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BEAM USAGE ANALYSIS FOR DIFFERENT BEAMFORMING TECHNIQUES IN MOBILE COMMUNICATION SYSTEMS

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Abstract

Affief Ahmad: Beam Usage Analysis of Different Beamforming Techniques in Mobile Communication Systems
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Beamforming has emerged as a key enabler in modern mobile communication systems, offering significant improvements in signal quality, spectral efficiency, and user experience. This research presents a comprehensive analysis of beam usage associated with different beamforming techniques within live mobile network environments. The study was conducted at Nokia's Espoo campus and focuses on three primary research questions central to the optimization and future deployment of beamforming technologies.

The research begins by investigating the current implementation of beamforming within a mobile network cell and proposes a method for analysing and categorizing beams based on logs how many time frames or time slots associated with individual beams in the same cell. This categorization provides a foundation for understanding beam behaviour and performance under varying network conditions. In addition, the research explores how the derived beam categories can be leveraged to guide the future deployment and optimization of beams in live networks, aiming to enhance both performance and coverage. Furthermore, the study examines the transitions of User Equipment's (UEs) between beams within a cell, offering insights into the mobility behaviour and handover efficiency in beamforming-enabled networks.

Through empirical analysis and interpretation of live network data, this research work provides practical methods for evaluating and optimizing beamforming in real world mobile networks. By examining beam-level performance metrics and user behaviour, the study identifies key patterns that influence beam efficiency and mobility within the network. These insights form a foundation for more informed and data-driven decisions in network design and management. The outcomes of the research offer valuable guidance for network operators seeking to improve beam planning, streamline deployment strategies, and enhance overall user experience in the context of evolving 5G systems and beyond technologies.

Keywords: Beamforming [BF], Mobile Communication Systems [MCS], User Equipment's [UEs], Performance Counters [PC], Fifth Generation [5G]

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Preface

In the name of Allah, the Most Gracious, the Most Merciful.

All praise and thanks be to Allah Almighty, whose infinite mercy and guidance have sustained me throughout my academic journey and made the successful completion of this thesis possible. It is only through His grace that I have been able to reach this significant milestone.

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To my beloved parents, Mr. Zulfiqar Ali and Mrs. Rabia Naseem, and to my family especially my brother Dr. Zaeem Ahmad and my sister Dr. Yumna Ali thank you for your unconditional love, prayers, and sacrifices. Your support has been the foundation upon which I have built this academic journey, and I am forever indebted to you.

This thesis is not merely a culmination of individual effort, but a reflection of the collective support, encouragement, and contributions of all those mentioned above. I hope it stands as a modest tribute to their influence and as a meaningful contribution to the evolving domain of Wireless Communication.

Espoo, 29 April 2025

Affief Ahmad

Contents

List of Symbols and Abbreviations

1G	First Generation Cellular Communication
2G	Second Generation Cellular Communication
3G	Third Generation Cellular Communication
3GPP	3rd Generation Partnership Project
4G	Fourth Generation Cellular Communication
5G	Fifth Generation Cellular Communication
5GCN	5G Core Network
6G	Sixth Generation of Cellular Communication
ABF	Analogue Beamforming
AI	Artificial Intelligence
AoA	Angle of Arrival
AoD	Angle of departure
AMF	Access and Mobility Management Function
AMPS	Advanced Mobile Phone Services
B	Bandwidth
BCH	Broadcast Channel
BER	Bit Error Rate
BF	Beamforming
BTS	Base Transceiver Station
C	Capacity
CCI	Co-channel interference
CDMA	Code Division Multiple Access
cmW	Centimeter Wave
CP	Cyclic Prefix

CQI	Channel Quality Indicator
CSI	Channel State Information
CSI-RS	Channel State Information-Reference Signal
DB	Digital Beamforming
DM-RS	Demodulation Reference Signal
DL	Downlink
DU	Distributed Unit
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
EUTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GHz	Giga Hertz
gnB	Next Generation Node B
GSCN	Global Synchronization Channel Number
HB	Hybrid Beamforming
HSDPA	High-Speed Downlink Packet Access
ICI	Inter Channel Interference
IoE	Internet of Everything
IoT	Internet of Things
IQ	In-phase Quadrature
ISI	Inter-Symbol Interference
KPI	Key Performance Indicator
LOS	Line of Sight
Mhz	Mega Hertz
MIMO	Multiple Input Multiple Output

MIB	Master Information Block
MME	Mobility Management Entity
mMIMO	Massive MIMO
mMTC	Massive Machine Type Communications
MU-MIMO	Multiuser MIMO
NFV	Network Function Virtualization
NSA	Non-Standalone
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PBCH	Physical Broadcast Channel
PDN	Packet Data Network
PSS	Primary Synchronization Signal
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technologies
RB	Resource Block
RF	Radio Frequency
SA	Standalone
SCS	Subcarrier Spacing
SNR	Signal-to-Noise Ratio
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
TDMA	Time Division Multiple Access
UDM	Unified Data Management
UE	User Equipment
UL	Uplink

URLLC	Ultra -Reliable Low Latency Communications

List Of Figures

LIST OF Tables

1. Introduction

The emergence of 5G and the projected 6G networks have significantly increased the demand for higher data rates, improved spectral efficiency, and energy-saving solutions in mobile communication systems. Beamforming, a crucial technology that uses multiple antennas to create focused signal beams, has become a vital tool in addressing these challenges. By enabling precise signal transmission and reception, beamforming reduces interference and enhances signal quality [1].

Existing research has extensively investigated various beamforming techniques within mobile communication systems. Prior work provides a comprehensive overview of beamforming methods for massive MIMO systems in 5G, categorizing them and highlighting potential areas for future research. Additionally, another study offers a comparative analysis of different beamforming techniques in 5G, with a special emphasis on beam distribution [1][2].

Even with these valuable contributions, there remains a knowledge gap regarding actual usage patterns of beams in practice. We aim to fill this gap with a comprehensive analysis of the utility of beams for a range of beamforming methods. The analysis will take into account not only drive test results, but also parameters as diverse as beam allocation, channel conditions, user movement, beam transfer and network traffic, for a realistic estimate of beam usage scenarios [2].

The analysis of beam usage statistics and the factors influencing beam selection will enable the optimization of beamforming algorithms and further the development of efficient indications for future mobile communication systems. The findings from this examination will enhance the functionality of existing beamforming strategies, as well as set the stage for a new generation of adaptable approaches that can adjust beam usage according to live network states [3].

1.1 Overview

As the demand for data continues to surge and the number of connected devices grows, it is increasingly necessary to implement 5G wireless communication systems with significantly higher capacity and efficiency. Such challenges call for a viable solution, which is where the convergence of large-scale multiple-input multiple-output (MIMO) systems and beamforming antenna arrays comes into play. Massive multiple-input multiple-output (MIMO) [3], where a large number of antennas are installed at base stations, can greatly enhance spectral and energy efficiency so that more user terminals and higher data rate can be achieved in the same band.

Massive MIMO systems, which have a large number of antennas, use a signal processing technique called beamforming to build highly focused beams, with manipulation of the phase and amplitude of signals at the antenna array. Efforts for interference mitigation and performance optimization in massive MIMO systems are anchored in beamforming [4]. Beamforming uses the ability to control the phase and amplitude of signals at the antenna array to direct the majority of the energy towards preferred users and reduces the interference towards other users [4].

Beamforming not only mitigates interference but also increases energy efficiency through a decrease in power utilized for signal transmission and reception, as well as increases security for the system, making it harder for eavesdroppers to intercept transmitted signals. The significance of beamforming becomes even more pronounced at millimeter-wave (mmWave) communication, with high frequencies enabling large bandwidth but suffering from significant path-loss [4].

Beamforming allows for the creation of highly focused beams, overcoming path loss and enabling reliable communication at mmWave frequencies, making them suitable for 5G and future networks. The synergy between massive MIMO and beamforming is therefore instrumental in unlocking the full potential of next-generation wireless networks, paving the way for unprecedented data rates, enhanced coverage, and improved spectral efficiency [4].

1.2 Background

Beamforming is not a recent invention; its roots trace back to the early 20th century, where it found initial applications in radar and sonar systems for directional signal manipulation [9]. These initial uses paved the way for beamforming to become a more advanced technique founded on antenna theory and signal processing. Here the base idea is using a multiple antenna array that collectively shapes the radiating pattern of the emitted signal. The array acts similarly to a spotlight, where the signal leaking from each antenna can be fine-tuned in both its phase and amplitude to steer the beam in the desired direction [5].

Beamforming development over many years has been tightly coupled with digital signal processing and antenna array design evolution. The increasing processing power and cost-effectiveness of digital signal processors allowed the implementation of sophisticated beamforming algorithms, resulting in considerable performance gains [5]. At the same time, improvements in the design and fabrication of compact and efficient antenna arrays enabled beamforming to be integrated into more types of devices and systems from mobile phones to base stations. The convergence has accelerated the deployment of beamforming across many different use cases which has enabled more creativity within the wireless domain. [8].

The emergence of Multiple-Input Multiple-Output (MIMO) technology marked a watershed moment for beamforming in wireless communications. MIMO systems, which employ multiple antennas at both the transmitting and receiving ends, presented new opportunities for enhancing signal quality and throughput. Beamforming, with its ability to focus signals on specific directions naturally complemented MIMO by allowing for spatial multiplexing and diversity gain [8].

This synergy between beamforming and MIMO has played a crucial role in the development of 5G networks, where massive MIMO systems leverage a large number of antennas to achieve unprecedented levels of performance and efficiency. The study in [4] offers a detailed exploration of how beamforming and MIMO have evolved together to shape the landscape of modern wireless communication.

1.3 Usage in Networks

Beamforming is a significant breakthrough in current wireless communication systems, with a crucial role in improving overall network performance. By directing radio frequency signals toward designated user devices rather than broadcasting uniformly across all directions, beamforming improves signal quality, eliminates interference, and boosts the efficiency and reliability of data transfer.

1.3.1 Cellular Networks (5G and beyond):

The use of beamforming in 5G networks, particularly in the millimeter-wave (mmWave) frequency bands, has been instrumental in overcoming the challenges associated with high path loss and susceptibility to blockage. By enabling precise beam steering towards user devices, beamforming enhances signal strength and quality, thereby extending coverage and improving data rates [6]. This is particularly crucial in dense urban environments, where obstacles and interference can significantly degrade signal quality. Furthermore, beamforming facilitates the efficient use of spectrum resources by allowing multiple beams to be formed simultaneously, serving multiple users with minimal interference. This not only increases the network capacity but also enhances the overall user experience by providing faster and more reliable connections [6].

1.3.2 Wireless LANs (Wi-Fi):

Now a staple for most modern Wi-Fi networks, beamforming helps improve the performance and reliability of wireless connections. Explicit beamforming and implicit beamforming, which create the Wi-Fi signal and focus it as much as it can on the devices for optimum performance. This leads to more powerful signals, increased range, and better data rates, especially in circumstances when numerous devices or barriers would weaken the signal otherwise [7].

1.3.3 Satellite Communications:

Beamforming is one of the critical concepts in satellite communication that changes the way signals are transmitted and received. Combining signals from multiple antennas, it creates focused, steerable beams, which results in higher signals, reduced interference, and greater capacity. This technique finds applications in sectors like broadband internet delivery using High-Throughput Satellites (HTS), tracking of mobile users, provision of high-capacity backhaul links, secure military communication, etc. While it has advantages, beamforming comes with challenges related to the complexity of the system and the requirement for accurate channel estimation. But new studies and research, to improve its potential, remain active in this direction [10].

1.4 Research Objectives:

The primary aim of this thesis is to examine and implement various beamforming techniques, evaluating their impact on network behavior. This technology, crucial for communication but still under development, presents numerous concerns that require careful consideration after deployment in the mobile communication system. The potential benefits of beamforming, such as increased capacity, improved coverage, and enhanced spectral efficiency, are significant. Several objectives must be addressed before implementation step, and some challenges must be answered prior to network integration

Q1. Since beamforming is a technology that is already implemented in a cell in the mobile communication system, how can we analyze the implementation of beamforming techniques and categorize them based on counters per beam in the same cell in mobile network system?

Q2. How to use the categorization of beams in mobile networks for further deployment of beams in the live network in future to enhance performance and coverage?

Q3. Beamforming is already being deployed in the mobile communication network so how we would categorize the transition of UEs from one beam to another beam in a cell in mobile network?

2. Mobile Evolution and Beamforming Techniques

Wireless technology has transformed how we connect and communicate, making it easier to send information between devices and across platforms. This technology has become widespread, and we see it in Wi-Fi, our phones (3G, 4G, 5G), Bluetooth devices, and more. Its growth has led to new ideas in many areas, from healthcare and schools to factories and how we travel. [11]

Wireless technology has been evolving steadily over the years and has been getting faster, more efficient, and supporting more connected devices. We've transitioned from older technologies such as 2G to newer 5G that can transmit data quickly, with minimal latency, and serve as many devices as possible at a time. This is a whole new frontier for augmented reality (AR), virtual reality (VR0 and Internet of Things IoT. [12]

This innovation has also done wonders for the healthcare sector with the wireless tech as well. It has transformed how patients are treated, how health is remotely monitored and how medical devices communicate with each other. Special sensors we can wear, systems that monitor our health when we aren't in a hospital, visits with doctors online — all of that is the work of this technology. These0 tools allow doctors to gather health data in real time, diagnose issues remotely and respond rapidly, which enhances the quality of care we provide to patients and can reduce costs. [13]

Even with all this progress, wireless technology still has some issues to solve. Managing who gets to use the airwaves, dealing with signals getting in the way of each other, using less energy, and keeping things secure are all important challenges. To make things better, researchers are looking into smart radio networks, new ways to send signals, and networks that can adjust on their own to get the best performance. [14] Wireless technology has become a key part of how we stay connected today, and it affects almost every part of our lives. Also, the ongoing research will help us in tackling present and potential problems.

2.1 Overview of Mobile Communication Technologies.

Mobile communication has changed dramatically in the past few decades. This evolution has been steered by the relentless improvements in network data speed and capacity, with reduced latency and an ever-growing user base in a very scalable network foundation. [17]

The history of mobile communications started with the innovative work of pioneers who figured out how to send voice over the airwaves. The problem with these systems was that they were limited by wired connections, making them less mobile and more inconvenient. It was this challenge that birthed mobile phones, a revolutionary invention that enabled two-way communication without wiring. [15] [17]

The advent of mobile phones ushered in the first generation (1G) of mobile communication networks. These analog networks were mainly used for voice calls. Despite their limitations, they laid the groundwork for the digital revolution in mobile communication.[16] The second generation (2G) introduced digital networks, enabling text messaging and paving the way for more advanced data services.[16]

The third generation (3G) marked a significant advancement, providing faster data speeds and greater flexibility compared to its predecessors. This enabled data-intensive applications such as mobile internet browsing and video calling. The fourth generation (4G) further improved speed and efficiency, making mobile broadband a reality for millions worldwide.[16]

The fifth generation (5G) represents the latest in mobile communication technology, offering unprecedented data rates and bandwidth. This opens up new possibilities, from seamless streaming of high-definition videos to the widespread use of Internet of Things (IoT) devices. As the world embraces 5G, researchers and engineers are already looking towards the sixth generation (6G), which is expected to include advanced features like cloud storage and even faster speeds.[16]

The development of mobile communication technology is a testament to human creativity and the unwavering pursuit of advancement. Every generation has improved speed, capacity, and added new capabilities by expanding on the achievements of its forebears. The way we engage with the outside world, communicate, and obtain information has changed as a result of this progress. From analog phone calls in the early days to 5G's high-speed capabilities, mobile communication technology has grown to be an indispensable aspect of our daily existence. With 6G predicted to bring even faster speeds, lower latency, and new uses we can't even begin to anticipate, the future of mobile communication seems very bright. The development of mobile communication technology is a testament to human creativity and the unwavering pursuit of advancement.[16]

2.1.1 Evolution from First Generation to Sixth Generation

The evolution of mobile technology has been a remarkable journey, spanning from the humble beginnings of 1G to the anticipated arrival of 6G. Each generation has brought about significant advancements, revolutionizing the way we communicate and interact with the world. [17]

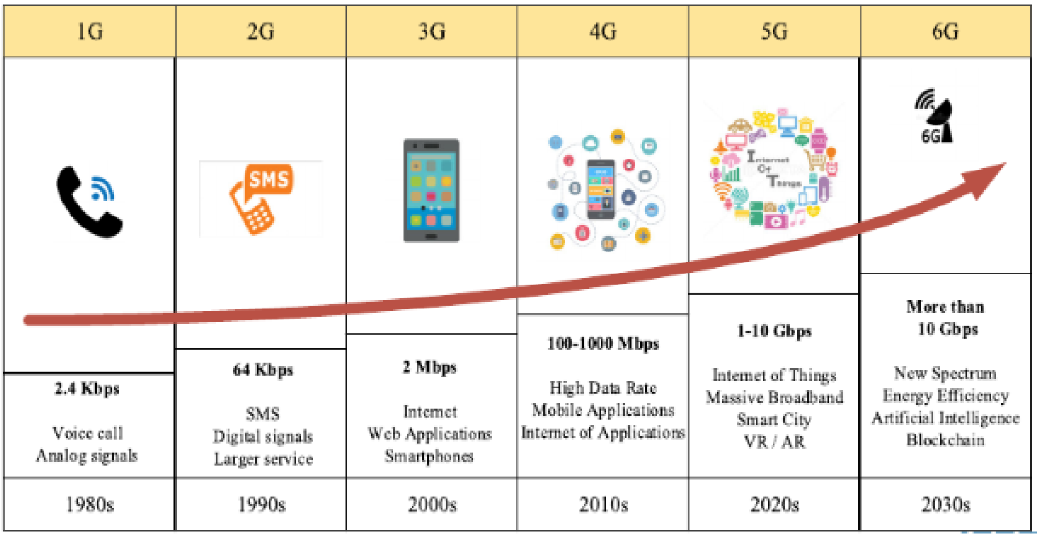

Figure 1.The Evolution from 1st generation to 6th generation. [18]

