in the UL direction. The main difference between both approaches is related to the precoding matrix selection. In a) a dedicated beam is allocated to the UE, whereas in b) based on approximate UE location, a set of beams are allocated. The DL-based communication is described in the previous chapter; in the case of SU-MIMO, SRS and CSI_RS based modes can be used, whereas in MU-MIMO CSI_RS based is most commonly used with or without beamforming enabled. The other way to estimate the best DL beams for multiple users is by exploiting SRS_UL reference signals and using the principle of reciprocity in the TDD domain to achieve directive beams for each user. [87]

5. METHODOLOGY

This chapter will contain the approaches for implementing the designed MU-MIMO scenarios in the RF OTA chamber. For this purpose, the process goes through different phases. To start with, the study plan thoroughly includes the initial chamber investigation and feasibility. Following that, in the learning phase, the complete design has been examined with the required changes and requirements. The relative topics and in-depth study of the literature have been written in chapters 2,3, and 4. After studying and analyzing the chamber, the required changes involve the calculations for other UE separation, distance, and angular differences. Later, the calculations imply the implementation of the solution to perform real-time testing. In the end, the analysis procedure and suggested approaches have been discussed. The flow chart for the attempted methodology is given below:

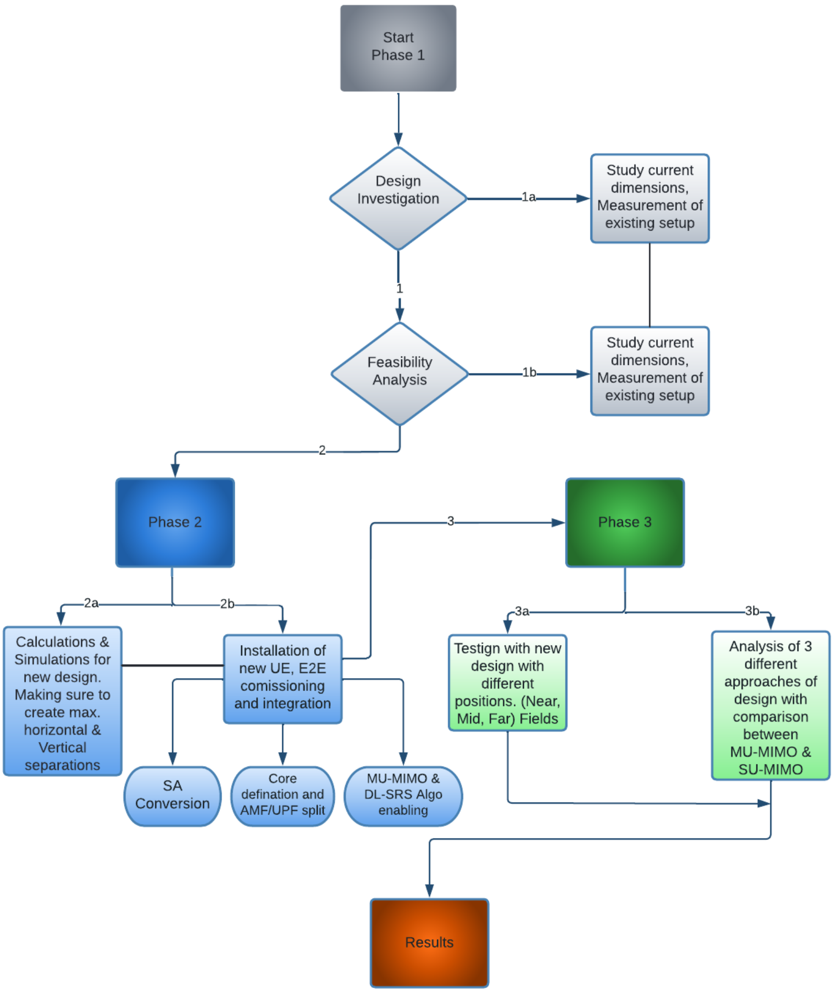


Figure 33. *Methodology*

The overall methodology has been divided into three phases to implement this solution. A comprehensive literature review has been conducted in previous chapters to deeply understand the theoretical backgrounds of the techniques used in this work. The phases of conducted methodology have been explained in detail below:

5.1 Methodology Phase 1

Before starting the actual work, the idea is to study the limitations of the existing scenarios. The study includes a detailed analysis of the designing part and possibly adjusting more UE's. In the design investigations, the current dimensions of the OTA-Sea container (Sub 6 GHz) have been explored concerning the distance between the measuring devices and the angular separation between the Vivaldi antennas. The findings from this study contains:

- the measuring distance between the radio and the UE antennas
- the separation angle between the far and mid antennas to avoid any interference
- the distance between the co-existing Vivaldi antennas
- radio positioning and rotating mechanism
- the system for vertical and horizontal movement of the Vivaldi antennas
- the UE (Port) connectivity for +/- polarities
- the system to measure and analyze the signal spectrum.

Following our objective, a scheme has been proposed which contains the Vivaldi antenna location for the second UE. It is carried out by simulating the best positions from Wall testing scenarios. The existing dimensions of the chamber are pasted below:

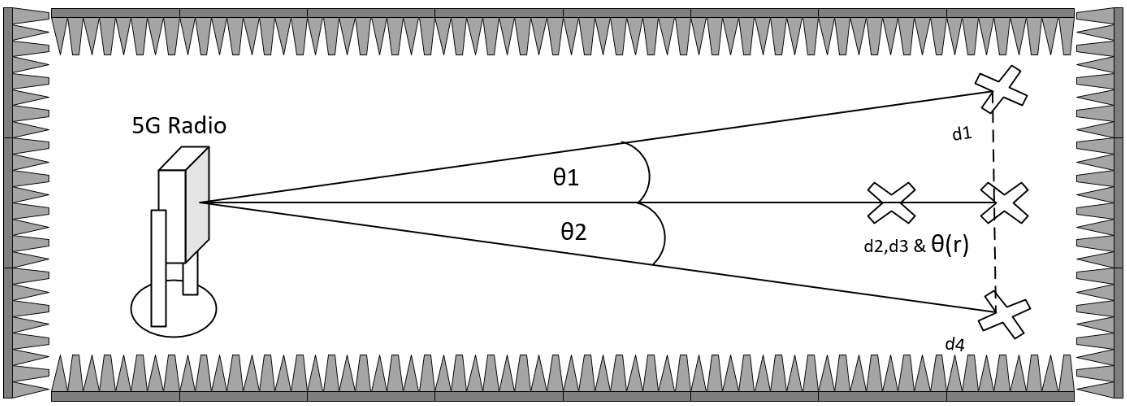


Figure 34. *OTA-Sea Container Existing Environment*

Fig.34 explains the existing testing scenario in OTA-Sea container with a single UE. The left side of figure contains the radio and Vivaldi antennas in opposite direction. The different combinations of these antennas are used to perform SU-MIMO testing.

5.2 Methodology Phase 2

In this phase, the simulated results are considered for the new calculations. In the existing scenario, the antennas are located at a distance d and angle θ from the radio midpoint point. The possibility of creating maximum horizontal and vertical separation to avoid beam interference below diagram illustrates the proposed positions of the UEs. The distance calculations are made by taking a reference point at 90 degrees in the boresight of the radio using the Pythagorean theorem. The horizontal and vertical distance from the reference point is equal between both UEs. The distance between the co-existing antennas is also calculated based on the minimum separation to un-correlate the polarities for the UE. The calculations are made by considering all spatial planes i.e., (X-plane, Y-plane, Z-plane) to get the required coordinate sets to install and perform testing to measure and analyze the performance of the system. In the next part, the new UE is installed as per calculated distance and angle and cabled with the ports. After installation, integration and commissioning part is covered in this phase; initially, the test line is converted into SA mode by configuring the access and core part. With the existing setup, a UE is assigned with a single Ip address; by adding a new UE (different subnet), the AMF/UPF split is configured to avoid any resource allocation delay. The MU-MIMO algorithm with the combination of DL-SRS based beamforming is configured to check the proposed solution performance. Phase 2 of the chamber design is depicted below, having the new location for the existing and second UE.

