Tampere University

Samir Ahmed

BEAMFORMING MANAGEMENT AND BEAM TRAINING IN 5G SYSTEM

Master of Science Thesis
Faculty of Information Technology and Communication Science
November 2019

ABSTRACT

Samir Ahmed: Beamforming management and beam training in 5G system
Master of Science Thesis
Tampere University
Master of Science in Electrical Engineering
November 2019

Massive multiple-input-multiple-output (MIMO) antenna system with beamforming technique is an integral part of upcoming 5G new radio (NR) system. For the upcoming deployment of 5G NR system in both stand-alone (SA) and non-stand-alone (NSA) structure, beamforming plays an important role to achieve its key features and meet the estimated requirement. To be employed with massive MIMO antenna structure, beamforming will allow 5G system to serve several users at a time with better throughput and spectral usage. Beamforming will also minimize the path loss due to high susceptibility of millimetre wave and provide beamforming gain. For a wide range of benefit scheme, beamforming is currently a hot topic regarding the deployment of 5G. With the advantage of both analog and digital beamforming, hybrid beamforming structure can provide better system benchmark performance in terms of cost and flexibility. Switched beam training and adaptive beam training approaches and algorithms are developed in order to reduce training time, signalling overhead and misdetection probability. Some of the approaches and algorithm are addressed in this thesis. Beamforming management ensures the initiation and sustainability of the established link between transmitter and receiver through different processes. Beam tracking helps to keep track of the receiver devices during mobility. As beamforming is related to antenna configuration, near-field spherical wave front incident problem was ignored, and all the references and examples presented in this topic was obtained with a far-field propagation perspective. To avoid mutual coupling between antenna elements and grating lobe problems in antenna radiation pattern, each element is separated by half of the wavelength. This thesis paper aims to provide a broader view into beamforming scenario, starting from the basics of beamforming to training the beams and management aspects in the hardware part of 5G structure. Another goal is to present the necessity of beamforming in a 5G system by stating different benefits scheme such as spatial diversity, interference suppression, energy efficiency, spectral efficiency and so on. These benefits are justified by evaluating various research paper and MATLAB simulations.

Keywords: 5G NR, Beamforming, Beam management, Beam training

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

PREFACE

This master thesis, “Beamforming management and beam training in 5G system” was carried out to fulfil the requirement of Master of Science degree in Electrical Engineering, with a specialization in wireless communication.

First of all, I would like to express my gratitude and admiration to Dr. Jukka Talvitie, my thesis supervisor, for bringing me this interesting topic and mentoring me throughout the process. It would not be possible for me to complete the thesis in time without his continuous support and guidance. I would also like to thank Dr. Toni Levanen, my thesis co-supervisor for his valuable suggestions and comments regarding the improvement of this thesis.

Secondly, I would like to express my gratefulness towards my parents for their unconditional love and prayer. Thirdly, I would like to thank my friends, classmates and others who have helped me in various way to complete this thesis.

Finally, I thank Almighty Allah for making me believe that anything is possible with hard-work and determination.

Tampere, 20 November 2019

Samir Ahmed

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

5G NR	Fifth generation new radio
5GPPP	5G infrastructure public private partnership
3GPP	Third generation partnership project
AMPS	Advanced mobile phone system
AR	Augmented reality
BER	Bit error rate
CQI	Channel quality indicator
CG	Conjugate gradient
CMA	Constant modulus algorithm
CSI	Channel state information
CSI-RS	CSI- reference signal
D-AMPS	Digital advanced mobile phone system
DTX	Discontinuous transmission
DM-AIS	Dynamic mutated artificial immune system
DoA	Direction of arrival
AoA	Angle of arrival
AoD	Angle of departure
eMBB	Enhanced mobile broadband
EPC	Evolved packet core
EIRP	Effective isotropic radiated power
GSM	Global system for mobile communication
GSMA	GSM association
HSPA	High speed packet access
GSA	Gravitational search algorithm
IMT	International mobile telecommunications
IoT	Internet of things
ITU-R	International telecommunication union-radio sector
L1-RSRP	Layer 1 reference signal received power
LTE	Long term evolution
LS-CMA	Least square constant modulus algorithm
LCMV	Linearly constrained minimum variance
LMS	Least mean square
MVDR	Minimum variance distortion-less response
MIMO	Multiple input multiple output
mMTC	Massive machine type communication
MTC	Machine type communication
NDP	Null data packet
WLAN	Wireless local area network
PDC	Personal digital cellular
PDF	Probability density function
PBCH	Physical broadcasting channel
PSS	Primary synchronization signal
PMI	Precoder matrix indicator
PDCCH	Physical downlink control channel
PSO	Particle swarm optimization
RSRQ	Reference signal receive quality
RSSI	Reference signal strength indicator
RSRP	Reference signal receive power
RI	Rank indicator
RAR	Random access response
RLS	Recursive least square
SNR	Signal -to-noise ratio