The Figure 1. shows that how communication technology changes during the spam of time from 1G to 6G. In the 1980s, 1G introduced analog cellular communication, primarily facilitating voice calls. While limited in speed and reception, it laid the groundwork for future developments. The 1990s saw the emergence of 2G, which embraced digital cellular technology, enabling SMS and improving call quality and security. 2G solidified the mobile phone's place in our lives. [18]

The 2000s ushered in 3G, marking a turning point with the advent of mobile internet. With increased speeds, it allowed for multimedia messaging, video calls, and basic apps, paving the way for the smartphone revolution. 4G, introduced in the 2010s, significantly boosted speeds, enabling high-definition video streaming, online gaming, and a myriad of sophisticated apps. It transformed how we work, play, and connect on the go. [18][19]

Currently, 5G is redefining mobile technology with unprecedented speeds, ultra-low latency, and massive device connectivity. It supports emerging technologies like virtual and augmented reality, promising to reshape industries and drive innovation in smart cities and beyond. Looking to the 2030s, 6G is on the horizon, even with faster speeds, holographic communication, and integration with brain-computer interfaces. It has the potential to blur the lines between the physical and digital worlds, ushering in a new era of technological possibilities. [19]

Each generation of mobile technology has built upon its predecessor, propelling us into an increasingly connected and digital world. The ongoing evolution promises to bring even more groundbreaking innovations, transforming how we live, work, and communicate in the years to come. [20]

	1G	2G	3G	4G	5G	6G
Year	1970-84	1990-2000	2000-03	2010	2020	2030
Technology	Analogy	GSM	CDMA 2000	Wi-Fi	IPv6 LAN/WAN/PA N	IPv6/Orthogonal Chip division Multiplexing (OCDM) Modulation
Data Rate	2.4 kbps	Up to 64 kbps	3 Mbps	>200 Mbps	>1 Gbps	>1 Tbps
Switching	Circuit-switched	Circuit and Packet switched	Packet-switched	Packet-switched	Packet-switched	Packet-switched
Photonic Frequency	30 kHz	200 kHz	5 MHz	15 MHz	15MHz	>25 MHz
Bandwidth	150 kHz	Maximum 20 MHz	Maximum 30 MHZ	100 MHz	1-2 GHz	>5 GHz
Authentic Network	Public switched Telephomic Network	Public Switched Telephonic Network	Packet N/W	Internet	Internet	Internet
Carrier Multiplex	FDMA-scheme	TDMA and CDMA scheme	CDMA-scheme	LTE	MIMO	OAM (oribital Angular Momentum
Key Features	Voice Calls only	Voice Calls, and Text	Video calls, text, Video conferenci ng	High-Definition video, super-speed broadcasting	Ultra HD videos, high-speed uploading and downloading	eHealth monitoring, Advanced IOT applications, Bio-medical core networking

Table 1. Comparison Between 1G to 6G Technology [20]

The table 1 summarizes the evolution of mobile networks from 1G to 6G. It shows how the technology, speed, and features have improved over time. Also provide information about the data rate of each technology, year-to-year evolution, bandwidth and photonic frequency information. Older generations 1G and 2G used circuit and packet switching and had limited bandwidth, while newer ones utilize packet switching and offer much faster speeds. [20]

Each generation has brought new features,1G only used for calls while SMS included in 2G, mobile internet in 3G and 4G, and ultra-fast speeds in 5G. While 6G is still under development, it promises even greater speed, lower latency, and enhanced security, with potential applications in Health care and other innovative areas. [19] [20]

Essentially, each new generation builds upon the previous one, offering faster speeds, more features, and better connectivity. [20]

2.2 Beamforming Techniques in Mobile Communication.

Beamforming technology in smart antennas is a key component of massive MIMO systems, enhancing signal transmission and reception in wireless communications. By intelligently identifying the direction of incoming signals, smart antennas can focus their beams on the desired mobile device, improving signal strength and overall network performance. This technology finds applications in diverse fields, ranging from auditory signal processing and astronomy to radar and cutting-edge wireless communication systems like LTE and 5G. [21]

2.2.1 Classification of Beamforming

Due to the diversity in its implementation and application makes it classified by several criteria. As you may know, one popular approach is to classify techniques according to their physical features, in particular the beamforming type and the array antenna design. Beamforming can mainly be classified into two types, including switched beamforming and adaptive beamforming, each, in turn, classifiable into linear antenna array, circular antenna array, and rectangular antenna array categories [22].

Another classification method focuses on signal processing, categorizing techniques as analog, digital, or hybrid analog/digital beamforming [23, 24]. Analog beamforming, utilizing less expensive phase shifters, is often favored in massive MIMO systems due to its cost-effectiveness. However, it may not match the accuracy and speed offered by digital beamforming, which processes signals using advanced algorithms. Digital beamforming, while capable of superior performance, can be complex and expensive, limiting its practicality in large-scale systems.

The emergence of hybrid analog/digital beamforming aims to strike a balance between cost and performance, particularly in massive MIMO scenarios. By combining elements of both analog and digital processing, hybrid beamforming can leverage the advantages of each approach. [22]

In addition to these classifications, extensive research has led to the development of numerous algorithms aimed at enhancing adaptive beamforming performance. These algorithms optimize various parameters, such as bandwidth, directivity, and signal-to-noise ratio to improve the overall effectiveness of beamforming systems.

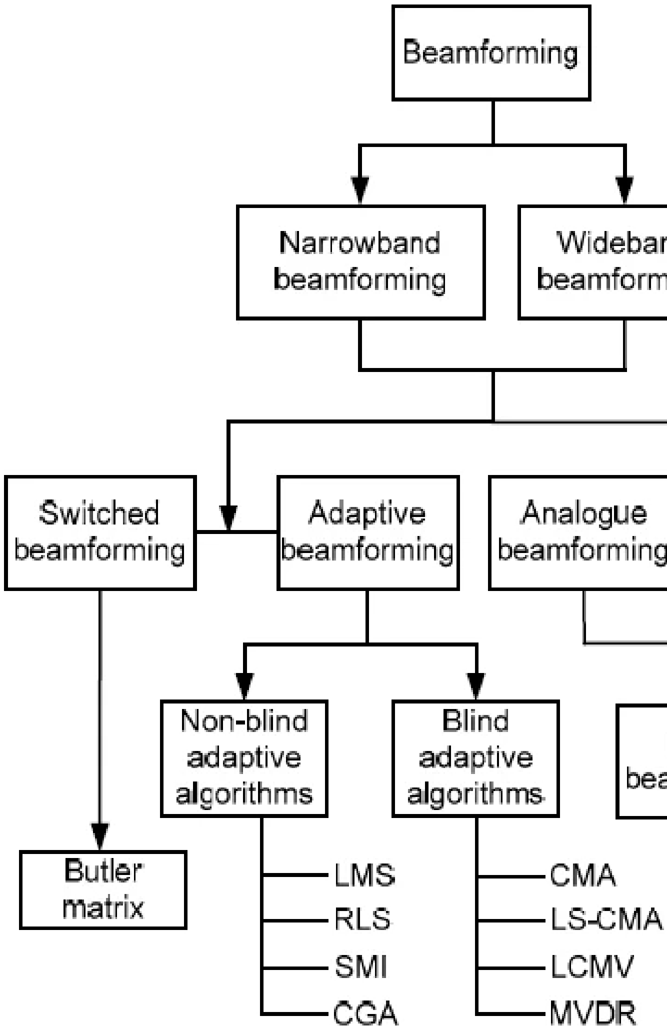

Figure 2. General Beamforming Classification [22]

Figure 2 depicts the structured overview of general beamforming techniques showcasing their classification, subcategories and algorithms used within each category.

2.3 Previous Studies

The previous studies done on beamforming examined various ways to categorize the techniques based on antenna configuration and signal processing methods. These studies have also evaluated their performance, particularly in the context of 5G and emerging technologies, focusing on factors like energy efficiency, signal quality, and data speeds. Researchers have compared different types of beamforming, such as analog, digital, and hybrid, to determine the most suitable approach for specific applications. Additionally, they have explored the practical implementation of beamforming through antenna design and hardware development. Recently, there has been growing interest in leveraging artificial intelligence to further enhance the performance of beamforming techniques.[21][22]

3. MULTI-ANTENNA TECHNOLOGY

MIMO (Multiple-Input Multiple-Output) is a wireless communication evolution technology which utilizes multiple antennas at both transmitter and receiver components to improve communication performance. This technique improves capacity and minimizes interference by sending and receiving multiple signals concurrently over the same frequency band. [17]

As below Figure 3 illustrates a MIMO system with multiple antennas at both ends, represented by Tx (transmitter) and Rx (receiver), while arrows indicate the communication signals exchanged between the antennas.

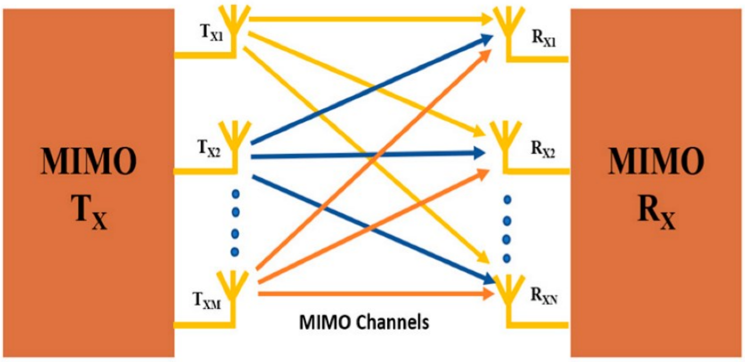

Figure 3. MIMO transmitter, receiver and channel [24]

With the increasing number of mobile applications consumers will need higher internet speeds on the move, whether walking or driving. To obtain these improved speeds, mobile devices are moving away from single antennas, as MIMO (Multiple Input Multiple Output) antennas are replacing them. MIMO allows mobile devices to serve improved services such as continuous signal, increased data rate, increased capacity and better use of the available bandwidth.

MIMO technology enhances signal quality by reducing fading, interference, and noise. Some of the most common techniques—SISO (single input, single output)—send a single stream of data from the transmitter to the receiver, but the nature of the antenna as a wide beam, as shown in Figure 4 causes more interference and fading at the edge of coverage area.

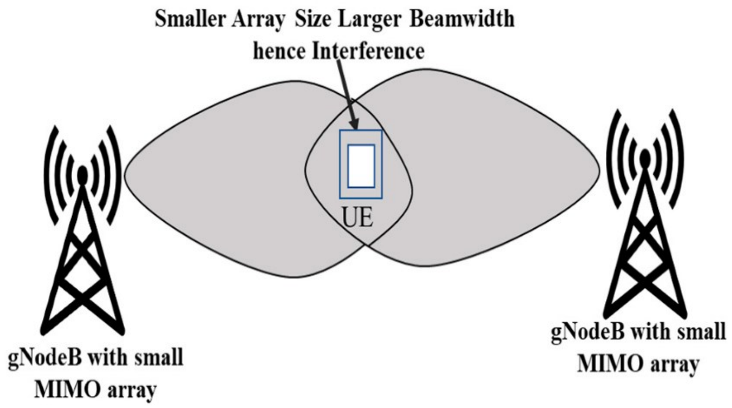

Figure 4. An illustration of Beamwidth using a Small Array Size [24]

While, in contrast, gNodeB (5G base station antenna) MIMO or massive MIMO generates a tighter beam, thereby enhancing coverage and reducing waste of interference at the coverage boundary, as shown in Figure 5.

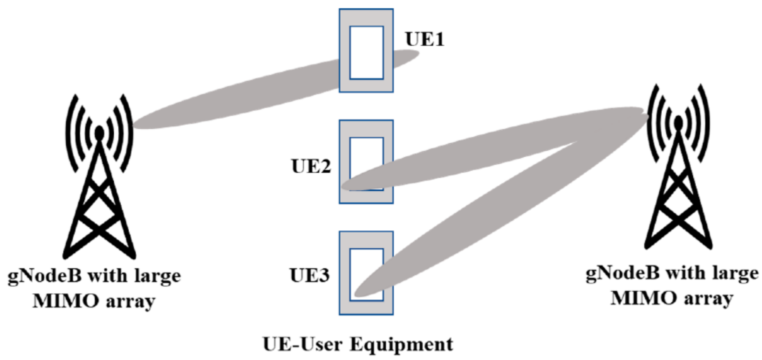

Figure 5. An illustration using Larger Array Size [24]

MIMO provides significant range and coverage expansion of wireless networks by improving link quality and reducing the chance of dropped packets. As shown in the next Figure 6, a larger MIMO array or massive MIMO system will create a more tightly focused beam.

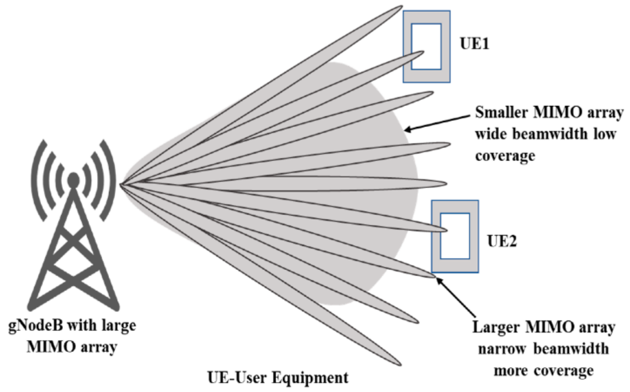

Figure 6. An illustration of Directional Beam [24]

This focused beam improves the coverage area and performance of the network, offering a significant advantage over traditional SISO (single input single output) systems, which have a broader, less directed signal. [24]

3.1 MU-MIMO

MU-MIMO (Multi-User, Multiple Input, Multiple Output) is a technology that increases the capacity of a network by allowing many antennas to manage multiple connections simultaneously for different devices. That’s especially helpful in environments where multiple users simultaneously are attempting to connect to the same wireless network. Unlike traditional MIMO that transmits one data stream to multiple antennas, MU-MIMO can deliver numerous data streams to different devices simultaneously. [37]

MU-MIMO builds upon the concept of beamforming, a technique that focuses signals in a specific direction to improve reception and minimize interference. This is feasible when the base station features sufficient antennas to handle a number of devices simultaneously, allowing each user a potent signal while minimizing interference for other users. [38]

Figure 15. shows a Multi-User Multiple-Input Multiple-Output (MU-MIMO) system, a core technology in today's mobile networks. MU-MIMO lets a base station shown (towers) talk to many user devices (phones) at the same time, all using the same frequency band. This works because both the base station and the user devices have multiple antennas. Applying these antennas wisely, the base station can send separate data streams to each user, greatly increasing the network's capacity and amplifying its efficiency. This is a significant improvement over earlier Single-User MIMO (SU-MIMO) systems, where the base station could communicate with only one user at a time on a particular frequency. [36] [38]

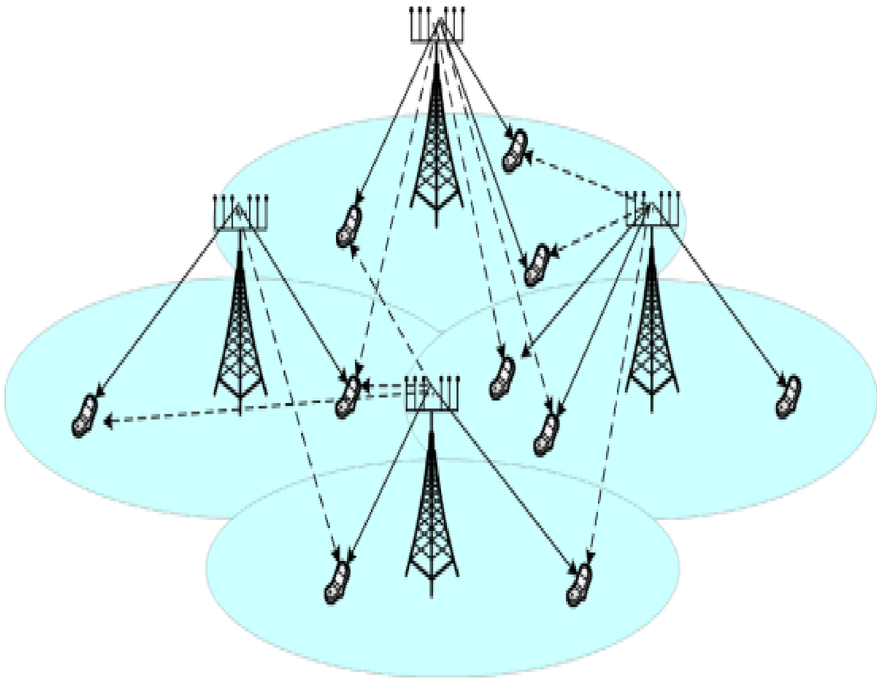

Figure 6.1. Illustration of Multiuser MIMO [36]

The blue circles in the figure 15 show the areas covered by different base stations. Inside each of these areas, the base station can talk to many users at once, thanks to MU-MIMO. This is shown by the solid lines connecting the base station to multiple phones. The dotted lines show where there might be interference between users in different areas something that MU-MIMO is designed to handle. By carefully managing the signals from each antenna, the base station minimizes this interference and makes sure everyone has a clear connection. [37]

MU-MIMO has a big impact on how mobile networks work. By letting many users connect at the same time, it boosts network capacity, uses frequencies more efficiently, and gives users a better experience. This means faster speeds and less lag, especially in crowded areas. This technology is vital for meeting the growing demand for mobile data and making new things possible, like streaming HD videos, playing online games, and connecting all sorts of devices through the Internet of Things. As mobile networks keep getting better, MU-MIMO will become even more important for delivering fast, reliable, and efficient wireless communication. [39]

3.2 Beamforming

Beamforming is a method used to amplify the power of a signal. It means directing the signal toward where the signal is stronger. This is done by shifting the phase of the signal and amplitude in that direction. It is only possible to merge all the elements of the signal in this way to generate the beam with a maximum signal in that direction. It amplifies the strength of the signal. [17]

Beamforming has now emerged as the driving force behind mobile cellular and radar systems. The main benefit of is the multiple antennas that can be utilized to improve the Signal-to-Noise Ratio (SNR) at the receiver and reduce co-channel interference (CCI) at the multiuser (MU) level. By carefully controlling the magnitude and phase of the signal coming from individual antennas a method known as Transmit Beamforming, the combined signal offers the greatest possible strength to the receiver. This nearly doubles coverage, especially on the cellular periphery.