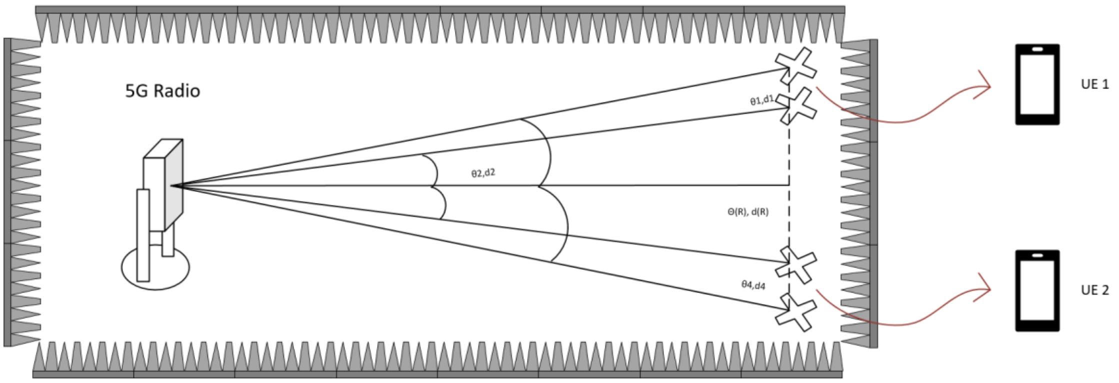


Figure 35. *Proposed UE positions for implementing MU-MIMO*

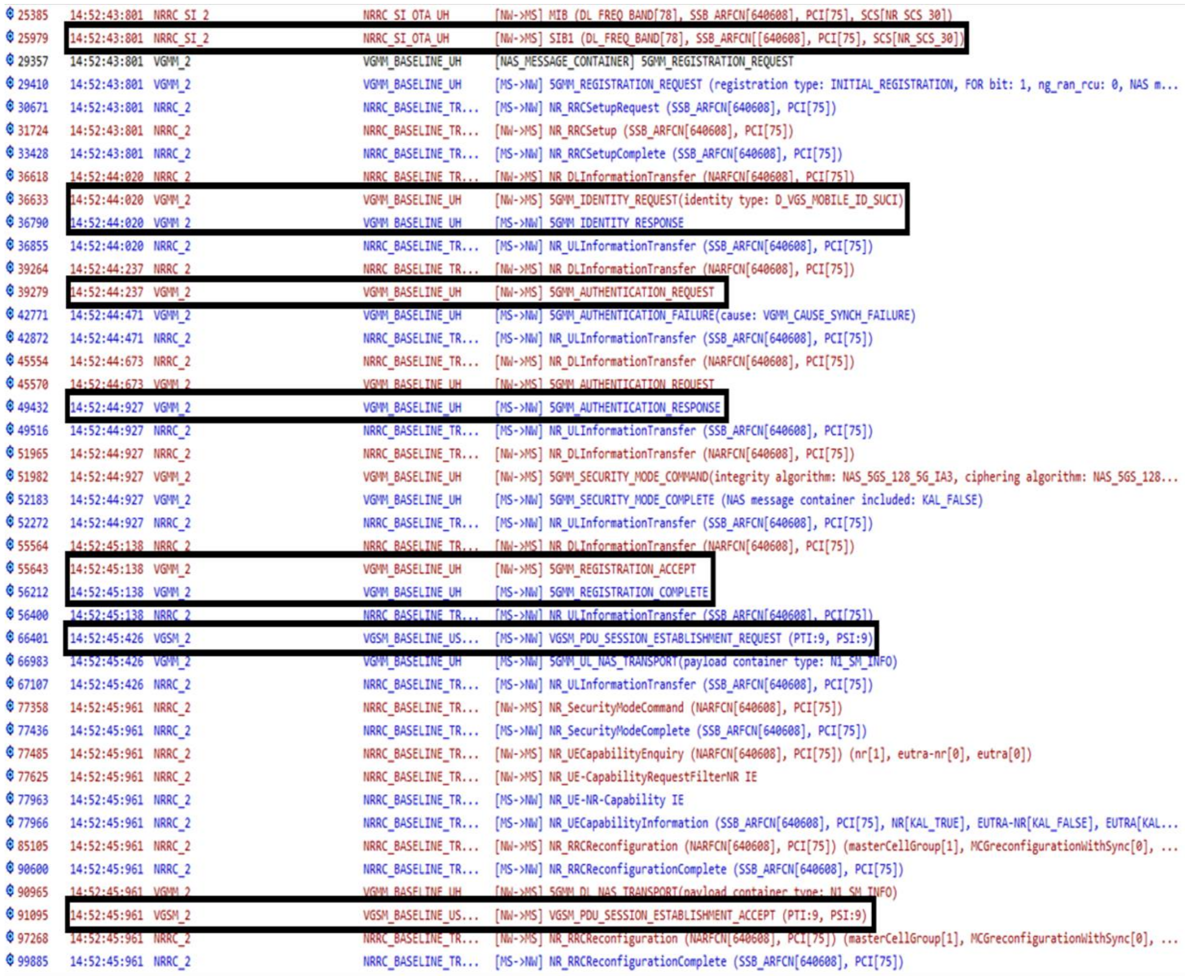
The above figure illustrates the new proposed setup for testing multi-users in the existing resources by overcoming the limitations. The major thing involved here is the coordinate calculations based on different factors. The combination of Vivaldi antennas is also modified to create spatial separation between both UEs to avoid interference.

5.3 Methodology Phase 3

Having installed new UEs with the positions mentioned earlier, the actual part of testing is covered in phase 3. Before testing, several steps are performed to verify that the implemented configuration is working. The steps include:

- checking radio software
- calibrating antenna elements
- ngap-c link setup
- L3 call establishment
- ngap-u and pdu establishment

The detailed RRC and NAS layer over the air signalling followed in 5G SA mode is illustrated below while verifying the L3 call establishment:



25385	14:52:43:801	NRRC_SI_2	NRRC_SI_OTA_UH	[NW->MS] MIB (DL_FREQ_BAND[78], SSB_ARFCN[640608], PCI[75], SCS[NR_SCS_30])
25979	14:52:43:801	NRRC_SI_2	NRRC_SI_OTA_UH	[NW->MS] SIB1 (DL_FREQ_BAND[78], SSB_ARFCN[[640608], PCI[75], SCS[NR_SCS_30])
29357	14:52:43:801	VGMM_2	VGMM_BASELINE_UH	[NAS_MESSAGE_CONTAINER] 5GMM_REGISTRATION_REQUEST
29410	14:52:43:801	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_REGISTRATION_REQUEST (registration type: INITIAL_REGISTRATION, FOR bit: 1, ng_ran_rcu: 0, NAS m...
30671	14:52:43:801	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_RRCSetupRequest (SSB_ARFCN[640608], PCI[75])
31724	14:52:43:801	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_RRCSetup (SSB_ARFCN[640608], PCI[75])
33428	14:52:43:801	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_RRCSetupComplete (SSB_ARFCN[640608], PCI[75])
36618	14:52:44:020	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_DLInformationTransfer (NARFCN[640608], PCI[75])
36633	14:52:44:020	VGMM_2	VGMM_BASELINE_UH	[NW->MS] 5GMM_IDENTITY_REQUEST(identity type: D_VGS_MOBILE_ID_SUCI)
36790	14:52:44:020	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_IDENTITY_RESPONSE
36855	14:52:44:020	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_ULInformationTransfer (SSB_ARFCN[640608], PCI[75])
39264	14:52:44:237	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_DLInformationTransfer (NARFCN[640608], PCI[75])
39279	14:52:44:237	VGMM_2	VGMM_BASELINE_UH	[NW->MS] 5GMM_AUTHENTICATION_REQUEST
42771	14:52:44:471	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_AUTHENTICATION_FAILURE(cause: VGMM_CAUSE_SYNCH_FAILURE)
42872	14:52:44:471	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_ULInformationTransfer (SSB_ARFCN[640608], PCI[75])
45554	14:52:44:673	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_DLInformationTransfer (NARFCN[640608], PCI[75])
45570	14:52:44:673	VGMM_2	VGMM_BASELINE_UH	[NW->MS] 5GMM_AUTHENTICATION_REQUEST
49432	14:52:44:927	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_AUTHENTICATION_RESPONSE
49516	14:52:44:927	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_ULInformationTransfer (SSB_ARFCN[640608], PCI[75])
51965	14:52:44:927	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_DLInformationTransfer (NARFCN[640608], PCI[75])
51982	14:52:44:927	VGMM_2	VGMM_BASELINE_UH	[NW->MS] 5GMM_SECURITY_MODE_COMMAND(integrity algorithm: NAS_5GS_128_5G_IA3, ciphering algorithm: NAS_5GS_128...
52183	14:52:44:927	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_SECURITY_MODE_COMPLETE (NAS message container included: KAL_FALSE)
52272	14:52:44:927	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_ULInformationTransfer (SSB_ARFCN[640608], PCI[75])
55564	14:52:45:138	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_DLInformationTransfer (NARFCN[640608], PCI[75])
55643	14:52:45:138	VGMM_2	VGMM_BASELINE_UH	[NW->MS] 5GMM_REGISTRATION_ACCEPT
56212	14:52:45:138	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_REGISTRATION_COMPLETE
56400	14:52:45:138	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_ULInformationTransfer (SSB_ARFCN[640608], PCI[75])
66401	14:52:45:426	VGSM_2	VGSM_BASELINE_US...	[MS->NW] VGSM_PDU_SESSION_ESTABLISHMENT_REQUEST (PTI:9, PSI:9)
66983	14:52:45:426	VGMM_2	VGMM_BASELINE_UH	[MS->NW] 5GMM_UL_NAS_TRANSPORT(payload container type: N1_SM_INFO)
67107	14:52:45:426	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_ULInformationTransfer (SSB_ARFCN[640608], PCI[75])
77358	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_SecurityModeCommand (NARFCN[640608], PCI[75])
77436	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_SecurityModeComplete (SSB_ARFCN[640608], PCI[75])
77485	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_UECapabilityEnquiry (NARFCN[640608], PCI[75]) (nr[1], eutra-nr[0], eutra[0])
77625	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_UE-CapabilityRequestFilterNR IE
77963	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_UE-NR-Capability IE
77966	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_UECapabilityInformation (SSB_ARFCN[640608], PCI[75], NR[KAL_TRUE], EUTRA-NR[KAL_FALSE], EUTRA[KAL...
85105	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_RRCReconfiguration (NARFCN[640608], PCI[75]) (masterCellGroup[1], MCGreconfigurationWithSync[0], ...
90600	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_RRCReconfigurationComplete (SSB_ARFCN[640608], PCI[75])
90965	14:52:45:961	VGMM_2	VGMM_BASELINE_UH	[NW->MS] 5GMM_DL_NAS_TRANSPORT(payload container type: N1_SM_INFO)
91095	14:52:45:961	VGSM_2	VGSM_BASELINE_US...	[NW->MS] VGSM_PDU_SESSION_ESTABLISHMENT_ACCEPT (PTI:9, PSI:9)
97268	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[NW->MS] NR_RRCReconfiguration (NARFCN[640608], PCI[75]) (masterCellGroup[1], MCGreconfigurationWithSync[0], ...
99885	14:52:45:961	NRRC_2	NRRC_BASELINE_TR...	[MS->NW] NR_RRCReconfigurationComplete (SSB_ARFCN[640608], PCI[75])

Figure 36. *Over-the-air 5G L3-Signalling*

**The above depicted signalling-chart with same scenario is followed for both RNTI's separately.*

The detailed real-time signalling is presented by Fig.36. After the system information block is scheduled and UE decodes it, the network requests for the UE identity based on the configured SUCI code in the 5GCN. Before doing the testing, separate SUCI codes for both UEs are written in the 5G core. After the UE responds to the identity request to the network, the network requests for the authentication key from the user. The UE delivers the encrypted key to the network, the network matches the given key with the stored database in the authentication register (AUSF). The UE then requests for the PDU session establishment after the authentication is accepted by the network. The network than manages the resources to allocate separate PDU bearer for data transmission. In this research work, as explained in methodology phase 2, the GW tunnel is split for both UEs to avoid any mismatch.

The testing strategy is designed so that each user is spatially separated enough (as per Phase 2 calculations) so that individual beams can be allocated to them. Each UE should get two separate beams (1 per Vivaldi) without interfering with co-existing and far-end antennas. At first, both UEs are tested separately to get SU-MIMO theoretical maximum. After single-user testing and meeting the initial criteria, MU-MIMO testing is started. Initially, it was carried out by placing the users at the far end. To check other spots and levels, the system model is designed in a way that the testing can be done at different levels, i.e., far-field, mid-field, and near-field. All the fields are considered as a separate coordinate set which contains the geometrical calculations including (Distance, Angle, Azimuth and Elevation) for testing each coordinate set separately. Based on this system model, the analysis is carried out by testing SU & MU at three fields separately and comparing the KPIs with each other based on these locations. The analysis is filtered depending on 5G major KPIs for multi-user MIMO, including throughput gain, RANK/UE, DL layers, beam toggling, MCS, MU-Pairing, and Prb count.

6. SYSTEM MODEL OVERVIEW

The complete systems model and used approaches are pasted below. The first figure explains the E2E design and implementation, whereas the second figure explains the testing strategies that are being carried out.