SINR	Signal-to-noise-plus-interference ratio
SRS	Sounding reference signal
SS block	Synchronization signal block
SSS	Secondary synchronization signal
SMI	Sample matrix inversion
UE	User equipment
URLLC	Ultra reliable low latency communication
VR	Virtual reality
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle

1. INTRODUCTION

With the current advancement in mobile communication sectors, fifth generation (5G) mobile communication system is going to be a super ´techy´ highway where others predecessor like third generation (3G) and fourth generation (4G) mobile communication systems would look like country roads. 5G new radio (NR) deployment will open endless opportunities for every aspects of our life. Starting from smart cities and smart industries to augmented reality and autonomous car, 5G will influence the future to a great extent. However, 5G NR is not fully deployed yet as it is still under research for further improvements. The key features and importance of 5G NR system is set in international mobile telecommunication-2020 (IMT-2020) standards, recommended by international telecommunication union- radiocommunication sector (ITU-R) in 2015 [43]. Considering different use cases, it is prominent that 5G will solve many connectivity problems and provide better system enhancement. Over the past few years, researchers and implementors of 5G system devices are trying meticulously to improve the overall performance benchmark compared to existing long-term evolution (LTE) system. With the requirements specified in release-15 by 3rd generation partnership project (3GPP), 5G is intended to operate primarily with LTE as a non-stand-alone (NSA) structure in 2020 [4].

The millimetre wave (mmWave) used in 5G NR is highly susceptible to path loss in multi-propagation environment due to its nature. Along with pathloss, low power consumption of devices, higher data rate, better coverage area, increased spectral efficiency and supressing interference are some design aspects considered in 5G. Various techniques and algorithms are invented or being researched to achieve these system requirements. One of them is beamforming. Though beamforming is not a new concept, its implementation with massive MIMO in 5G has made it an indispensable part of 5G NR system. This thesis aims to establish this link-up of beamforming and 5G in a broad manner.

The main idea of beamforming is to concentrate the information or energy in a desired direction while neglecting interference from undesired direction. It was first demonstrated by the German inventor and physicist Karl. F. Braun in 1905 by creating a phased array of 3 antenna element [48]. This idea is widely accepted in the field of radar, sonar, seismology, acoustics, bio-medical and wireless communication. However, with advancement of time, beamforming has evolved as an integral part of mobile communication system. The effects of beamforming employed in a transmitter-receiver link has showed more advantage than disadvantage.

Beamforming management refers to establishment of beam in downlink and/or uplink, adjusting the beam in different adverse situation or during user mobility and also recovery of established link, if hampered. In this process, the beams need to be trained to find users or receivers to initiate beamforming. While generic beam training protocols are often described in the system specification, there is no detailed algorithm set for the beam training which governs the whole process. In this thesis, a brief overview of these algorithms along with some comparison is presented for better understanding.

This thesis is written from a literature-review perspective. The main theme is to analyse the role of beamforming in 5G NR system in a progressive way along with beamforming management and beam training procedures. In chapter 2, evolution of 5G and some key features are described to emphasise the importance of 5G in future. Then basic parameters of beamforming are described with appropriate examples and illustrations. In chapter 3, the benefits of beamforming in 5G system is described elaborately such as increased spectral efficiency, interference suppression, energy efficiency, increased security and so on. The claims are deducted from evaluating different research papers and MATLAB simulations. Chapter 4 focuses mainly on the management procedure of beamforming, how it is initiated and maintained throughout the operation. Beamforming management also includes beam tracking for mobility and a set of protocols to restore connectivity in case of failure. Configuration of the transmitter and receiver devices were briefly analysed to show that communication system supports beamforming fully. In chapter 5, some of the most conventional beam training approaches and algorithms were briefly described. Comparison of some of the approaches are also presented in this chapter. All illustrative examples and simulations results were created by Microsoft Visio and MATLAB 2019b software respectively. Finally, chapter 7 concludes the thesis with some discussion and potential future works intended for the deployment of beamforming in upcoming 5G system.