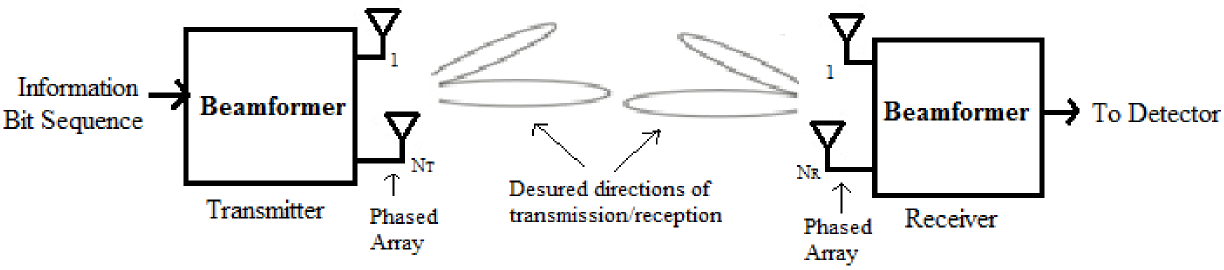

Figure 7. Basic Beamforming Principle [25]

Furthermore, Receive Beamforming allows for the accurate detection of the wavefront's direction of arrival (DoA) and the removal of unwanted signals by creating a beam pattern null in the direction of interference. The basic concept of beamforming is illustrated in Figure 7, where beamformers are implemented at both the transmitting and receiving ends. [25]

3.3 Beam Methodology

The image depicts the radiation pattern of an antenna, illustrating how it directs electromagnetic waves. The main part called the Main Lobe is where the antenna directs most of its energy. The width of this main part is shown by the HPBW (Half-Power Beamwidth), which tells us the angle where the power is at least half of its highest value. A narrower HPBW means the beam is more focused. Around the main lob, there are smaller parts called Side Lobes, which are areas where unwanted energy is sent out. These side lobes can cause interference and reduce the antenna’s efficiency.

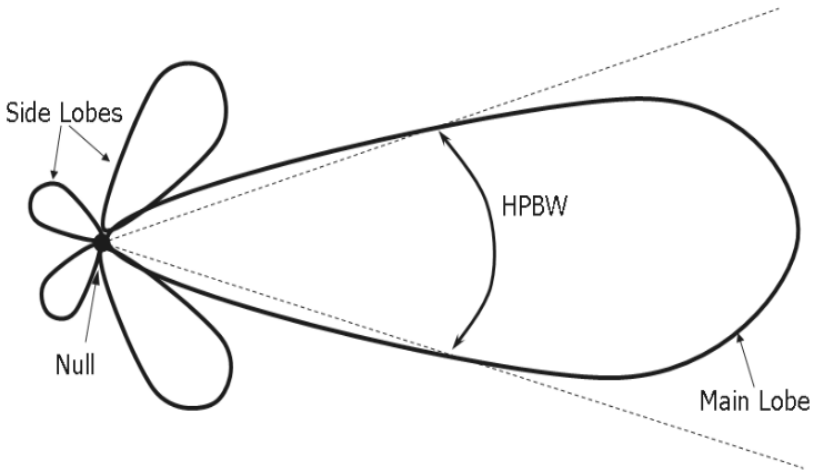

Figure 8. Antenna Beam [28]

The figure 8 also highlights a null, which is a direction where the antenna sends out little or no energy. This can be useful for blocking signals from unwanted directions. Understanding these parts helps in designing antennas for better performance in areas like telecommunications, broadcasting, and radar technology. Overall, the diagram as a whole provides a strong understanding of the antenna's operation and directionality.

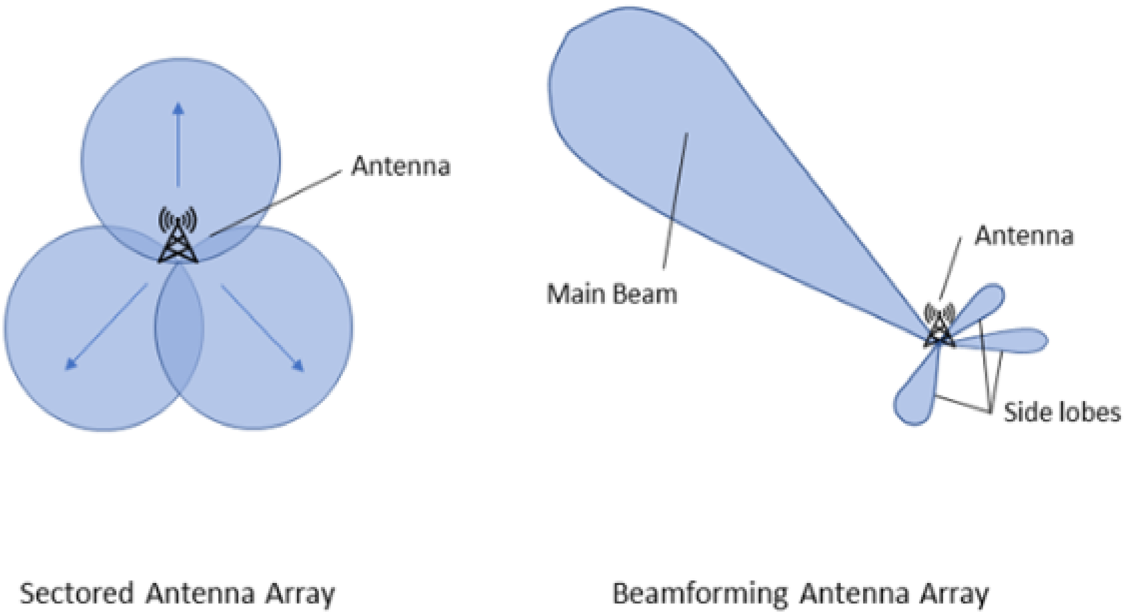

Figure 9. Sectored Antenna Array Vs Beamforming Antenna Array [29]

The Figure 9 shows two different antenna configuration methods that sectored antenna arrays and beamforming antenna arrays. In sectored antenna arrays, the coverage area is divided into several sectors, wherein each antenna is allocated to a certain sector. This arrangement strengthens the signal and reduces interference in each sector, making it perfect for applications that need uniform coverage in a wide area. Figure 9 also shows that beamforming antenna arrays use several antennas to create a highly focused steerable beam. The direction of this beam can also be adjusted electronically, which allows for dynamic and target-oriented signal transmission. This becomes important in the following situations since the transmission receiver is moving thus allows good quality of the signal and maximizes the range but minimizes the interference. [29]

Figure 9 also provides the overview that sectored arrays provide fixed segmented coverage whereas beamforming arrays deliver adaptable concentrated coverage with the added advantage of beam steering. Both methods are essential in optimizing wireless communication systems by customizing signal transmission and reception to meet specific needs. [29]

3.4 Deployment of Different Beams in Network

3.4.1 Analog Beamforming

Analog beamforming in MIMO systems is performed by means of phase shifters, which modify the signal phase at each antenna element. These phase shifters dictate the phase of the beam as it goes out, producing regions of constructive and destructive interference to steer the signal toward the desired receiver. Analog beamforming is an approach that simplifies the system structure by using one RF chain for each antenna element thus minimizing the design complexity and hardware requirements.

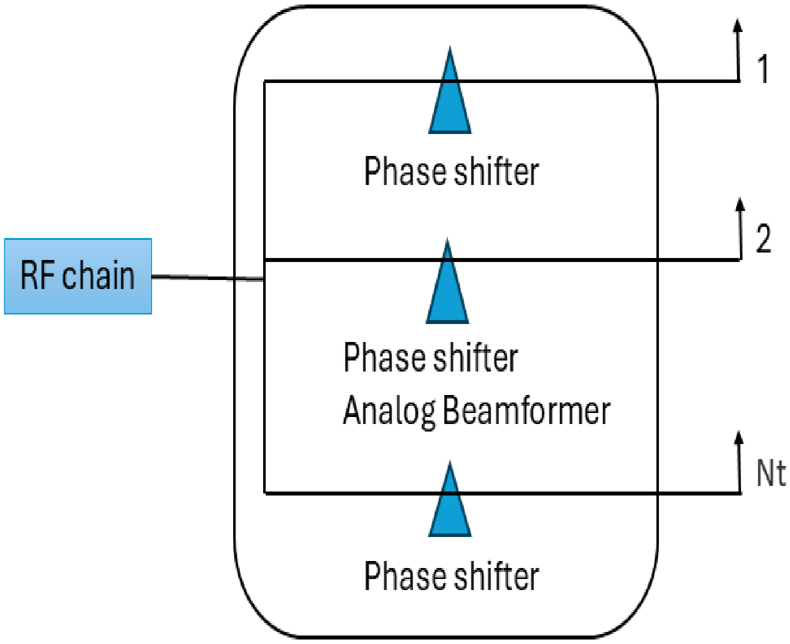

Figure 10. Analog Beamforming Architecture [26]

In analog beamforming, figure 10 illustrates that the beam direction is generally fixed once the system is designed, making it less efficient for MIMO systems where channel conditions and user locations change rapidly. Despite this limitation, analog beamforming remains a cost-effective and simple solution for scenarios with less demanding beam steering needs, where the primary objective is to enhance signal strength from a relatively stable direction and reduce interference.

3.4.2 Digital Beamforming

Digital beamforming in MIMO systems is a technique that manipulates signals digitally at the baseband. Figure 11 illustrates every antenna element has its own dedicated RF chain, consisting of components like mixers, filters, and data converters. The signals from each antenna undergo complex algorithms to create multiple beams that can be directed towards different users or devices. This approach is more adaptable and precise than analog beamforming, allowing real-time adjustments to the beam's direction and shape based on the current channel conditions and user locations. It also allows for the simultaneous creation of multiple independent beams, enabling multi-user MIMO functionality. However, the increased number of RF chains and the more complex design of digital beamforming make it significantly more costly and power-hungry than its analog counterpart.

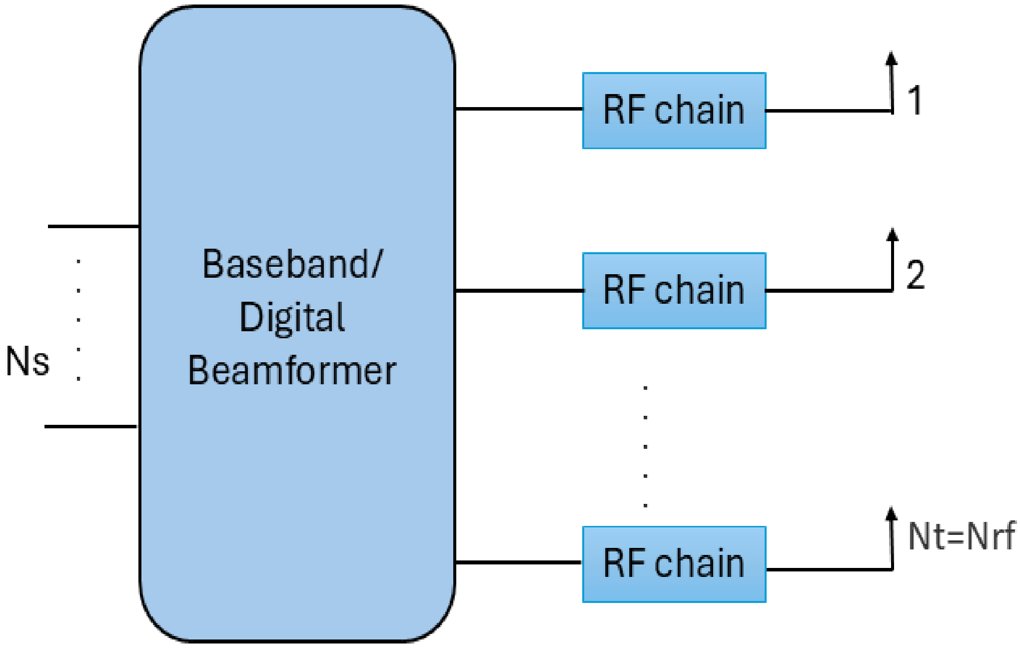

Figure 11. Digital Beamforming Architecture [26]

3.4.3 Hybrid Beamforming

In MIMO systems, hybrid beamforming combines the benefits of digital and analog beamforming. Hybrid beamforming creates a balance by using both techniques, although analog beamforming is more straightforward and economical. It extends beyond the beam space associated with many antenna elements coupled to a single RF chain by using analog phase shifters to form beam pairs. This method offers additional flexibility while maintaining the basic characteristics of analog beamforming.

The Figure 12 illustrates that utilizing digital processing at the baseband level enhances the flexibility and precision of beam pointing and shaping. The main function of the architecture is to minimize the number of RF chains needed, with each RF chain connected to antenna elements through analog phase shifters. Although this approach simplifies and reduces power consumption relative to digital beamforming, it still provides a favorable balance of flexibility and adaptability. Hence due to its cost-effectiveness, performance benefits, and reduced complexity, hybrid beamforming continues to be a prevalent choice in MIMO systems.

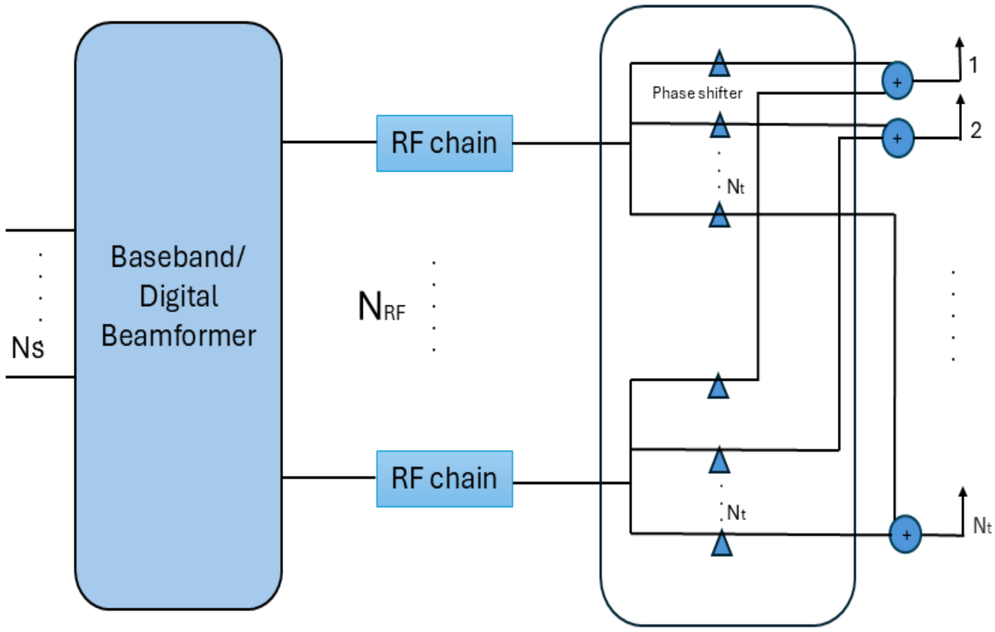

Figure 12.Full connected Hybrid Beamforming Architecture [26]

3.5 Functional Beam Types in 5G NR

In modern wireless communication systems, especially with the advent of 5G technology, efficient signal transmission and reception are essential to achieving high data rates, low latency and reliable connectivity. Therefore, modern networks utilize two types of beams Synchronization Signal Block (SSB) beams and Sounding Reference Signal (SRS) beams.