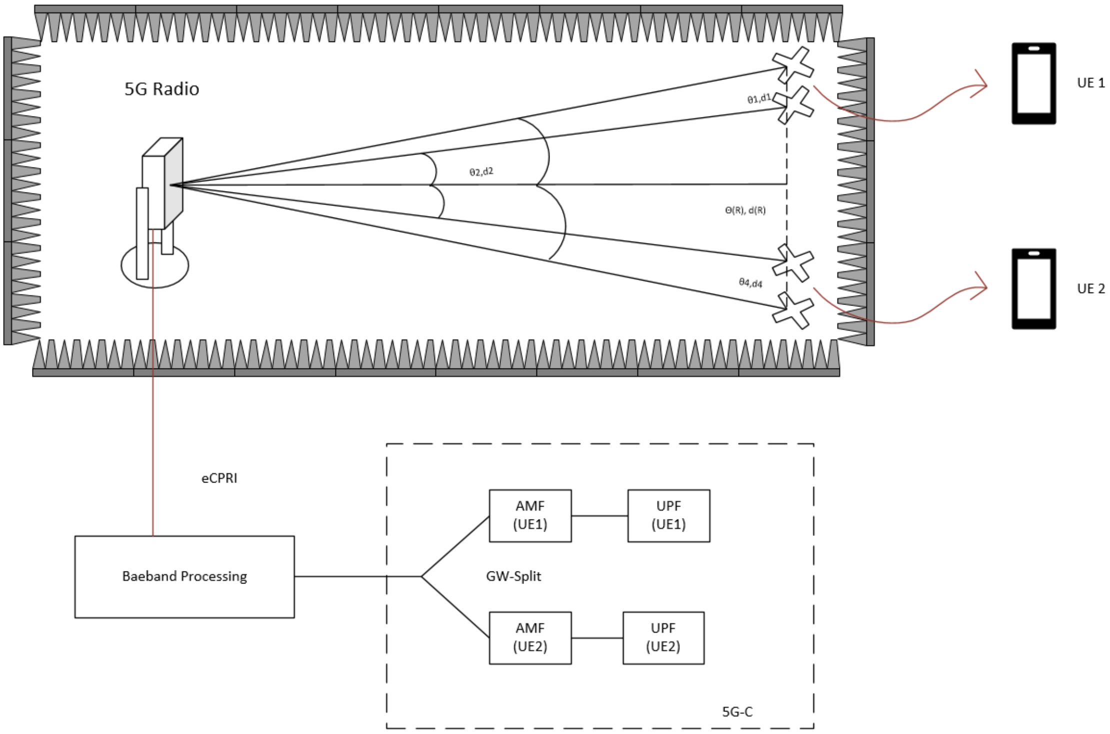


Figure 37. *E2E System Model*

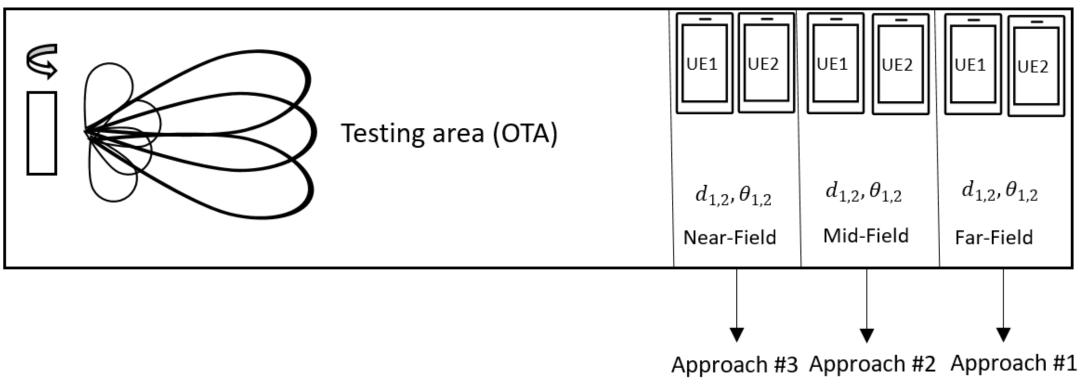


Figure 38. *Testing Approaches with reference to the System Model*

Fig.38 depicts the overall connectivity and operations that are performed to make the test line capable for MU-MIMO. The UE positions are based on $d, \theta,$ azimuth & tilt (Co-ordinate set) which can be seen in the above figure. Separate calculations for both UEs from phase 2 are considered with the cabling of the Vivaldi antennas with 5G testing

UEs. The fronthaul interface between the radio and baseband unit is eCPRI. The base-band connects with the 5G-C on the EF interface. Based on UE configuration and Ip allocation, the AMF/UPF split is configured so that both UE's get their separate core NEs for bearing and route establishment. The L3 call is established in both UL & DL direction meeting the SU theoretical expectations. After successfully integrating and implementing the idea, the testing approaches with different fields can be seen in Fig.37. Calculations are made for each field to check the impact on 5G KPIs. Approach 1 is considered as the far-field scenario based on the chamber length. The in between field is considered a mid-field-testing area, whereas the closest distance with the radio is observed as near-field. These three approaches are implemented and tested individually and compared with SU-MIMO in the results section. The illustration of the expectations is given below:

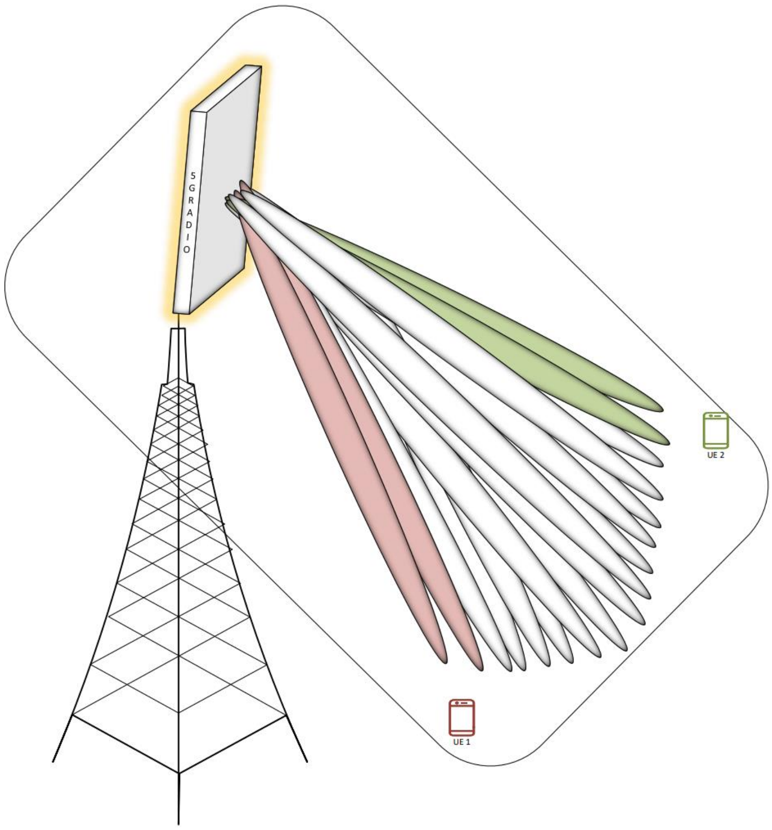


Figure 39. *Spatially Separated Beams in OTA Chamber*

After implementing the required changes, the overall mechanism should follow a certain pattern. This relates to separate resources for both UEs avoiding interference with each other. Fig.39 explains this pattern in which both UEs are placed spatially separated with each other so that each of them can get two separate beams to achieve the expected outcomes. As described in Chapter 1 the expectation is to get more than 4 DL layers, so that two separate Vivaldi antennas are installed for each UE. The beam pattern creating a focused energy in a particular direction consists of two polarities which are received on these antennas individually. Hence, 4 layers per UE can be achieved by implementing the geometrical calculations and changing the radio directions.

7. RESULTS

The thesis work has been completed in collaboration with Nokia OTAVA Laboratory. OTAVA stands for Over-The-Air Validation Area and considered as one of the Nokia's state-of-art Research and Development facility for 5G testing and verification. Undoubtedly, OTAVA is playing a significant role in the system validation by using advanced Nokia Radio units before delivering it to the customers to have the best performance from day one. OTAVA is considered as the biggest R&D centre by having conclusive strategies to measure and anlayze complex air interface communication in 5G wireless networks. The modern equipment and automated platform with the unique laboratory assistance helps to combat the critical real time field scenarios. The field environments are replaced ideally with different setups including Walls and Sea-Containers to observe 5G performance by enabling new features and scopes. [88]

To address the subject of dealing with the enhancement of the test-lines, I have the privilege to contribute in the progressive 5G technology, which could increase the chances to adopt different strategies to measure the multiple users' scenario in the R&D environment.