1.1 Motivation

The 5 G infrastructure public-private partnership (5GPPP) is a joint project between the European Commission and the European ICT industry (Telecommunications Operators, Service Providers, ICT Producers, SMEs and Research Institutions). The 5GPPP is now in its 3rd phase and working with many projects to provide solutions and standards for

5G. The challenges of 5GPP also includes creating opportunities and establishing European leadership in global ICT markets such as e-health, automation, smart cities etc. key challenges for the 5GPPP are [51]:

- Achieve mobile area capability 1000 times higher and more diverse network capabilities compared to 2010
- Focusing mainly on mobile communication, achieve energy saving up to 90% in each service.
- Reduce the average time cycle from 90 hours to 90 minutes.
- Construct a stable, safe and efficient Internet with "zero perceived" downtime for the provision of services.
- Enabling very large wireless communication networks to link more than 7 trillion wireless devices that serve more than 7 billion people
- Provide access to a wider range of services and software at a lower cost for everyone and everywhere

Beamforming management and beam training procedures can help to overcome these challenges in terms of hardware implementation cost and spatial resource allocation flexibility.

2. 5G NETWORKS AND BEAMFORMING OVERVIEW

2.1 Evolution of 5G

Emerging around 1980, the first generation (1G) of mobile communication was based on analog transmission where the main technology was advanced mobile phone system (AMPS) [1]. Then some other developments appeared in the early 1990s, such as personal digital cellular (PDC), digital AMPS (D-AMPS), global mobile communication system (GSM) for second-generation digital mobile communication (2 G). The fast-wireless internet access was possible by early 2000, in third generation (3G) of mobile communication due to high speed packet access (HSPA) technology. LTE based fourth generation (4G) technology has converged the world into a single global telecommunication industry with lots of improvements in connectivity, security and data management. As the demand goes higher and higher for faster speed, ultra-low latency and massive number of device connections, a new generation technology was required to meet all the demands. Finally, the emergence of fifth generation (5G) mobile communication system was declared in 3GPP release-15. Fig. 1 depicts the journey from 1G to 5G.

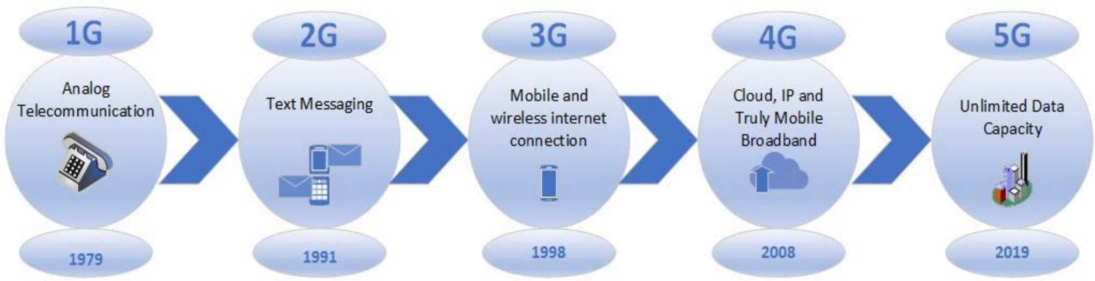

Figure 1. *The evolution of 5G [2]*

According to Ericsson forecast, nearly 20% of the world will be covered by 5G connecting 20 billion Internet-of-things (IoT) devices and 9 billion mobile devices by the year 2023 [3]. Since the 3GPP release-15, researchers and engineers are working towards IMT-2020 release to provide a stand-alone (SA) 5G architecture. In the meantime, 5G has evolved as an NSA architecture with LTE/LTE-Advanced (LTE-A). 5G has some quite large specification to meet the upcoming global challenge in connectivity and security. The 3GPP release-15 includes work on [4]:

- The 5G system – Phase 1
- Internet of things (IoT) and machine-type of communications (MTC)
- Vehicle-to-everything communications (V2X) Improvements

- Mission critical (MC) improvements
- Wireless local area network (WLAN) and unlicensed spectrum
- System enhancements

2.2 5G use cases

5G has 3 distinctive classes of use cases: massive machine-type communication (mMTC), enhanced mobile broadband (eMBB) and ultra-reliable and low-latency communication (URLLC). Fig. 2 shows 3 important use cases of 5G.