The deployment of Synchronization Signal Block (SSB) and Sounding Reference Signal (SRS) beams is essential in 5G communication systems. SSB is key for tasks such as initial cell search, synchronization, and beamforming, whereas SRS beams are employed for uplink channel sounding, enabling the network to assess uplink channel quality and fine-tune beamforming and scheduling decisions. Combined, SSB and SRS beams are critical in enhancing connectivity and overall performance in 5G networks. [31][32]

3.5.1 Synchronization Signal Block (SSB)

The Figure 13 presents the time-frequency layout of a Synchronization Signal Block (SSB) within a 5G New Radio (NR) system. The diagram is organized into a grid, where the horizontal axis represents Orthogonal Frequency Division Multiplexing (OFDM) symbols, numbered from 0 to 3, and the vertical axis shows subcarriers, with a total of 240 spread across 20 resource blocks (RBs). This structure is vital for initial network access, enabling cell search and synchronization, allowing user equipment (UE) to establish communication with the network. [31]

The Figure 13 depicts that the Primary Synchronization Signal (PSS) shows in blue occupies 127 centrally located subcarriers during the first OFDM symbol (symbol 0). Similarly, the Secondary Synchronization Signal (SSS), shown in green, also spans 127 subcarriers but is transmitted during the third OFDM symbol (symbol 2). These synchronization signals are critical for the UE to achieve timing and frequency alignment with the base station. [30]

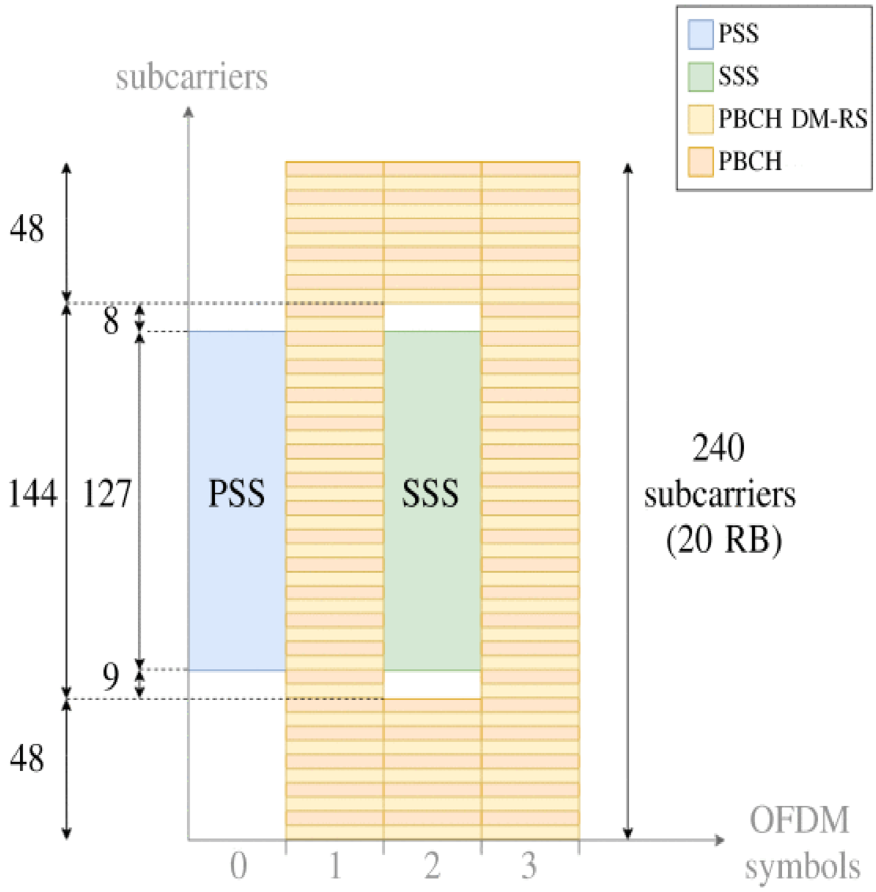

Figure 13. SSB Beam Structure [30]

The Figure 13 depicts the SSB beam structure that describes the Physical Broadcast Channel Demodulation Reference Signal (PBCH DM-RS) and the Physical Broadcast Channel (PBCH), both marked in yellow. These signals are distributed across all four OFDM symbols, using the subcarriers not occupied by the PSS and SSS. The PBCH and Physical Broadcast Channel Demodulation Reference Signal (PBCH DM-RS) are essential for conveying system information to the UE, helping it understand the network configuration and proceed with establishing a connection. This figure 13 structure provides a clear representation of how time-frequency resources are allocated within an SSB, a key element of 5G NR communication. [30]

3.5.2 Sounding Reference Signal (SRS)

The Sounding Reference Signal (SRS) is an uplink reference signal transmitted by the User Equipment (UE) to the eNodeB (base station) for assessing uplink channel quality across a wide bandwidth. This data helps the base station make informed decisions about resource allocation, ensuring optimal performance by focusing on areas with better signal quality. [34]

SRS facilitates various functionalities, including efficient spatial multiplexing, precise uplink transmission timing, and enhanced downlink precoding in multi-user MIMO setups. It essentially enables the network to adapt to changing channel conditions and optimize the use of available resources. In 5G NR, SRS takes the form of an OFDM signal, known to both the user device and the base station. This shared understanding allows for accurate channel estimation and synchronization, leading to improved communication reliability and efficiency. As a whole SRS enables the network to proactively manage resources and deliver a superior user experience by adapting to the ever-changing wireless environment. [35]

The Figure 14 provides a detailed representation of how Sounding Reference Signal (SRS) resources are structured and utilized in a 5G NR (New Radio) system. The resource grid depicted in the image is divided along two axes. The horizontal axis represents time specifically within a single slot while the vertical axis corresponds to frequency resources measured in resource blocks (RBs). [33] The blue-colored blocks indicate the SRS resources available for potential transmission indicate how these resources are distributed across both time and frequency. While In contrast the red-colored blocks illustrate where the actual SRS transmission takes place within these available resources. The placement of these transmissions within the grid highlights how the network selectively uses a subset of the available resources for the actual SRS transmission, depending on the specific configuration and requirements. [33]

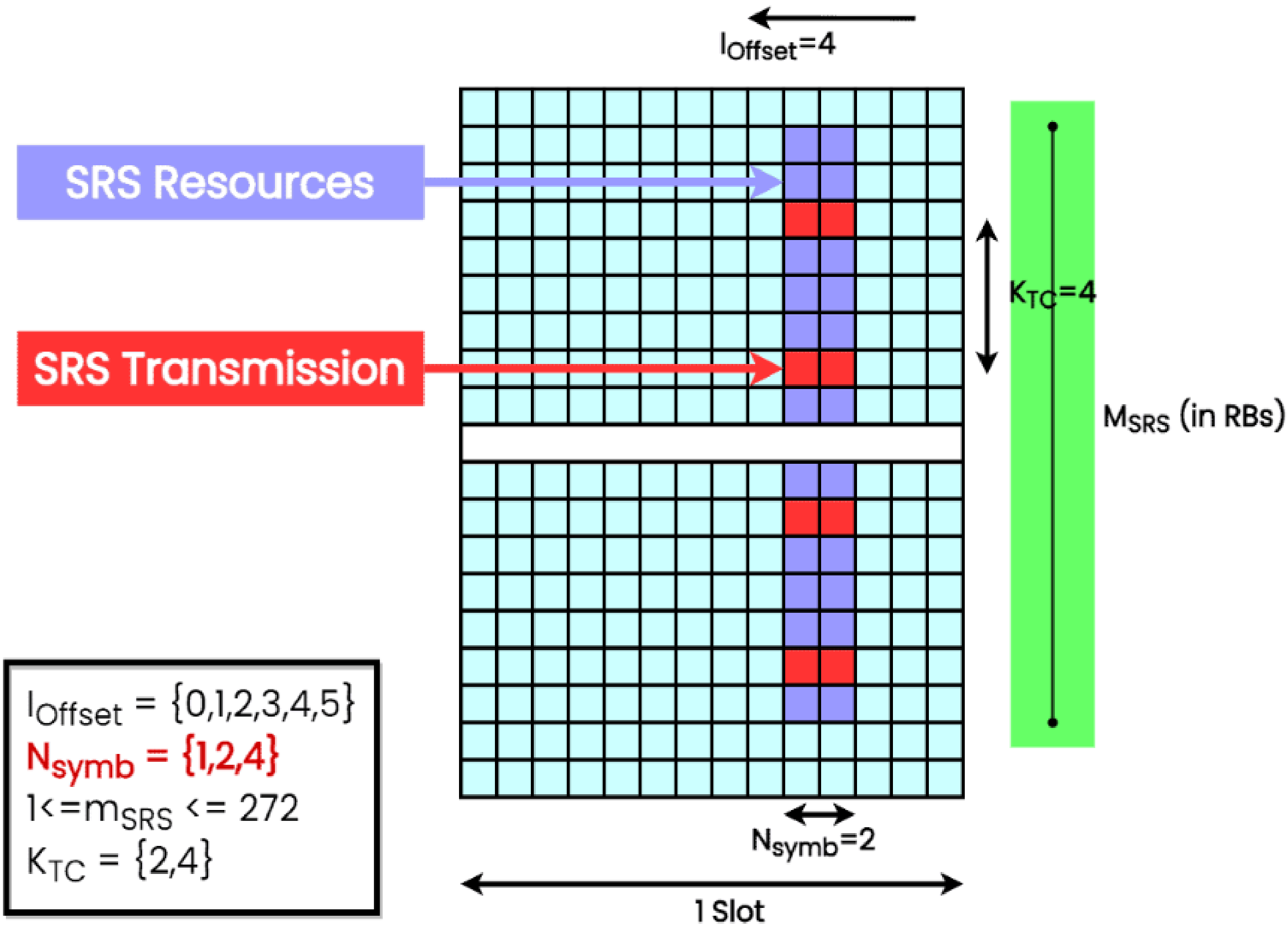

Figure 14. Sounding Reference Signal Structure [33]

The Figure 14 also illustrates the key parameters that define the sounding refrence signal SRS allocation and transmission. l_offset specifies the offset in symbols within the slot where the SRS transmission begins with possible values ranging from 0 to 5. The N_symb parameter indicates the number of symbols within a slot that are dedicated to SRS transmission, which can vary between 1, 2 or 4 symbols. Additionally, K_TC represents the comb size determining the spacing of SRS transmission across the frequency domain, with possible values of 2 or 4. M_SRS denotes the number of resource blocks allocated for SRS transmission, represented by the green bar on the side of Figure 14 showing how frequency resources are allocated for this purpose. [33]

This kind of allocation and transmission structure is crucial for the efficient operation of the uplink channel in 5G networks. By transmitting SRS, the user equipment (UE) sends known signals to the network, allowing it to measure the uplink channel's quality. This information is vital for optimizing communication parameters, such as power control, frequency allocation, and beamforming, ensuring reliable and efficient communication between the network and the UE. The SRS setup thus plays a key role in enabling the advanced features of 5G, such as massive MIMO and dynamic beamforming, which rely on accurate and timely channel state information.

3.6 Impact of Beamforming on Network performance

Beamforming has become essential technology for improving wireless network performance, especially in modern cellular and Wi-Fi systems. It works by directing signals towards specific receivers, offering several important benefits. First, beamforming boosts signal strength and quality at the receiving end, which leads to faster data speeds and better overall network performance. It is particularly effective in situations where there are obstacles or interference as it helps increase average throughput. Second, beamforming helps reduce interference. By focusing the signal energy on the intended user, it minimizes disruption to other users which in turn enhances the network's efficiency. This is especially useful in crowded environments where many users are sharing the same resources. [40]

3.6.1 Beam Utilization

In communication network counters per beam are important for improving beamforming in mobile networks. These counters track the number of measurements the system takes to find the best direction for each signal. This is especially useful in environments where users are moving around, and network conditions are constantly changing. By using these counters, the system can adjust to keep the signal strong and steady, even as conditions vary.

While increasing the number of counters can lead to more accurate beam alignment and improved signal strength, it also introduces additional processing overhead and resource consumption. Therefore, finding the right balance between accuracy and efficiency is essential. The number of counters directly impacts key network performance factors, such as data rates, coverage, and overall capacity. With sufficient study counters, beamforming can boost data speeds, extend coverage in challenging environments, and enhance network capacity by reducing interference, allowing more users to connect simultaneously without compromising performance. [41]

3.6.2 User Analysis

Beamforming works best when the network understands important details about users, such as where they are, how they move, the quality of their connection, and how many users are nearby. By studying these factors, beamforming can be adjusted to focus signals better, improve coverage, and reduce interference. This is especially useful in busy or changing environments where signals might not always be strong. By customizing how beams are directed based on users' needs and the current network conditions, the system can work more efficiently and avoid interference.

Beamforming has a big impact on network performance, affecting things like data speeds, coverage area, network capacity, and delays. It helps by directing signals to users more precisely, reducing traffic, and improving both coverage and reliability. However, as factors like user movement, varying signal strength, and crowding become more complex, beamforming needs smarter technology and quick adjustments to keep up. We must know what the user needs first to make the network perform well and ensure users get a fast and reliable connection.

3.6.3 Uplink Pathloss

Uplink path loss occurs when a signal weakens as it travels from a user's device to the base station or access point. This loss is primarily due to the natural attenuation of radio waves as they spread over distance and encounter obstacles like buildings, trees, or atmospheric conditions. Even though beamforming directs signals towards specific users to improve quality, uplink path loss still happens due to factors such as the user's location, mobility, and interference from other devices or environmental factors. The further the user is from the base station or the more barriers in the environment, the greater the path loss and the weaker the signal. [42]

This signal degradation can have a noticeable impact on network performance, especially when it leads to a lower signal-to-noise ratio. A reduced SNR results in slower data speeds, less reliable connections, and higher latency. In severe cases, it may even cause dropped calls or poor-quality communication [43].

To compensate for higher uplink path loss, base stations may need to increase their transmission power, but this can create interference for other users, reducing overall network efficiency. To overcome these challenges, we may implement adaptive beamforming, power control, and interference management techniques that are employed to enhance network performance, particularly in areas with difficult signal conditions. [44]

3.6.4 Vector Level Analysis

In wireless networks, vector-level analysis is an approach used to better analyze and optimize signal behavior, particularly in beamforming and MIMO systems. [45] In order to record and examine how signals interact with their surroundings, including the effects of interference, fading, and noise it entails expressing signals as vectors in a multi-dimensional space. Compared to traditional techniques this approach offers a more realistic view of signal behavior enabling the creation of systems that can more efficiently respond to changing network conditions. [42]

The vector-level analysis has several advantages, but one of them is simplifying the complex interactions that take place on wireless channels. Both multipath propagation and Doppler shift create random variations in signal amplitude, phase, and direction. Vector analysis mathematically describes such effects, enabling us to evaluate their influence and adapt transmission parameters as necessary. This is helpful in systems where many antennas or complex signal paths must be carefully adjusted to mitigate interference and increase data overhead, as is the case with MIMO and beamforming, to make a more reliable network overall. [46]

4. METHODOLOGY

This chapter explains the methodology of this thesis and approaches and strategies that were applied to perform the research in the mobile network. Research methodology comprises two sections as illustrated in figure 16, each concentrating on a significant vine of optimizing a live mobile network.

The Initial phase 1 as depicted in the light blue block mainly focus on gaining knowledge on the existing network environment. In this phase, we conducted a feasibility analysis to assess whether we could achieve the project's goals given the limitations of the live network. Furthermore, in an attempt to understand prior research on the matter, a detailed literature review was also needed which guided the methods and techniques in the next stage.

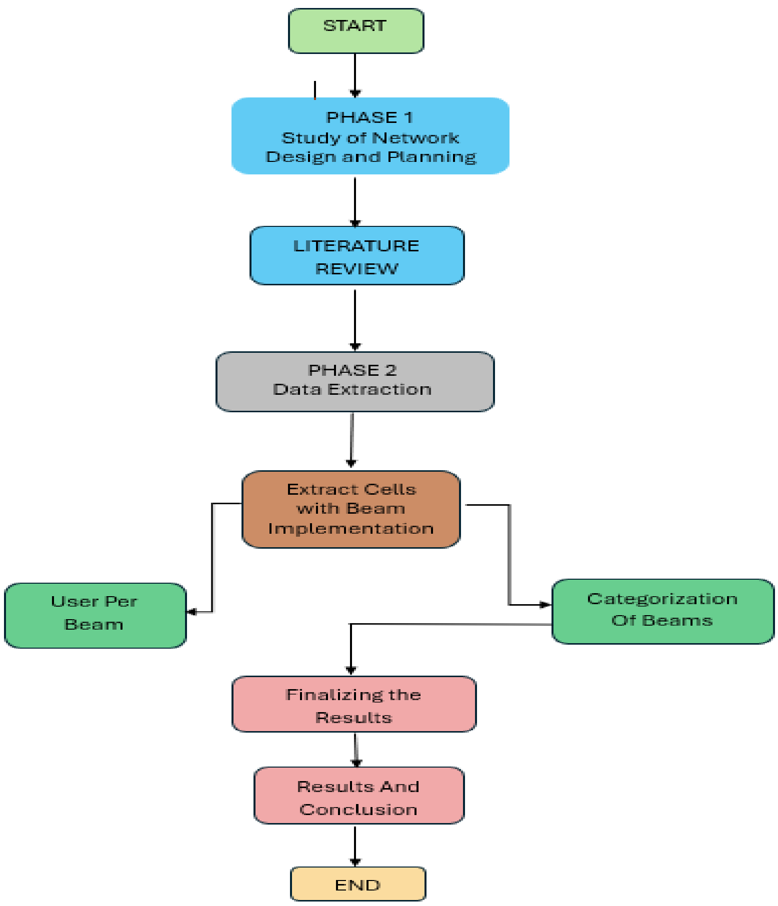

Figure 15. Research Methodology

The second phase concentrates more in extracting data and analysis from the live network. It required a meticulous collection of network data, which was an arduous and time-intensive exercise. Upon extracting the dataset, filtering was performed to determine the cells corresponding to areas where each of the required beams has already been installed. Based on their potential for network performance improvement, these beamforming configurations were classified.