After completing the initial phases of the deployment, real time testing is carried out to observe the scenarios. The results are made in comparison to the existing setup, in which a single user is tested. It follows a pattern in which the calculations named as coordinate sets in Chapter 6, are implemented firstly for a single user to measure the behaviour of the existing environment and to highlight any degradation. After getting results for SU-MIMO in OTA-Sea Chamber, the installation and configuration for the MU-MIMO is carried out. Similarly, the MU-MIMO scenarios are tested on different locations to observe the performance. Many attempts are made on a single location and the best result is then compared with the SU-MIMO measurements. The major KPI's that are discussed in this chapter are: Throughput gain, Prb count, Channel Quality Indicator, & Rank/DL_Layers. At the end of this chapter the contrast between MU-MIMO is illustrated to check the performance of the system at different locations and points. The soft configuration implemented at the base-station is given below:

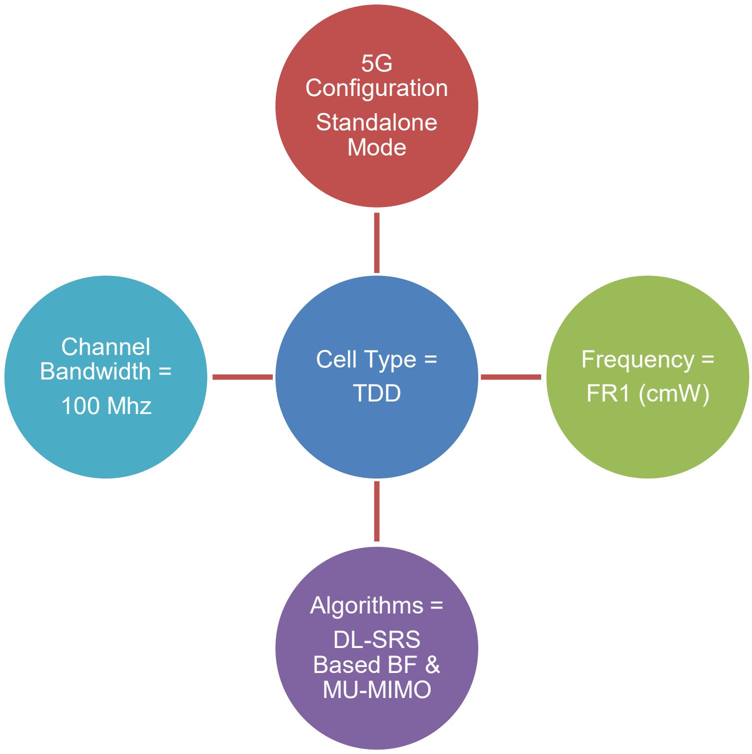


Figure 40. *5G soft configuration*

The first plot is a comparison of throughput between SU-MIMO & MU-MIMO, As described earlier both are tested separately on each coordinate set. The delta comparison between them is given below:

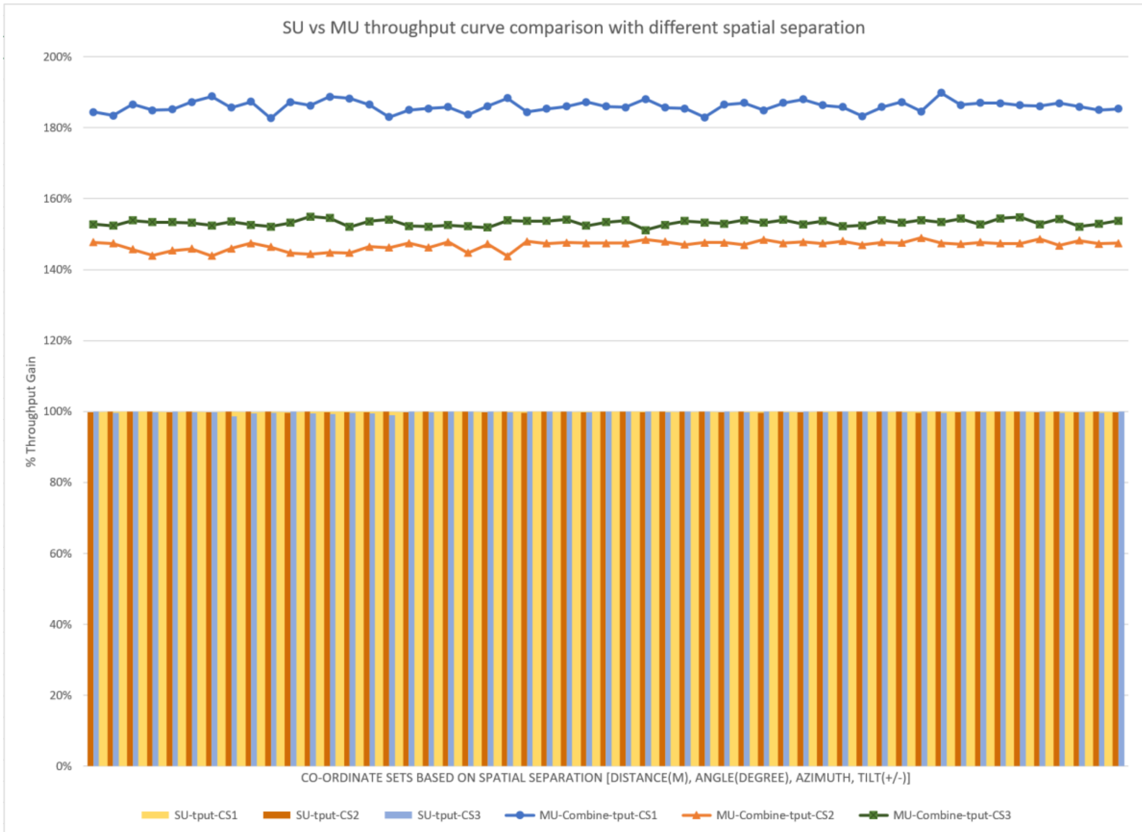


Figure 41. *Throughput Comparison between SU & MU-MIMO*

The terminologies used in this graph are:

- CS (1,2,3) It represents the different coordinates that are calculated at different locations. It mainly includes the geometrical computations i.e., Distance, Angle, Azimuth, and Elevation. The CS value varies by changing the distance, the distances are considered as Near, Mid, and Far fields. i.e., D1<D2<D3
- The term combine is used for MU-MIMO as the data is represented for two UEs collectively.

To start with, the vertical axis represents the throughput in %, and horizontal axis shows the CS approaches. The SU-MIMO at different CS seems to perform as per theoretical expectations. No certain degradation is observed, and it lies in 100% bracket, which is the ideal theoratical throughput gain for a single user in the RF chamber. To generalize, the MU-MIMO outperforms in all cases compared to SU-MIMO. The combine throughput for MU-MIMO at CS1 is considered as the highest gain achieved by the setup maintaining the throughput above 180% approximately. The variation of throughput between MU-MIMO is observed in case where the coordinate sets are changed. The far-field results are the second best compared to the near-field by maintaining the avergae throughput curve just below 160% approximately. Whereas the mid field holds the lowest throughput among all i.e., 150% approximately. The degradation is caused in mid & far field due to interfering beams that in turn reduces the rest of the gain. To check the performance in MU-MIMO scenarios the critical thing is the pairing status of the UEs so that they can be scheduled in the same slot avoiding the resource wastage and efficient utilization. The sweet spots for MU pairing are calculated and implemented, during the testing the pairing status is observed as stable in all locations, so that it is not causing any effect on the throughput. The main concern is that due to large number of overlapping beams or burst of beams, it depends on the reported SRS signal from the UE. Based on the CSI-RS it only considers the best and second-best serving SRS beam and calculates the channel in those two particular directions. Hence, the base station schedules the data on PDSCH channel using those two spatially separated beams, avoiding any interference in the PDSCH channel which may cause SNR drops. The effect can be observed in the cases during the beam toggling scenarios where drops were observed in Mid and Far field causing decrease in the overall gain, while no beam shifting is observed in Near field. The overall pairing status at different CS is illustrated below:

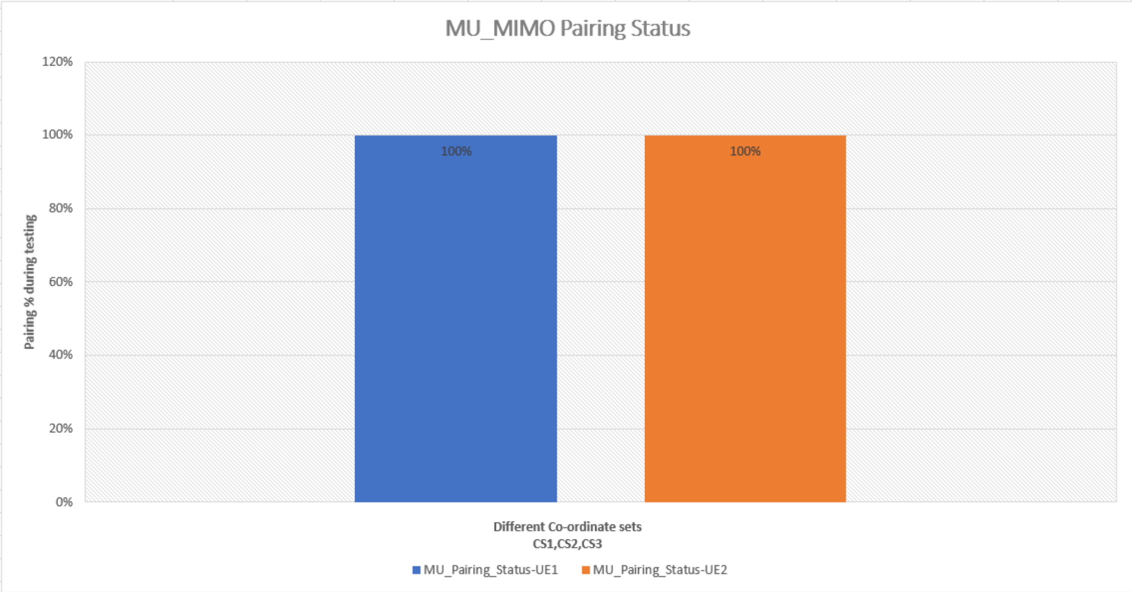


Figure 42. *MU-MIMO Pairing status*

Fig.42 explains the overall pairing status of two separate UEs and irrespective of the CS* coordinates two UE case outperforms SU-case in given conditions. As depicted under mentioned coordinate sets the pairing status is achieved fully without any "no-pairing" status which means that irrespective of degradation at different stages the paring status is constant. Other factors including interference and toggling of beams are the main reasons in this regard.

It is evident from the above plots that MU-MIMO outperforms in all cases to achieve the theoretical maximum. The target in this research work is not only to achieve overall gain but also maintain the major 5G KPIs. The expectation from this setup is to double the overall results as explained in the objectives of this thesis. The other affecting KPIs are illustrated below:

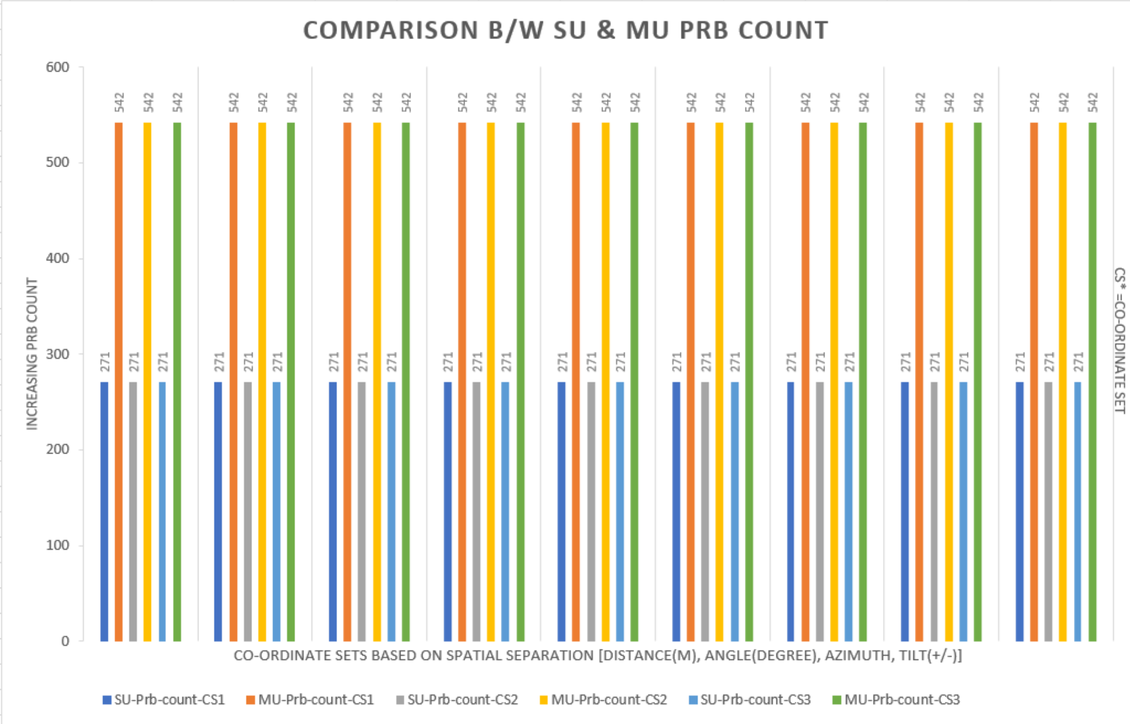


Figure 43. *Comparison of the Prb count between SU & MU-MIMO*

Fig.43 demonstrates the overall comparative summary of the differences in the physical resource block counts. As per used numerology, the single user utilizes 271 resource blocks out of 273. The remaining two resource blocks are used to send synchronization signals. Hence depending on the different coordinate sets the prb count for single user is stable and as per configuration. In case of multiusers the count of physical resource block doubled, which means each user in this scenario can utilize full 271 resource blocks for data transmission separately. Which is practically possible by spatial separation of DL data streams in a single slot. So, in a given radio frame, each of the users' PDSCH is scheduled in time and in frequency simultaneously in a single DL slot. This graph shows that irrespective of the various coordinate sets the count is constant throughout, without any missing resource block. Hence both 5G terminals are ideally separated spatially based on the calculations which allows both users to effectively avail the physical resources from the resource grid and maintain the pairing status. As a result, double the SU-MIMO peak throughput is realized with a 186% average gain approximately.