The primary goal of this research analysis was to identify beamforming strategies that would improve the network's efficiency and user experience. While Increased throughput focused on boosting data speeds for users, while reduced handover issues aimed to minimize disruptions as users moved between cell towers. Alote of beam categorization has been done with different thresholds and parameters to make network efficient.

4.1 Methodology: First Phase

This subsection explains the first component of the methodology. It all started with understanding the live network design, planning implementation, and defining the primary objectives. With this initial step outlined, you can begin to understand how this will lay the groundwork for the entire analysis, making sure the control/network exists for the goals of the research1. Once this consensus was established, it was then necessary to conduct an in-depth literature and research review to explore existing research in the area. This literature review compiles research articles, industry reports, and concepts from best practices covering the latest practices in network optimization.

This review allows me to explore for proven methods, emerging trends, and common challenges from extensive literature on optimizing potential, particularly in mobile networks and most importantly beamforming technology stage of work. This literature review not only informs the approach taken in the research but also provides a framework for understanding the context in which the research is situated and how it contributes to ongoing developments in the mobile network field.

Another significant part was the different beamforming techniques, that how beamforming works or implement is working in the mobile network and what the principal goal to used them directed to the specific direction or user to them.

4.2 Methodology: Second Phase

During secondary phase it retrieves relevant data from the live mobile network, focusing on specific cells where the target beamforming technology has been implemented. This stage is crucial as it offers the essential raw data to evaluate how well the network performs. This process of data collection of specific cells from the live network is quite time taking. All of this is done to collect the data, which is then used to analyze the user load on every beam, which tells how many users are connected to each beam and what impact that load can make on network performance.

After this, the data undergoes a categorization process where beams are grouped according to shared characteristics, such as user per beam, signal strength or the direction in which signal is transmitted. This categorization process provides a more detailed understanding of how the network behaves and reveals patterns that might not be immediately obvious.

The objective of this analysis and categorization is to identify areas where the network's efficiency and performance can be improved by categorizing the beams based on user density. This approach allows for the targeted implementation of beamforming technology in cells that do not yet have it. By evaluating how beams perform in relation to factors such as user distribution, interference, and signal quality, it becomes possible to identify specific areas that require optimization. This may involve adjusting beam configurations to better support users in high density areas minimizing interference in overlapping beam zones or enhancing signal strength in regions with weak coverage. A comprehensive analysis of the data provides the foundation for developing strategies that fine-tune the network ensuring it operates at peak efficiency and delivers an improved user experience.

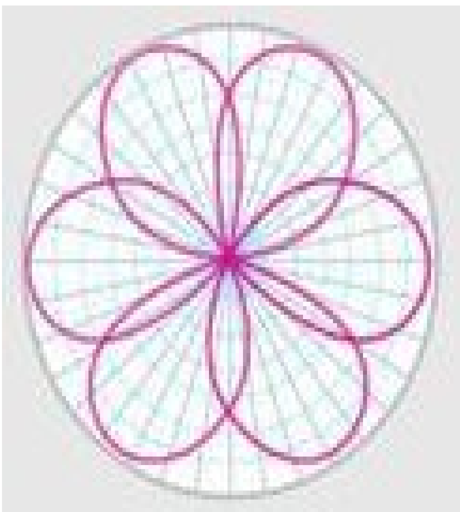

Figure 16. Beams Representation in Cell [47]

The final phase brings together the results from data analysis and drawing the conclusions based on the thresholds that we have been selected to categorize the beams in hundreds of cells.

4.3 Data Collection

In telecommunication industry data collection is very important to manage and improve the network performance. As networks become ever more complex with advances such as 5G and the demands of more discerning subscribers, operators need accurate real-time data to identify performance problems, troubleshoot network issues and provide seamless user experience. The above-mentioned problems need structured data collection process which enables Network operations analysis of network configurations, performance statistics, fault logs and user activities, which are very essential for diagnosing issues improving service quality and making informed decisions. Without this organized approach gauging the health of the network, identifying potential problems early on and enacting timely solutions becomes challenging. I use Network Performance Analytics Suite (NPAS) for my research problem.

4.3.1 NPAS Tool

The Network Performance Analytics Suite (NPAS) is a cutting-edge, fully cloud-native tool developed by Nokia to optimize network performance for modern telecom environments. It is specifically designed to enhance Network Performance Optimization (NPO) services by offering advanced capabilities such as data collection, performance monitoring, root cause detection, and data-driven insights. NPAS enables efficient analysis of subscriber and device performance, as well as the detection and management of interference issues.

NPAS built with a modular architecture, it separates data connectivity from processing, allowing it to adapt to evolving industry trends and specific use cases. It integrates multiple data sources, including configuration management (CM), performance management (PM), fault management (FM), and L3 logs, and supports data enrichment for improved correlation and causality analysis. The tool is highly scalable and deployable on Nokia's NESC Cloud, public cloud platforms, or private environments, utilizing modern technologies like Kubernetes and big-data frameworks for maximum efficiency.

NPAS ensures streamlined access to enriched datasets, making it an essential solution for improving user and device experience while addressing complex telecom challenges.

4.3.2 NPAS User Cases

The Network Performance Analytics Suite (NPAS) offers a comprehensive range of use cases that address critical challenges in the telecom sector. One of its key applications is subscriber complaint analysis, where NPAS identifies issues like low throughput, poor coverage, or failed handovers by correlating data from various sources. This enables telecom operators to resolve problems efficiently, enhancing customer satisfaction and service reliability. Another essential use case is interference detection and management, where NPAS analyzes uplink interference in LTE and 5G networks using configuration management (CM) and performance management (PM) data, ensuring optimal network performance.

NPAS also supports user experience analytics by assessing the impact of network changes, such as new software deployments or the introduction of 5G layers, on overall user satisfaction. Device performance analysis is another critical function, enabling the identification of issues tied to specific user equipment (UE) models or software versions. This allows operators to collaborate with device manufacturers to address hardware or software concerns promptly.

The network performance analysis suite excels in automated data collection and integration, gathering information from CM, PM, fault management (FM), and L3 logs. This data is preprocessed, enriched, and made accessible for analytics tasks or integration with other tools via APIs. Historical data analysis is also a valuable feature, supporting retrospective troubleshooting and long-term trend assessment. NPAS's modular architecture allows seamless integration with external tools, enhancing network management capabilities and enabling targeted network optimization, such as improving coverage, increasing throughput, and reducing latency.

Lastly, NPAS facilitates efficient resource allocation by identifying network bottlenecks, supports granular troubleshooting at the UE terminal level, and enables proactive measures to maintain service quality through enhanced subscriber impact analysis.

4.4 Data Collection Process

The data collection process for the Network Performance Analytics Suite (NPAS) involves multiple phases, ensuring seamless integration and enrichment of network performance data. The first step begins with diverse data sources, which include Nokia's NetAct, DCAP, custom or multivendor data, and site/antenna-specific data. These sources provide critical configuration, performance, and fault data essential for network optimization.

The raw data from these sources is aggregated and processed through DataHub, which is the connectivity layer of the system as depicted is figure 18. DataHub serves as the central pipeline, standardizing and transferring data from the sources to the input layer. The inputs include a variety of data types such as Configuration Management (CM), Performance Management (PM), Fault Management (FM), Layer 3 (L3) logs, and external data files like excel documents. This input diversity ensures a holistic view of network performance, allowing for detailed analysis and troubleshooting. We go for the excel document to get the data.

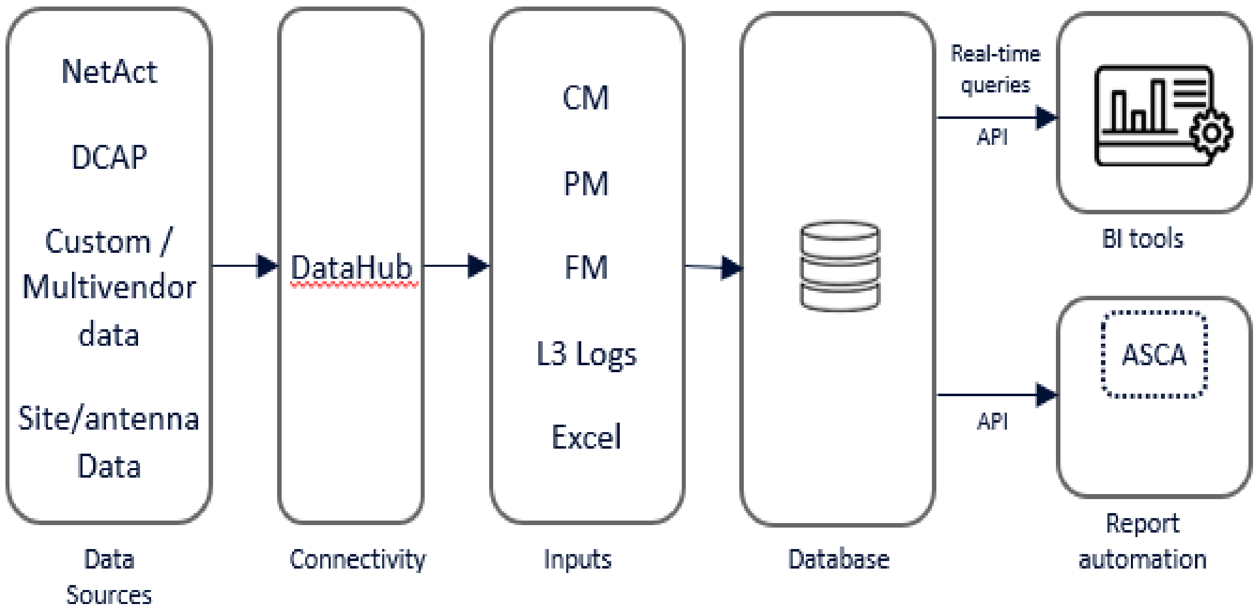

Figure 17. Data Acquisition Process

Figure 18 depicts, once the input data is collected it is stored in a centralized database, which acts as a repository for historical and real-time information. The database is designed to support efficient queries, data enrichment, and further analysis. Through secure APIs, the stored data is accessible to advanced Business Intelligence (BI) tools for generating real-time queries and visualizing insights. These BI tools enable us to explore network performance metrics interactively, facilitating informed decision-making.

While at the same time the database is integrated with ASCA (Automated System for Customer Analytics), which enables report automation. This automation streamlines report generation, allowing for consistent and accurate analysis of key performance indicators (KPIs) without requiring manual interaction. This is the whole process of getting network data.

5. Results

This thesis has been completed in collaboration with the Nokia NPO Network Design and Planning team. During this process, I learned many new concepts and gained valuable knowledge. I am proud to have contributed to this field and hope that the results of my work will help improve the deployment of new cells and the overall performance of the network.

The results were collected after developing strategies and setting thresholds based on detailed research. Once the data was gathered from the live network the first step was to organize it in a clear format. This made it easier to categorize the data and define thresholds for the beams implemented in the live environment, which was an important part of this thesis.

Efficient beam management is important for optimizing cellular network performance, as it maintains a connection to all users and optimizes the user distribution over all the network elements. The analysis in the thesis are based on a live network where six different beams serve approximately 1512 cells. Based on the coverage of cells that a given beam can connect to a cell tower, we categorized the beams, and this will allow us to understand the individual contributions of beams and determine where improvement may be possible. This analysis was limited to beams covering greater than 20 and less than equal 40 percent of the total cell coverage.

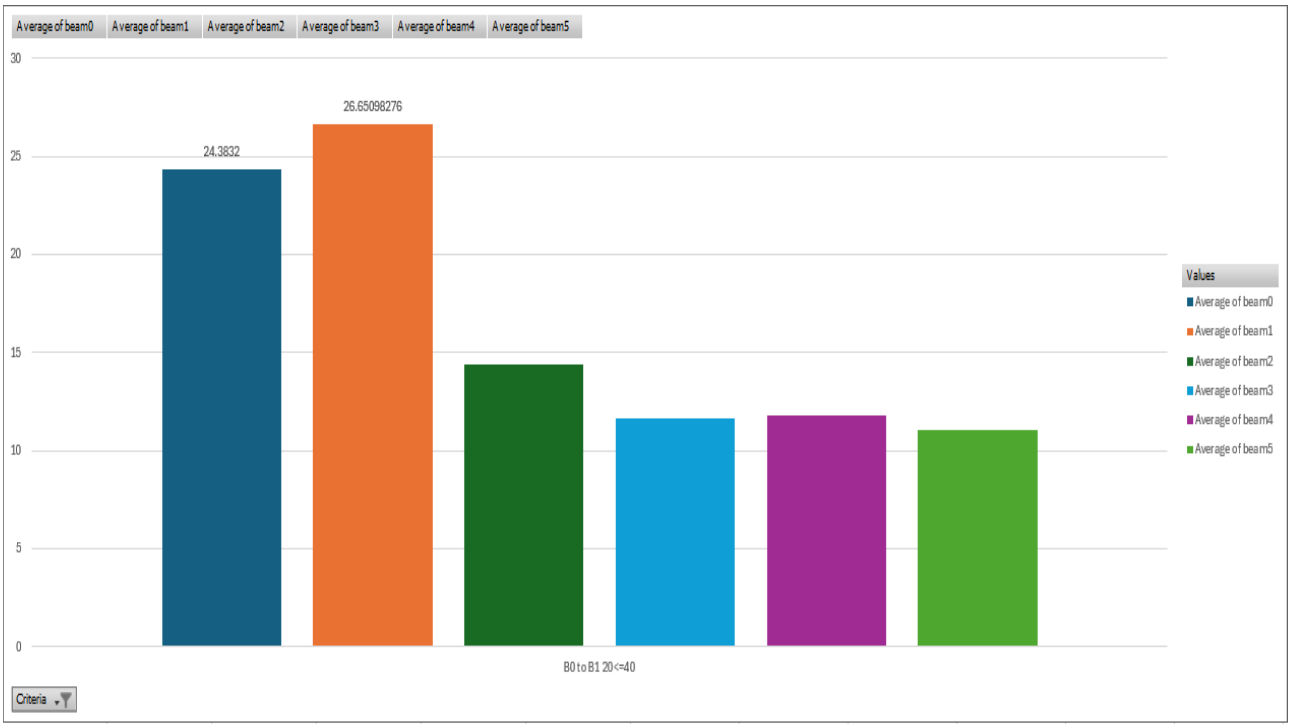

Figure 18. Beam Index vs Contribution

Figure 19 shows the notable variations in beam utilization within the selected threshold. Beam 0 and beam 1 emerged as the highest performers averaging approximately 24 and 27 percent of cells coverage which means that more than half of the cell capacity holds only these two beams respectively. This suggests their placement in high-traffic areas or broader configuration parameters.

On the other hand, it can be seen in figure 19 beam 5 exhibited the lowest percentage of cells coverage indicating potential for optimization through adjustments such as antenna tilt or directional modifications. Beams 2, 3 and 4 show comparable performance averaging around 10-12 percent of cells coverage each implying similar user demands or coverage configurations in their respective locations.

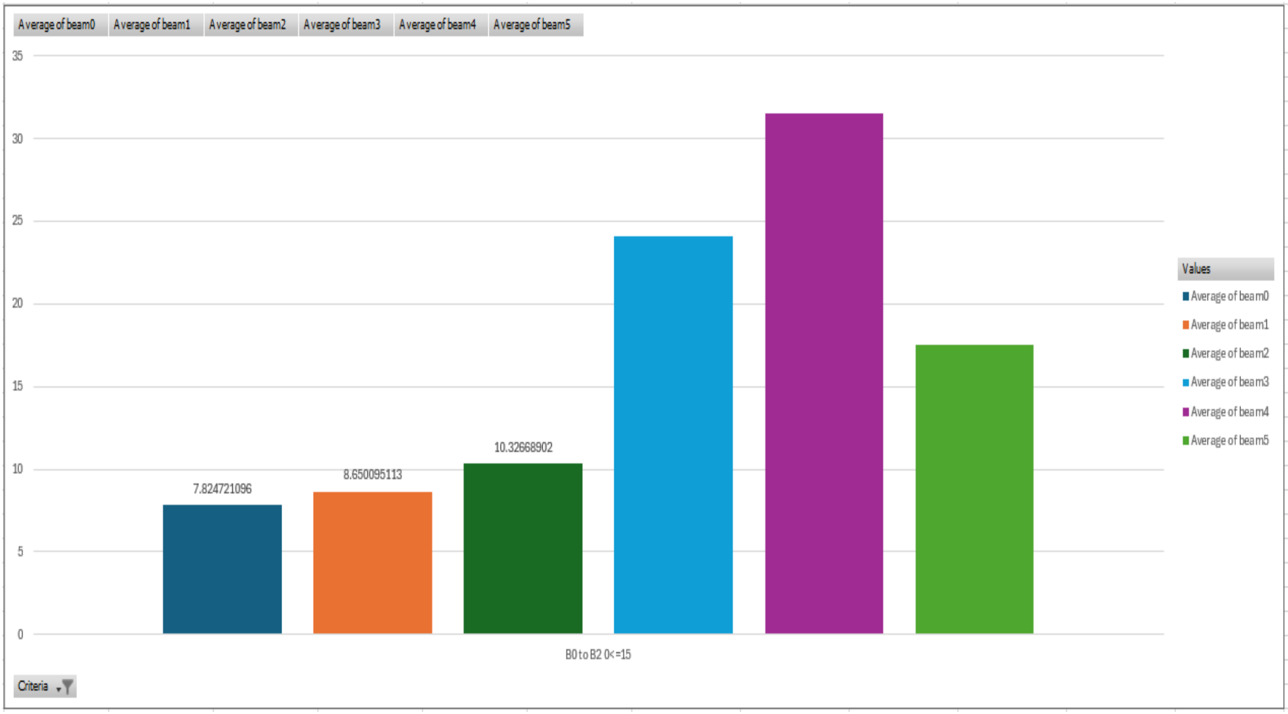

Figure 19. Beam Contribution Distribution

The Figure 20 depicts the average values for six beams (beam0 to beam5) under the criteria of "B0 to B2 0 ≤ 15" in multiple cells of mobile network. The first three beams from the left to right beam0, beam1 and beam2 show relatively very low contributions to the whole cell with average values of approximately 7.82, 8.65 and 10.33 percent respectively. While on the other hand beam4 that is purple in color stands out as the most influential with the highest average value of around 31 with the other two beam3 and beam5 that are having similar behavior and indicating a moderate impact. This distribution reveals that while the initial 3 beams contribute less than the later beams, particularly the last 3 beams have a significantly greater impact on the network.

This can be perceived from the figure 20 by efficient use of these beams can be a critical factor in increasing network efficiency and coverage. High-performing beams like beam4 covered the area with high user traffic. Conversely the underutilized beams beam0, beam1 and beam2 can be reallocated or adjusted to cover areas with weak signals or more users. By effectively distributing beam resources, interference can be reduced, spectral efficiency improved, and overall network reliability strengthened which will lead to enhanced connectivity and user satisfaction.

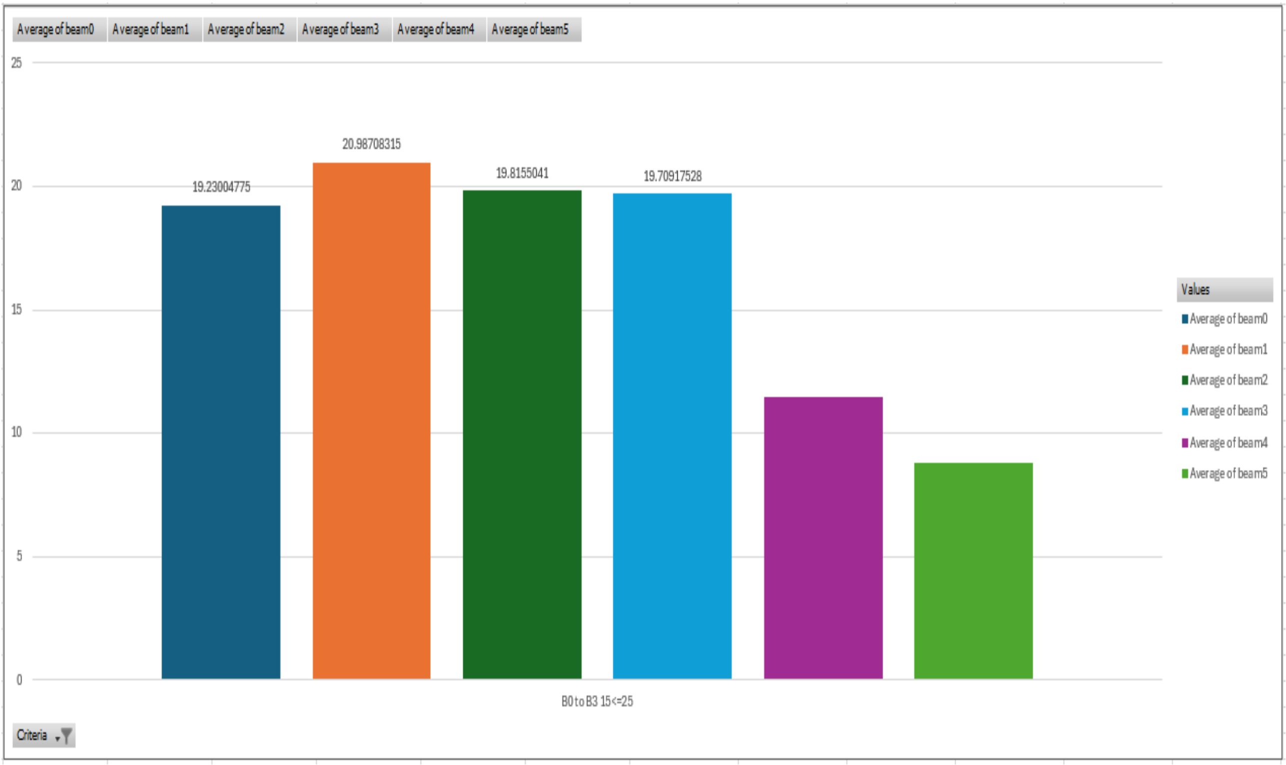

Figure 20. Contribution Share Per Beam

Figure 21 illustrates how the six sets of beams impact performance of multiple cells in the live network. The threshold sets for the cells data defined by B0 to B3 15 ≤ 25. According to the set threshold it can be seen in graph that first four beams from left to right with name beam0,1,2 and 3 covering the most coverage area about 80 percent or user in the cells that can leads to interference, week signals and handovers issue within the cells. While on the other hand the last two beams are just contributing to the remaining user that seems to be very less.

This analysis highlights the beam usage in live mobile network and indicates possible underutilization or coverage gaps where user experience can be improved through network resource reallocation or beam parameter reconfiguration. This optimization of the lower impact one's beam4 and beam5 that not only increases coverage area but also increases the efficiency and performance of the overall network.

Another result graph in Figure 22 shows the average performance of six beams (beam0 to beam5) in a cell revealing an uneven contribution to user coverage with criteria set for cells where beams are covering between 15 to 35 percent of the cell coverage. The first three beams (beam0, beam1 and beam2) account for a total of 65% of the total user coverage with beam1 contributing the most about 27 percent followed by beam2 and beam0. In contrast the remaining three beams (beam3, beam4, and beam5) provide significantly less coverage with beam4 and beam5 being the least effective.

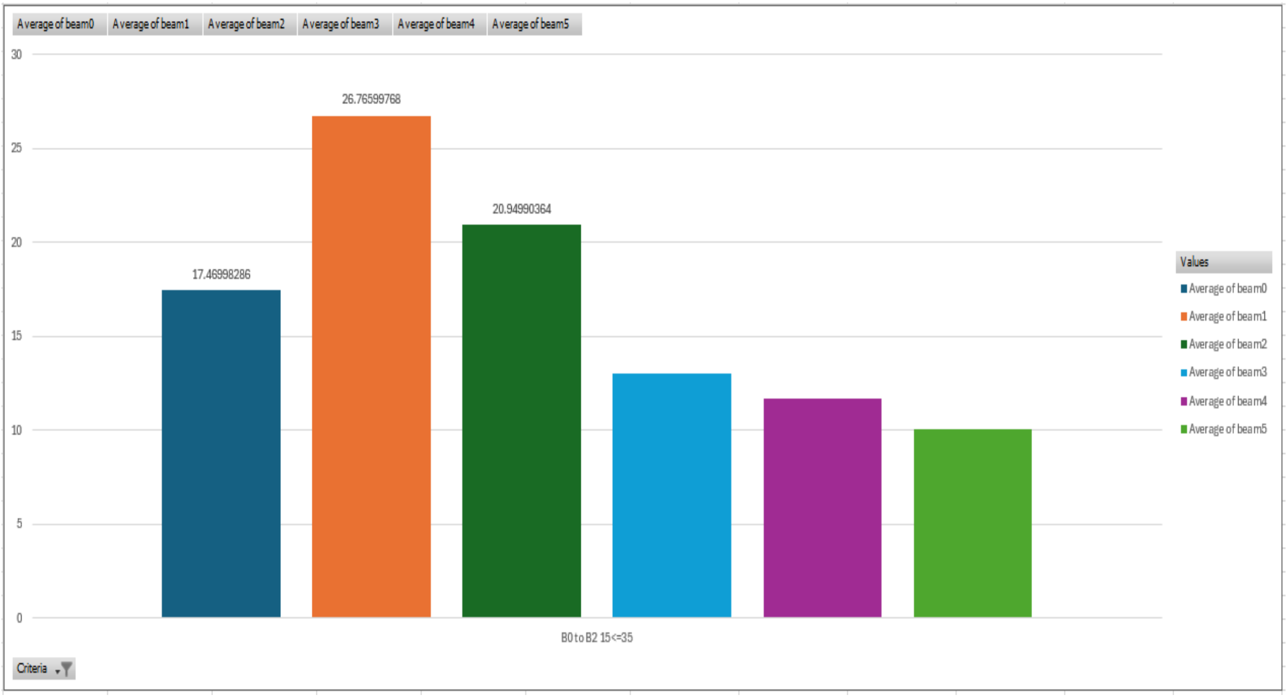

Figure 21. Per-Beam Impact Visualization

This figure 22 indicates that the imbalance suggests inefficiencies in how user traffic is distributed across the beams in all these cells. Possible causes include misaligned beam configurations, inadequate coverage in certain areas and low user activity in regions served by the weaker beams. To enhance the performance of these sectors adjustments to the beam alignment and configuration should be done to ensure more balanced coverage and better traffic distribution.

Additionally, analyzing user density and mobility patterns can help reposition weaker beams to target high-demand areas. Improving beamforming strategies or allocating additional power to the underperforming beams may further enhance their effectiveness. Figure 22 analysis provides a foundation for optimizing network performance and ensuring more uniform user coverage in all these cells where these beamforming techniques have been implemented.

The result figure 23 depicts that the average performance of six beams (beam0 to beam5) within multiple cells that lies in this threshold (B0 to B4 15 ≤ 25) and their respective contributions to total cell coverage. The result graph indicates that beams 0 through 4 collectively account for over 90% of the cells capacity with beam1 and beam3 making the most significant contributions followed closely by beam0, beam2 and beam4. While on the other hand beam5 which is last beam contributes only marginally, serving a very small portion of users indicating its limited impact on overall coverage. It's the area that needs to be optimized.

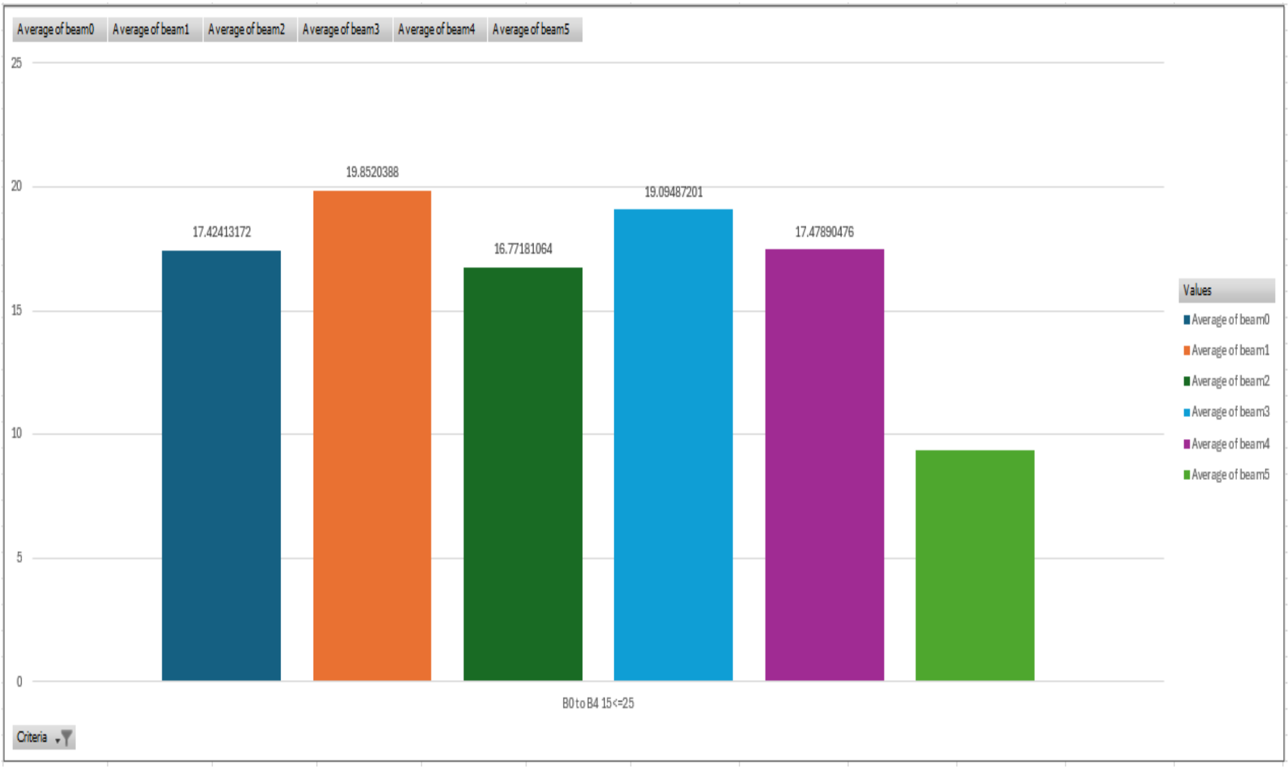

Figure 22. Contribution Ratio per Beam

The pattern in figure 23 highlights a high dependency on the first five beams for maintaining cell coverage and throughputs while sixth beam remains underutilized. The reduced performance of beam5 most probably due to the factors such as poor alignment, insufficient demand in its coverage area or an uneven allocation of resources. To address this imbalance and improve overall cell performance adjustments can be made to enhance the utilization of beam5. The most possible approaches include realigning the beam5 to target regions with higher user density or underserved areas, redistributing power resources to strengthen its coverage or refining beamforming techniques to balance user traffic more effectively across all beams equally. Additionally, by analyzing user distribution and mobility trends within the cell can help identify specific areas where Beam5's performance can be optimized. We need to use these strategies that would facilitate a more balanced distribution of resources, leading to improved cell efficiency and capacity.

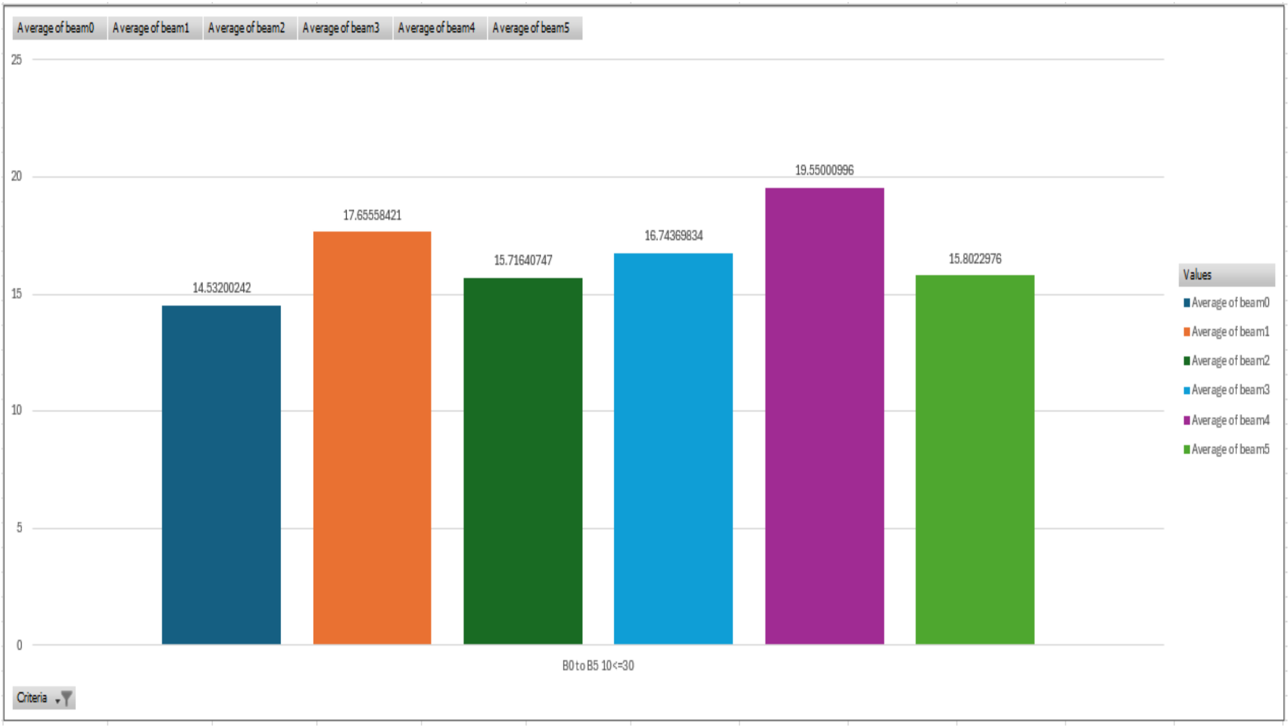

Figure 23. Graphical Representation of Beam Contributions

The figure 24 illustrates the percentage performance of six beams (beam0 to beam5) in the cells that are under the selected criteria (B0 to B5 10 ≤ 30). The result graph indicates the cell coverage is distributed evenly across all the beams. Although beam4 has a slightly higher average value but the difference is minimal. It shows that each beam contributes almost equally to the cell's overall capacity and user coverage.

The even distribution shown in figure 24 reflects good resource management since no beam is either overused or underused. This gives an assurance of the identical user experience throughout the cell along with the reduction in the chances of coverage holes or overloading. But, in order to maintain this balance, continuous measures need to be taken to meet changing consumer needs. This result emphasizes that the current beam configuration is well-suited for handling the specified operational criteria promoting efficient use of available resources.