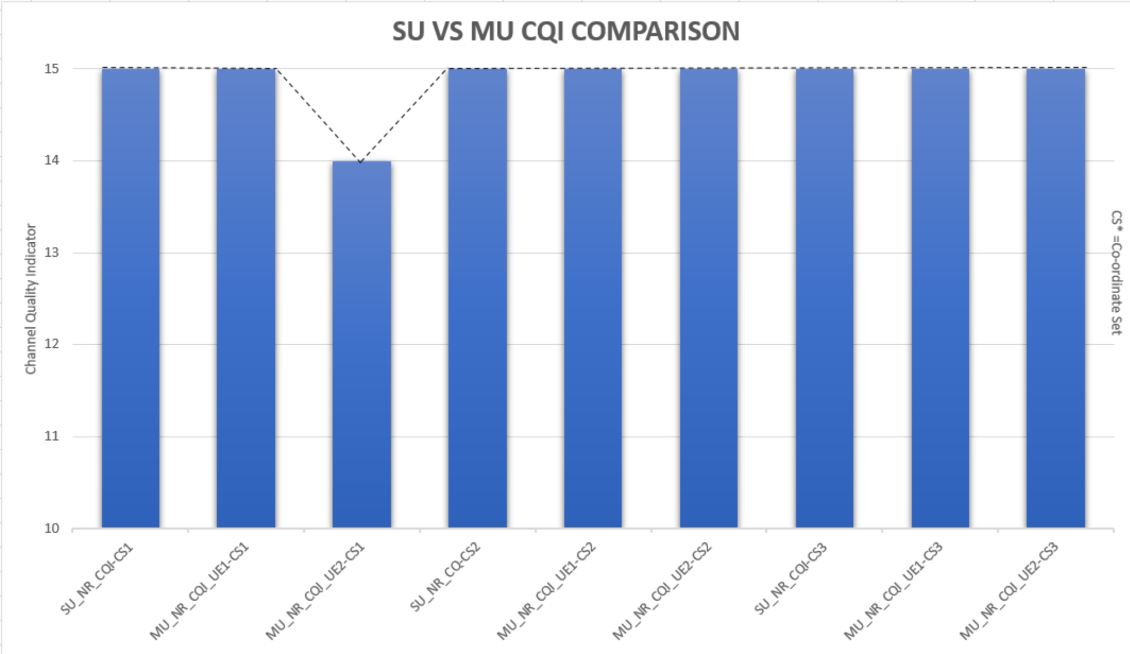


Figure 44. *Comparison of the CQI between SU & MU-MIMO*

The next KPI, Channel quality indicator is illustrated in above Fig.44. The CQI explains the quality of the RF coverage area of the air interface and ranks it based on the quality of the radio channel. Based on the CQI (One of the feedback parameters) the BS schedules the best possible data beams towards the desired UE. The CQI is send by the UE in response to the CSI-RS based reference signal from the BS using uplink channels, by calculating the signal power (RSRP) and SINR. The maximum value for CQI is 15, which means that the UE is reporting the best possible channel quality for transmission. When using the SU configuration on different coordinate sets, the graph shows the ideal channel quality, means that based on the quality indicator the situation is absolute to get maximum transmission gain as the BS is scheduling data on large transmit blocks. Considering the MU-MIMO perspective, all the UEs are reporting highest value for channel quality as they are getting best SINR and RSRP over all the CS, except some degradation is observed at coordinate set 1. The UE2 reports the channel quality 14, lower than the rest of the UEs, indicating that the UE is experiencing interfering beam in that direction, which causes degradation in overall received signal power. The other reason is large grating lobe interfering with the data beam in particular direction, moreover CQI 14 is not so vulnerable as the MU's still managed to get maximum gain at CS1.

The fourth critical KPI in this research work is the number of DL layers based on the reported rank by the UE. As discussed in the Chapter 1, the main concern for implementing the MU-MIMO scenario is to increase the number of DL layers. With the adjustments either Rank 2 with 4 UEs or Rank 4 with 2 UEs can be obtained. Due to confined space limitation, adding additional 4 UEs with ideal spatial separation is challenging. Given the limited vertical and horizontal spacing, the second approach is chosen to be used in this research work i.e., 2 UEs with Rank 4 each.

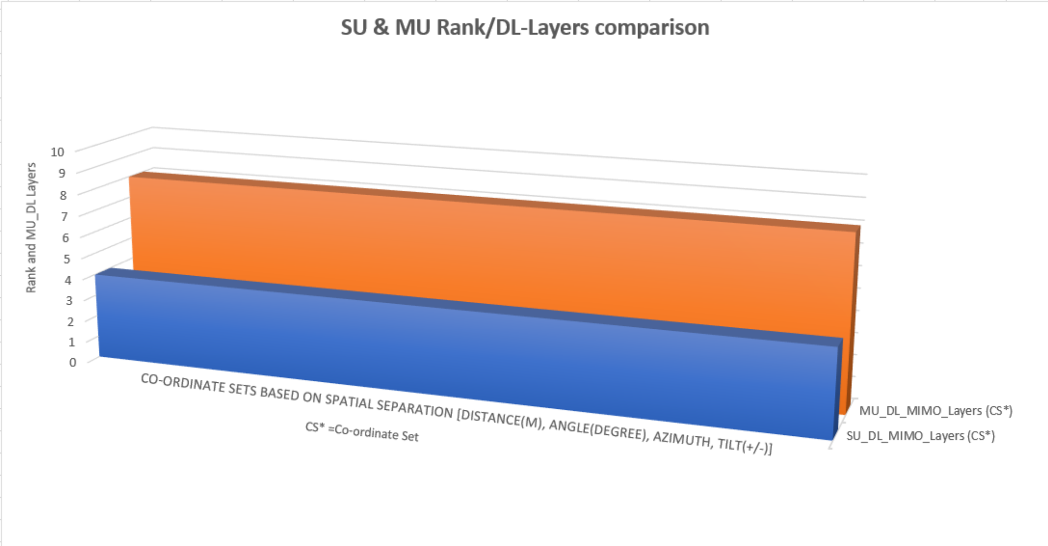


Figure 45. *Comparison of the RANK/DL layers between SU & MU-MIMO*

Fig.45 shows a comparison of achieved Rank and DL layers between SU and MU's. Since as part of the periodic CSI reports send by the UE in UL control channel reference RI is one of the key parameters which indicates the RANK of the UE, this KPI is studied and illustrated in Fig.45. Additionally, the feedback of the reference signal contains the parameters related to RI, PMI, and CQI. The RI information reported by the UE shows how favourable channel conditions are available for MIMO communication. For instance, if the UE reports Rank 4, it means that the UE has the capability to receive up to 4-DL layers. In other words, RI information shows that the number of antennas at the UE should have un-correlation with each other in a way that each signal from the antenna is independent of each other. In good conditions, the UE notices the un-correlated multipaths, which makes the UE antenna to transmit and receive information on separate antennas without any interference. Rank is the critical factor in our research work, as the environment is closely spaced to find the separate un-correlated paths for each antenna. In the existing setup, where a SU is tested, the graph indicates a clear stability in Rank and DL layers irrespective of the different UE CS and locations. Whereas in MU scenarios, the Rank is doubled as number of UEs increased to 2. Each of the UE has independent 4 data streams based on the reported RI, and collectively the both UEs in this scenario results into 8 DL layers by maintaining the gain and other KPIs.

After investigating the hidden challenges, the setup has overcome the afore-mentioned issues and outperforms in each scenario. As illustrated above, all the 5G major KPIs hold the uniformity and work together in achieving the goals. Having tested MU-MIMO at different points, some degradation is observed at various instances. Hence, to find and suggest the optimal solution to the problem, a comparison between the MU gains is described below:

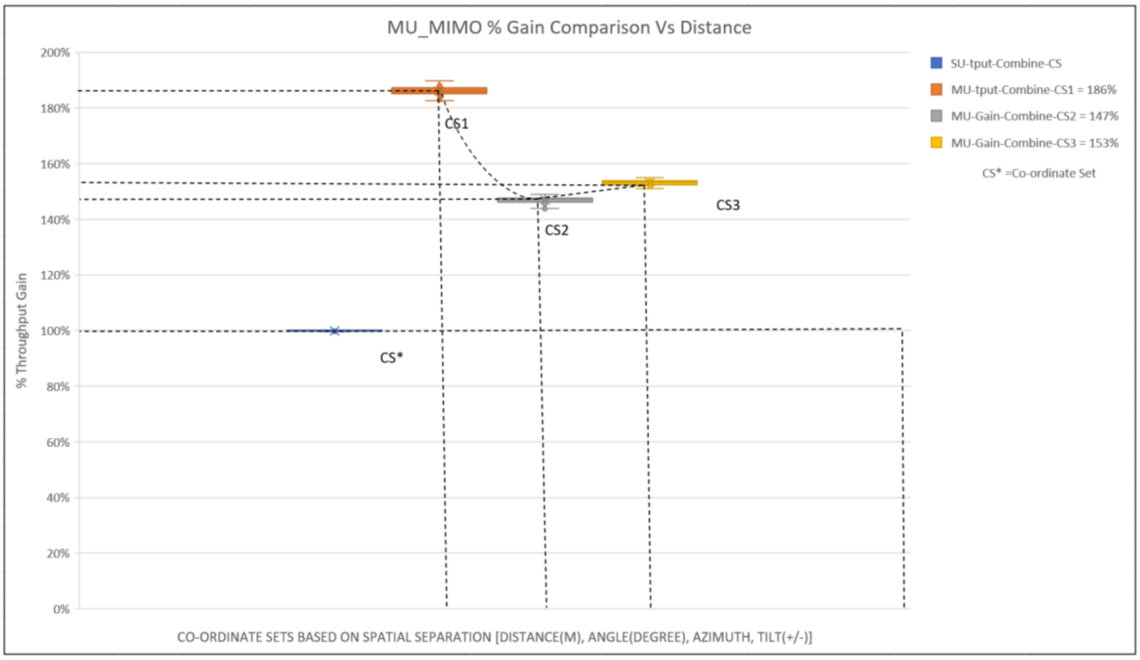


Figure 46. *Comparison of MU-MIMO at different instances*

Fig.46 represents the overall testing outcomes for MU-MIMO scenarios. It is evident from the graph that, implementing and testing MU-MIMO in OTA-Sea container is practically do-able, and the conclusion is that it performs as per expected theoretical performance. The graph shows a contrast between the results taken at different coordinate sets; the maximum throughput is observed when the environment setup is configured in the Near field. It gives the approximate double gain with reference to the SU gain. Following that the second maximum is observed at the Far field, where the UEs are placed at the maximum distance available, the overall gain is also greater than that of SU gain. The worst result in case of MU-MIMO is discovered at the mid-range distance or approximate centre of the RF Chamber. Comprehensively, it also surpasses the SU gain with-holding the stable performance. The figure also shows the amount of gain is percentage achieved by this research. The reference point for gain percentage is considered as the average value over all coordinate sets in single user case which is 100% approximately. The percentage gain for MU-MIMO at CS1 is considered as the best one giving the increment by 186% of the overall increase gain. It is than backed up by the MU-MIMO results at CS3, which contributes 153% expansion in the exiting results. Finally, the MU-MIMO results at CS2, improves the existing gain by accelerating it by 147% throughout. The percentage is calculated based on the average value at each CS for MU-MIMO & SU-

MIMO. The trend line shows a dip at a certain point where the throughput dropped by 6% at CS2, at that instance due to change in configurations and adjustments, the point appears to be severely affected by the interference which causes the drop in gain at that point. Overall, it is evident from the plot that the calculations for CS1 are ideal to get the expected results. Based on that, the terminology for calculations follows a relation with each other mentioned below:

CS1> CS3> CS2 (In terms of Gain)

CS1< CS2< CS3 (In terms of calculations)

7.1 Challenges

Given the physics and the physical challenges of the air interface and maintaining a stable radio channel, implementing multiple users in a confined space is always a challenging task, as the limitation factors affect the installation and performance of the system. During this whole procedure, many issues appeared. Before starting the initial installation, the main challenge is to use a 5G standalone test-line that requires the E2E system modification from scratch. After being deployed the configuration, the initial testing shows poor results. For instance, the first MU testing shows the throughput at 50% overall for each UE, which is even less than the SU gain in the existing setup. After investigation, two steps are performed, originally there was a single shield box for a UE, the second UE is also cabled and placed in the similar box that causes the interference with each other and effects the performance. An additional RF shield box is installed for the second UE to cater with this issue. Related to the soft configuration both C/U-plane packet gateways is divided into two separate GTP-C and U respectively and hence assigning separate IP paths for each UE. After doing the above-mentioned procedures, a minor improvement is seen in the performance. The expectations have yet to be met, by running multiple scenarios the outcome is still getting worse. The exploration continues unless some modification related to the algorithm has been made, which includes the adjustment of certain threshold values for better UE pairing. Together with the adjustments the UE starts to pair even without forcing, but results into severe Rank dropping. Undoubtedly, Rank is the most crucial factor in the research as the expectations for DL layers depends on it. Following the troubleshooting, the Rank issue is handled by changes in the installation procedure and by modifying the radio position to some degrees side by side with introducing continuous alteration in elevation and azimuth until a sweet spot is observed. To make the performance stable, the attenuation is also adjusted for all polarities of the Vivaldi antennas. To put in a nutshell, the desired results are achieved by the proposed system by some parameters and hardware adjustments.

8. CONCLUSION

Foreseeing the future needs of a technology given the ongoing advancements in existing wireless technologies ensures that previous gaps are bridged, and the forth coming expectations are realized at an early stage. 5^{th} generation is currently widely discussed around the globe due to its significance in terms of lower latency, higher performance gains, and network scalability. Since its inception, 5G has been deemed as an enabler to a variety of use cases. And having commercially rolled-out the 5^{th} generation outperforms all legacy technologies on the scale of key customer & user centric KPIs. As a general rule of thumb, the primary objective of disruptive technologies is to make a major impact and it takes intensive years and years of R&D work. It eventually comes down to two basics such as to improve network performance and to ensure that the technology benefits the users. As a result, researchers from academia and industry worldwide are working hard to develop scalable, secure, and flexible solutions. The principal objective of this thesis work was to investigate and improve 5G over-the-air beamforming so that multiple users in the Sea-containers can be utilized by enhancing the existing capacity and capabilities. The idea was followed by a chain of phases and real-time experiments. Specific approaches were suggested in various situations to achieve the best possible outcome.

The preliminary work includes the study of existing setup dimensions by proposing new locations of the UE's, creating enough spatial separation to avoid any possible interference. Following that and given the dimensional limitations of the OTA-setup, mathematical calculations were carried out to identify the suitable location candidates for the user equipment's. The used combination of the algorithms is MU-MIMO and SRS-based beamforming. 4 DL can be achieved by doing single user testing in the Sea-container, which is further enhanced to 8 DL layers by introducing the concept. After establishing the L3-call, the procedure is tested and observed at different coordinate sets. Initially, the single user is tested at all locations, maintaining the throughput curve at average 100% by keeping all the KPIs without degradation.

Starting the MU-MIMO testing at the first location (Far-Field), the average throughput by both UEs was 76% each by maintaining the stable pairing and RANK4. Compared with the theoretical maximum, each UE should get the throughput of a single user (Without MU-MIMO), i.e., approximately 100% gain should be achieved. Considering the first location, the calculation based second location was implemented to analyze the performance again. At the second location (Mid-Field), degradation was observed as one UE was reporting average throughput of 76%, whereas the second UE was getting 69% of gain. The conclusion between both approaches was clear, because by changing the location, one of the UE was degraded due to bad SINR and severe side lobe interference. The next location (Near Field), based on calculation, was then tested. The average throughput observed was 88% for the first UE and 98% for the second UE. The near field outperforms in all cases as the maximum gain is achieved at this point, and all the major KPIs were stable.

To summarize, all three locations perform better compared to the SU, and it is evident from the results that MU-MIMO maintains a stable throughput curve more significantly than the single user. Now, having discussed all three locations separately, the best possible results were achieved at Near-Field, i.e., (CS1). The maximum gain close to the theoretical is observed at CS1 by contributing a 186% increment in the overall gain.

MU-MIMO implementation in a confined space has a promising start as it holds all the major KPIs by providing expected gains. The reason to test multiple locations was to filter out the suitable approach to investigate 5G (Over-the-air) critical testing. The future work can be followed by introducing more UEs to the RF chamber. It can also include the rotating mechanism at the user end to test mobility scenarios. The proof of concept was based on the mentioned calculations, which can further be improved to avoid interference and beam toggling.

To conclude, in my opinion the proof of concept is envisioned by having implemented the suggested solution. In terms of expectations, the system outstands by giving the best possible outcomes. The experiment approximately meets the theoretical maximum, as compared to a single user, while 186% throughput gain is observed by 2 users simultaneously. Considering the performance evaluation of the setup, the best option to test MU-MIMO is at CS1 or Near field for effective data rates and stable KPIs. The acute aspects including the exact location of the candidates need to be further investigated to assist more users in the available separation. The future work can include the study related to calculate the spatial separation for third user in the RF chamber, the mobility cases can also be surveyed by considering the 3-D rotation mechanism for the end devices.

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