In another scenario the impacts of beams utilized in multiple cells that fall under the certain threshold (beam2 and beam5 15 ≤ 35) is illustrated in figure 25 These two beams contribute significantly accounting for nearly half of the cell's total capacity. Beam5 stands out as the highest performing beam while beam2 also plays a key role. In comparison the remaining beams (beam0, beam1, beam3 and beam4) contribute less to the overall capacity highlighting an inequality in resource utilization.

This uneven distribution in figure 25 suggests that beam2 and beam5 are handling most of the traffic potentially leading to congestion in these areas while the other beams remain underutilized. To enhance user balance, coverage and throughput across the cell adjustments can be made to optimize the distribution of resources. Beam alignment can be fine-tuned to redistribute traffic more evenly which helps in reducing the load on beam2 and beam5 while increasing the utilization of the other beams.

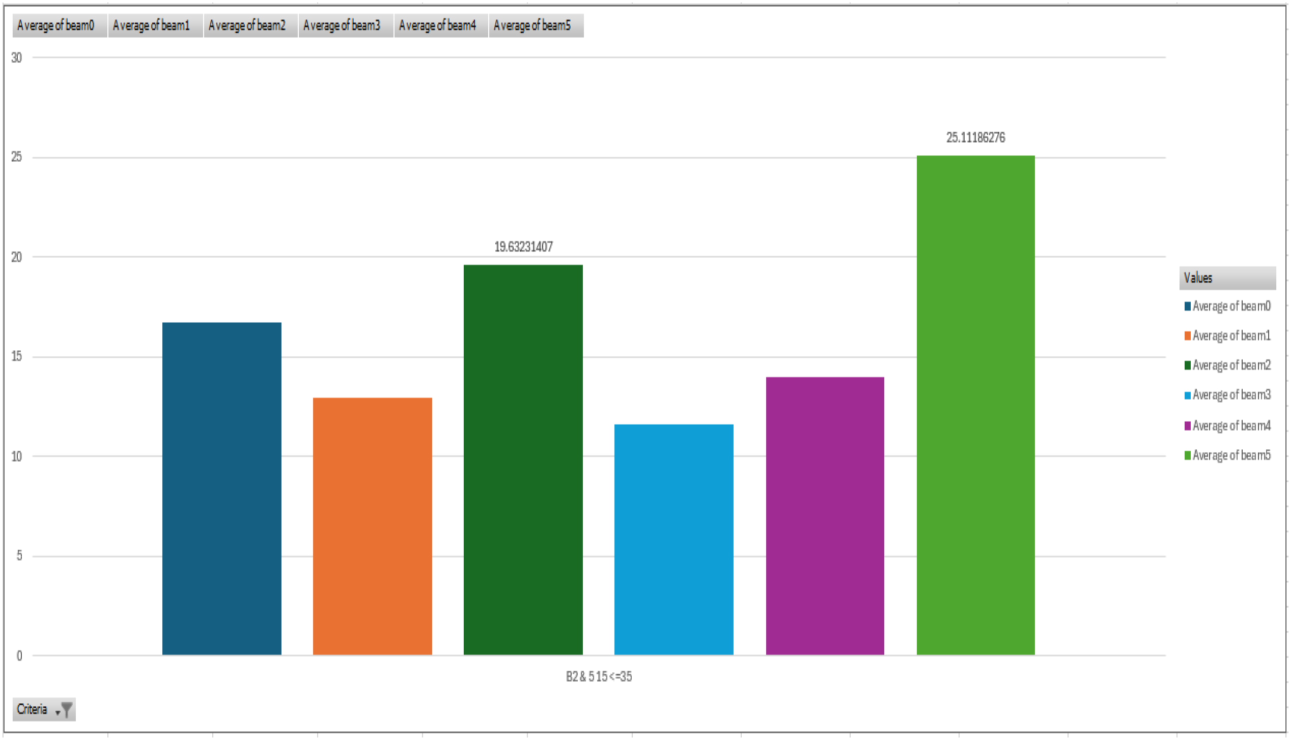

Figure 24. Beam Contribution Comparison

Power levels for the underperforming beams such as beam1 and beam3 can be adjusted to strengthen their coverage and improve capacity. Additionally, advanced beamforming techniques can be deployed to dynamically adapt to traffic patterns and ensure better utilization of all beams within these cells. Understanding user density and movement within the cell can further guide these optimizations. We advised by implementing these strategies the cell's performance can be improved ensuring efficient resource allocation and enhanced user experience.

In this case we choose to sort out the cells where 4 or more beams that are just contributing a quarter of the portion of the cell coverage and have impacted on the cell performance. In figure 26 the analysis reveals that he lasts four beams (beam2, beam3, beam4, and beam5) collectively contribute only a quarter portion of cell capacity. While beams0 and beam1 are the primary contributors accounting for most of the cell's capacity. This imbalance suggests that beams0 and beam1 are handling the bulk of the traffic potentially causing congestion in these areas while all the other beams are underutilized leading to inefficiencies in serving the users.

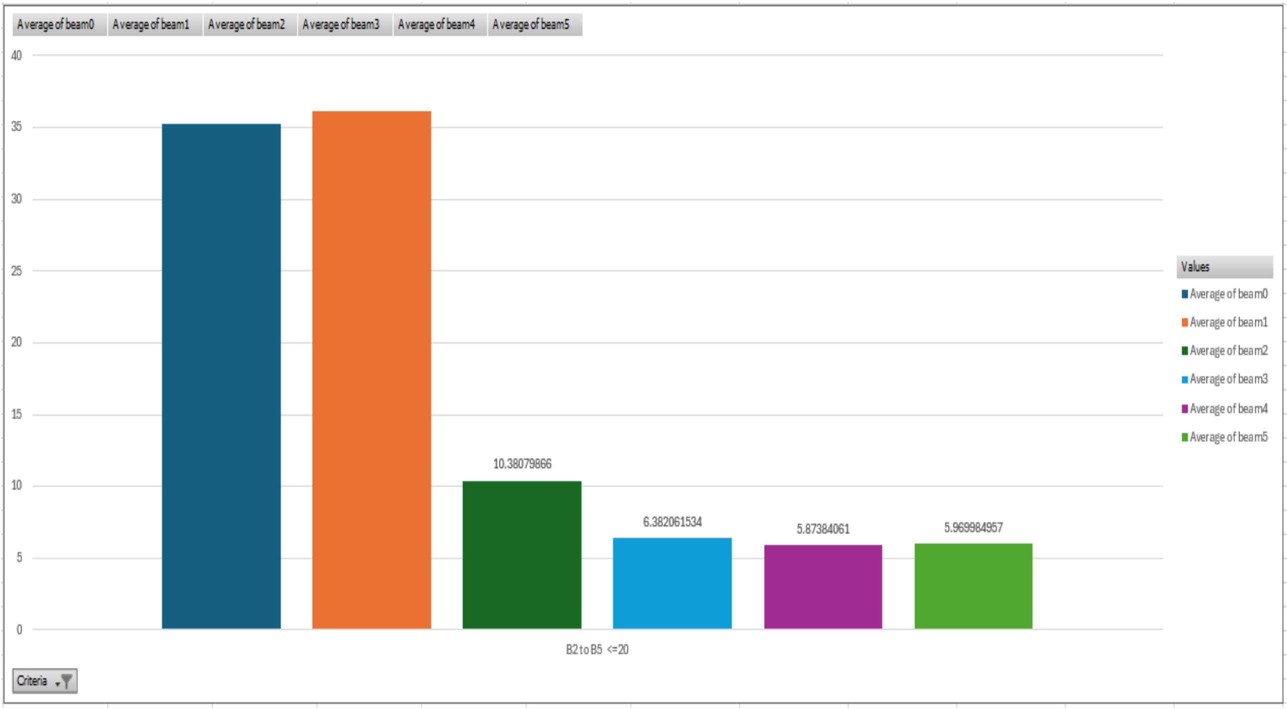

Figure 25. Contribution Ratio per Beam

By thoroughly analyzing figure 26, we can conclude several improvements that could enhance cell performance and coverage. An effective approach involves optimizing beamforming parameters to redistribute traffic, balancing the load more uniformly across beams. Such parameter adjustment would alleviate congestion on overburdened beams 0 and 1 while increasing utilization of underused beams. The second important step is to analyze the distribution of users within the cell to pinpoint high-demand areas. This information can then guide adjustments to beam alignment ensuring all beams effectively serve the users in their coverage areas.

Additionally advanced adaptive beamforming techniques can also be utilized to dynamically adjust beam parameters in real time based on changes in user demand and movement. If these measures still do not resolve the imbalance, then a reconfiguration of the cell sectors requires a more equitable distribution of resources.

We use another analytical approach to beam utilization by categorizing cells based on similar beam behavior and focusing on cases where a specific beam contributes minimally to overall cell coverage shown in figure 27. Two threshold criteria have been made B2 ≤ 15 and B5 ≤ 15 that are used to evaluate the distribution of beam coverage.

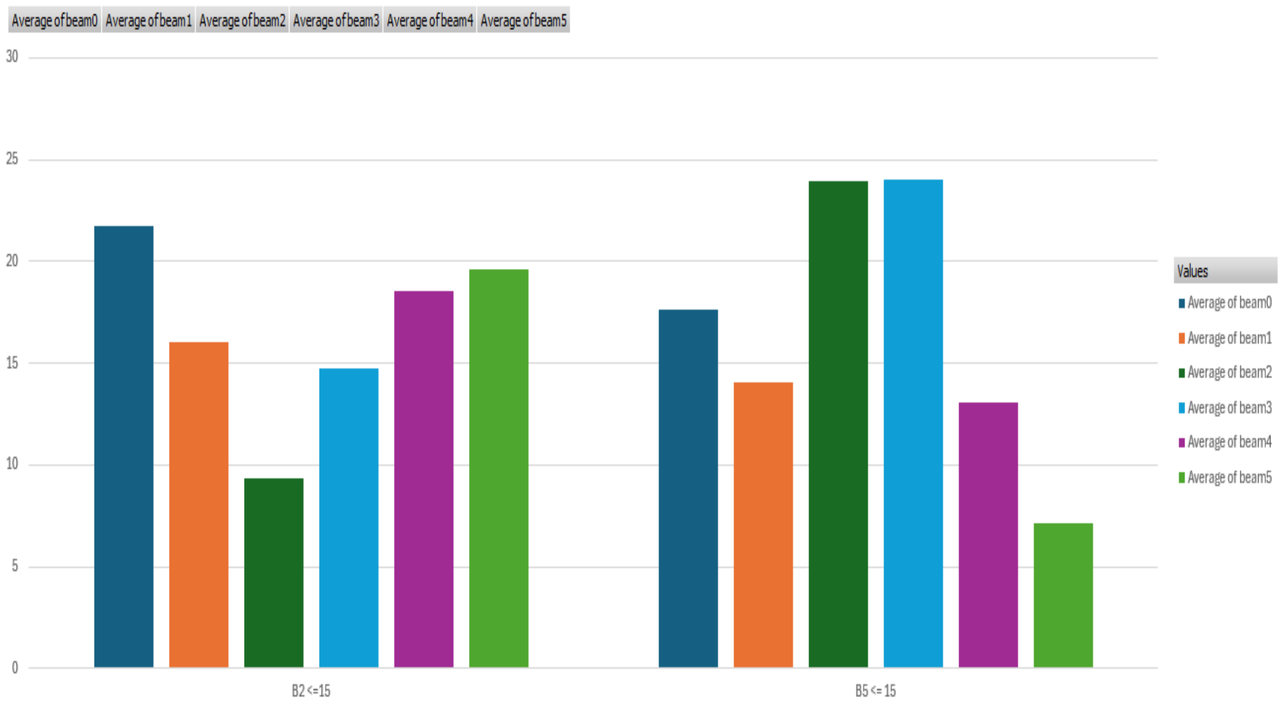

Figure 26. Comparison of Relative Beam Strength

Figure 27 illustrated that in the first scenario (B2 ≤ 15), beam0 beam1, beam3, beam 4 and beam5 accounted for most of the cell coverage contributing respectively, while beam2 showed the lowest utilization even less than 10% of the cell coverage.

In the second scenario (B5 ≤ 15), beam3 and beam4 dominate accounting for 24% and 23% of the total cell's capacity along with the beam0, beam1 and beam4 that are also contributing enough for the cell coverage. While beam5 provides just 9% of the cell coverage indicating an uneven load distribution where certain beams are underutilized.

By plotting these thresholds, we came to know that the refinement of beamforming strategies is needed so as to achieve a more balanced distribution across all beams in those cells. We can use approaches such as dynamic beam adjustment, improved traffic balancing and enhanced resource scheduling can be implemented to better allocate network traffic. These optimizations are essential to improving cell performance and coverage.

The result analysis presented in figure 28 illustrates the contribution of individual beams to cell coverage in scenarios where four out of six beams provide at least 15% of the total cell area. On the left side of the figure, beams 1, 2, 3, and 4 contribute almost equally collectively covering approximately 80% of the total cell area. This balanced distribution indicates efficient beam utilization and suggests that these beams are successfully sharing the load, resulting in stable cell performance within the specified threshold.

Similarly, the graph on the right side of the figure 28 four beams 2, 3, 4 and 5 are identified as the primary contributors. Among them beams 3 and 4 have the highest coverage, exceeding 20% each. However, beams0 and beam1 show relatively low contributions signaling underutilization. This disparity highlights potential inefficiencies where certain beams handle a disproportionate share of the user load while others are insufficiently engaged.

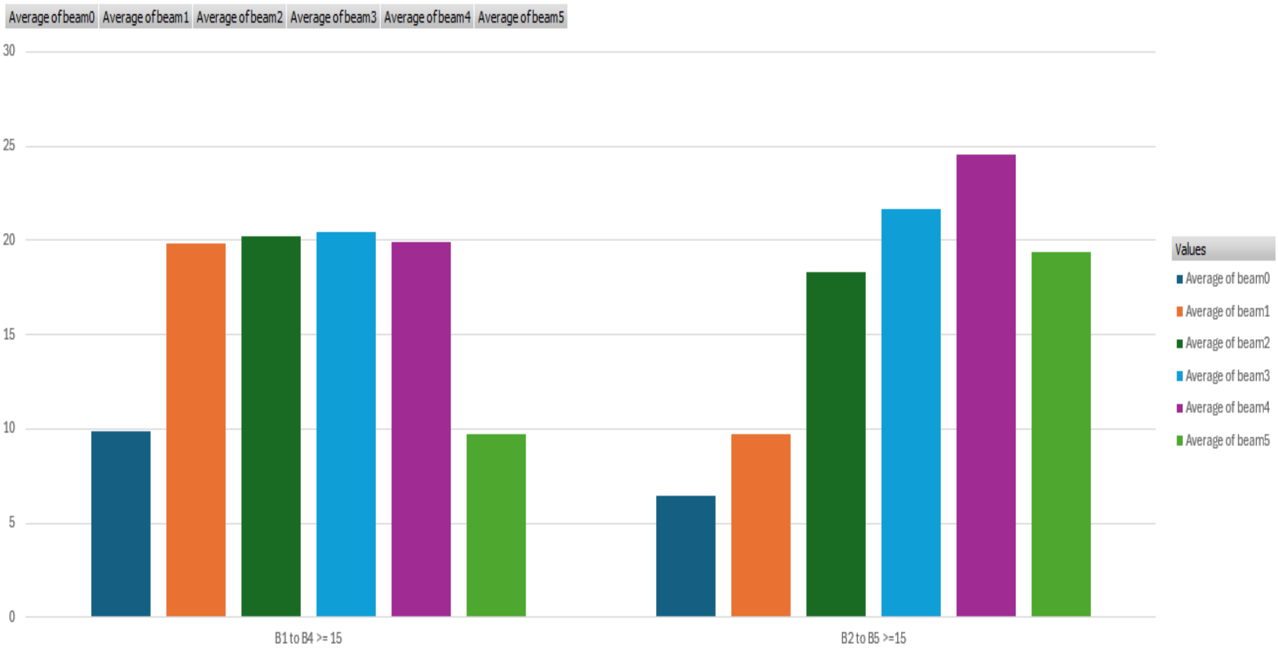

Figure 27. Comparison of Beam Level Contribution Chart

To overcome this kind of beam utilization and to optimize the overall cell performance several strategies can be adopted. First, implementing dynamic beam allocation systems can help adjust beam utilization based on real-time coverage and traffic demands ensuring optimal use of all available beams. Secondly redistributing traffic loads evenly across all the beams can mitigate over-reliance on high performing beams such as beams 3 and 4 and enhance the participation of underutilized beams like beams 0 and 1. Thirdly advanced scheduling algorithms, such as proportional fairness or maximum throughput strategies, can improve resource allocation efficiency while maintaining fairness across all beams. Lastly, the fine tuning of beamforming parameters including direction and gain can better align beam performance with user density and underutilized sectors.

The result analysis in figure 29 depicts that beam performance within two threshold ranges that have been selected B1 to B2 (20 ≤ 50) and B4 to B5 (20 ≤ 50) on the left and right side of the figure 29 respectively. In both cases the cell coverage is predominantly provided by two specific beams while the remaining four beams exhibit minimal utilization. Although the dominant beams differ between the two scenarios but the imbalance in coverage distribution remains consistent.

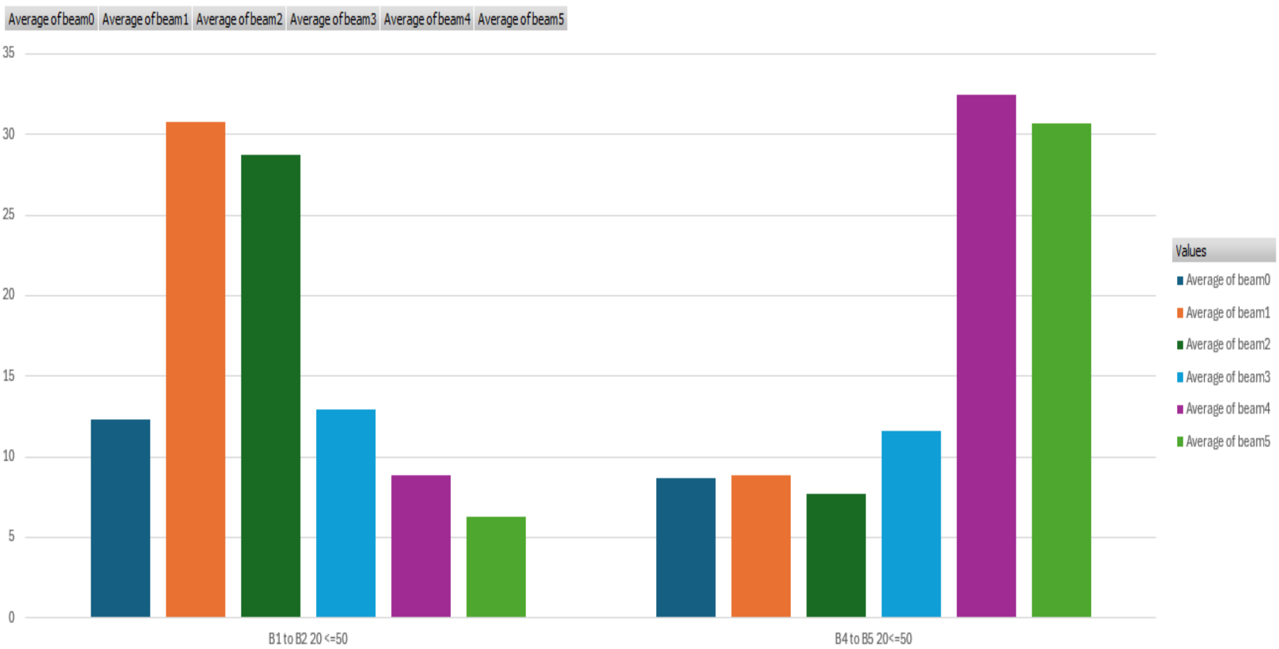

Figure 28. Illustration of Beam Role Across Multiple Cells

On the left side of the figure 29, beams 1 and 2 are the principal contributors, collectively accounting for most of the cell coverage. Beam 1 demonstrates the highest contribution followed closely by beam 2. Conversely, beams 0, 3, 4, and 5 contribute minimally, highlighting their underutilization. This uneven distribution places a disproportionate workload on beams 1 and 2, while the other beams remain largely idle.

A similar trend is observed on the right side of the figure, albeit with different dominant beams. Here, beams 4 and 5 take on most of the cell coverage, with each contributing significantly more than the remaining beams. Beams 0, 1, 2 and 3 in this case show limited utilization reflects the inefficiency identified on the left side. Despite the change in which beams dominate the general issue persists two beams handle most of the coverage responsibilities while the others remain underutilized. To overcome this imbalance of beams or resources in these cells, load balancing strategies should be implemented to enhance the performance and coverage of the network to provide better user services.

The result depicted in the figure 30 illustrates beam contribution patterns across two scenarios defined by the set thresholds B0 to B1 (20 ≤ 40) and B2 to B3 (20 ≤ 40). In both cases two beams dominate collectively, contributing over 50% of the overall cell coverage while the remaining beams exhibit minimal utilization. Despite the variation in which beams are predominant, the overall behavior and distribution pattern remain largely consistent.

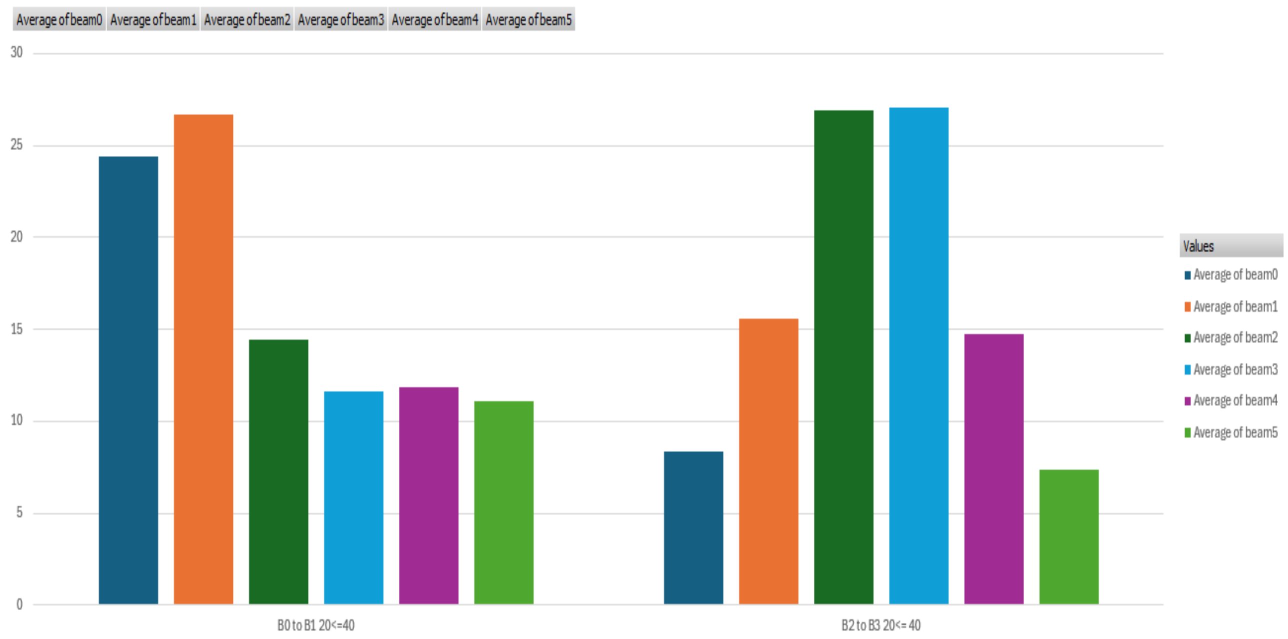

Figure 29. Comparison of Beam Role in Multiple Cells

On the left side of the graph in figure 30 beams 0 and 1 emerge as the primary contributors collectively exceeding 50% of the total cell coverage. Beam 1 provides the highest contribution followed closely by beam 0. However, beams 2, 3, 4 and 5 exhibit relatively low utilization resulting in an uneven workload distribution. This indicates that most of the coverage responsibilities are concentrated on just two beams leaving others underutilized.

On the right side the pattern remains consistent although with different dominant beams. In this scenario, beams 2 and 3 provide most of the cell coverage, collectively surpassing 50%. Beam 3 slightly outperforms beam 3 in terms of contribution, but the gap is marginal. Meanwhile beams 0, 1, 4 and 5 contribute significantly less mirroring the inefficiency observed on the left side.

The similarity in these two scenarios lies in the disproportionate reliance on only two beams for most of the cell coverage regardless of which beams dominate. To mitigate this imbalance, it is essential to implement strategies such as dynamic beam selection or adaptive beamforming. It can help distribute coverage more evenly across all beams, reducing the strain on the heavily utilized beams and maximizing the potential of underutilized ones. This will not only enhance network performance but also improve user experience by ensuring consistent coverage throughout the cell.

Another result figure 31 illustrates two scenarios where the distribution of cell coverage and user load is unevenly managed by six beams. In both cases three beams contribute less than 15% individually and with their combined coverage remains under 30%. The remaining three beams dominate accounting for most of the cell coverage and user load. While the specific beams contributing the most differ between both graphs the overall pattern of beam behavior remains consistent throughout the selected cells.

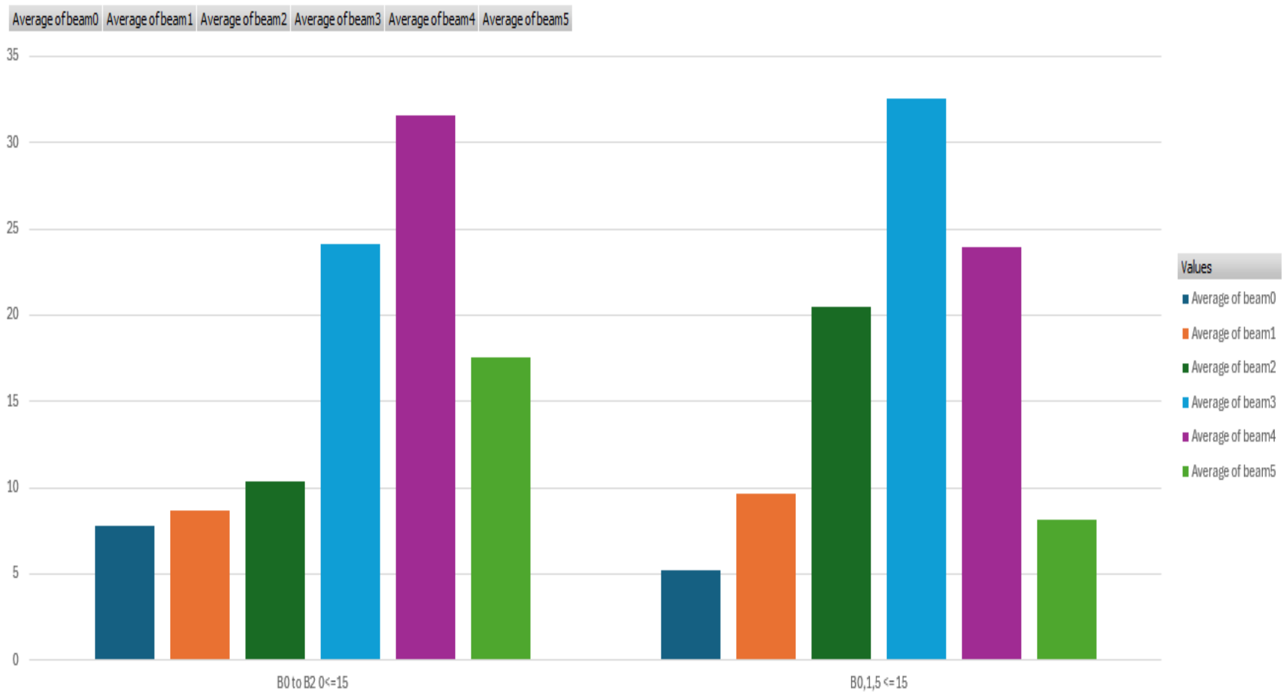

Figure 30. Side by Side Beam impact in Two states

In the left graph in figure31 depicts that beams 3, 4 and 5 are the primary contributors with beam 4 carrying the highest load followed by beams 3 and 5. Conversely beams 0, 1 and 2 show significantly lower contributions, each falling below 15% of the total cell coverage. Collectively these underperforming beams contribute less than 30% of the coverage, indicating a clear imbalance where most of the load is concentrated on just three beams.

On the other side of the result figure 31 beams 2, 3 and 4 emerge as the dominant contributors with beam 3 handling the highest load followed closely by beams 2 and 4. Meanwhile, beams 0, 1, and 5 contribute far less each remaining under 10% individually and their combined coverage stays below 30% of these selected cells coverage. This scenario reflects a similar imbalance observed in the left graph where only three beams are responsible for most of the coverage while the others remain underutilized.

Overall, the beam behavior is similar in both cases highlighting a pattern where three beams dominate carrying the bulk of the coverage in the cells, while the other three beams remain underutilized. To address this imbalance, we should implement the load balancing techniques that can ensure a more equitable distribution of coverage and user load to enhance the performance and reduce the congestion.

The result graphs in figure 32 demonstrate an uneven distribution of beam utilization where four beams collectively manage over 80% of the cell coverage or users while the remaining two beams are significantly underutilized. This disparity indicates inefficiencies in beam load balancing leading to a concentration of coverage on specific beams.

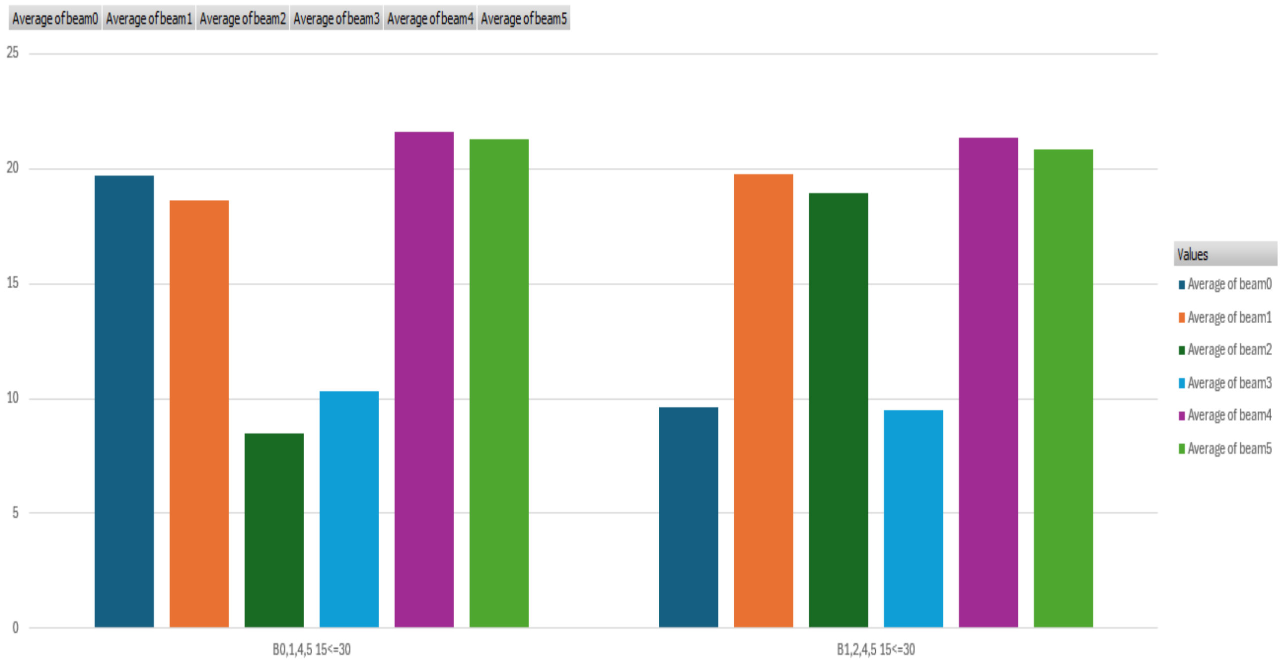

Figure 31. Beam Distribution Across Two Similar Scenarios

In the left graph, beams 0, 1, 4 and 5 contribute to most of the coverage, whereas beams 2 and 3 provide minimal support. Similarly in the right graph, beams 1, 2, 4 and 5 carry most of the load while beams 0 and 3 remain underutilized. Although the contributing beams differ in both graphs, the overall load imbalance is consistently observed.

To mitigate this imbalance, it is essential to employ beamforming optimization techniques and dynamic load balancing strategies across all the six beams in these cells. These approaches can redistribute the load more evenly across all beams, enhancing resource efficiency, reducing strain on heavily utilized beams and improving the overall performance and stability of these cells.

6. Conclusion

To conclude the research work, Beamforming offers several advantages over traditional mobile networks, including enhanced network scalability, more efficient utilization of resources, lower equipment costs, and easier maintenance and further deployment of new beams in the mobile network. This research thesis investigated the beam usage characteristics of different beamforming techniques, including analog, digital, and hybrid approaches, within mobile communication systems.

Through practical data analysis and performance evaluation, the study demonstrated that hybrid beamforming which combines the strength of both analog and digital methods, offers a favorable balance between network performance, flexibility and system complexity, while analog beamforming excels in cost effectiveness and simplicity and digital beamforming provides superior adaptability and control each approach presents distinct advantages depending on the specific application scenario and network requirements.

The study of Synchronization Signal Blocks (SSB) and Sounding Reference Signal (SRS) beams highlighted the critical role of efficient beam management mechanisms. Effective management of these beams is essential for improving network coverage, enhancing spectral efficiency, and supporting seamless user mobility across different cells and beam sectors. Additionally, the examination of user transition patterns, uplink path loss measurements, and beam-related counters provided deeper insights into how beamforming operates under real-world network conditions. This empirical analysis contributes valuable knowledge toward optimizing beam selection, tracking, and adaptation processes in dynamic mobile environments.

Moreover, this research offers significant insights into the practical utilization of beams within current 5G systems, highlighting the transformative impact of beamforming on network performance and reliability. However, as mobile communication technologies continue to evolve rapidly, there remains a need for further research in several critical areas. Future investigations should focus on the transition dynamics of users moving between beams, which is pivotal for maintaining consistent quality service during mobility events. Additionally, developing advanced optimization techniques for beam management, potentially driven by artificial intelligence and machine learning, can significantly enhance network efficiency. Research must also address the challenges associated with deploying beamforming at higher-frequency bands, such as millimeter waves, where propagation characteristics differ markedly from lower frequencies. Lastly, the ongoing development of beamforming strategies must be aligned with the evolving architectures anticipated in 6G networks, which are expected to introduce new approaches in connectivity, latency, and capacity.

In conclusion, the findings underscore the pivotal role of various beamforming techniques in ensuring the performance and reliability of next-generation mobile networks. The study provides a comprehensive overview of how beams can be effectively implemented in the future to further enhance the network coverage and improve reliability.

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