- mMTC refers to the connectivity for massive number of devices with very low cost and very low energy consumption. Such devices like monitoring networks, sensors, actuator (etc.) provides a long-time availability by increasing battery life and coverage.
- eMBB corresponds to larger data exchange between nodes and users' equipment. Augmented reality (AR), virtual reality (VR), cloud computing is such example for eMBB use cases.
- URLLC means very low latency and extremely high reliability. Example are automatic control, traffic safety, smart cities and factory automation.

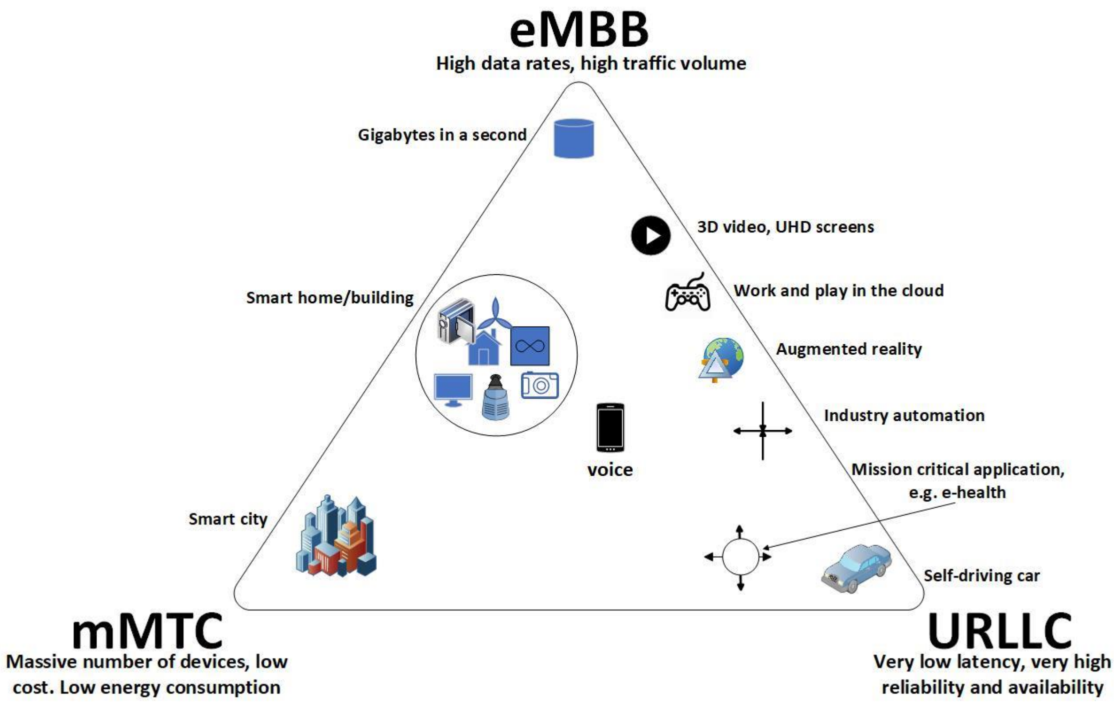

Figure 2. *High-level 5G use case classification*

2.3 5G key features

In comparison to existing 4G LTE technology, 5G will achieve a better performance benchmark depending on its key features. Some of them are already achieved and some them are still under research. ITU-R has specified some key specifications for 5G named as IMT-2020 [43]. The key features that distinguish 5G from the rest are stated below in table 1 and their importance in the upcoming 5G system is depicted in fig. 3.

Table 1. *5G NR key features [5]*

Features during implementation	Benefits	Features after full implementation	Benefits
Using both sub 6GHz and above 6GHz band	Capacity increases up to 100 times	Peak data rate	20 GB/s
Massive MIMO and beamforming	Better coverage and higher capacity	Latency	1ms
Lean carrier design	Less interference and low power consumption	Mobility	500 km/h
Flexible frame structure	High efficiency and low latency	Connection density	10^6/km^2
OFDM based air-interface	Enables diverse spectrum and services	User data rate	100 Mbit/s
Higher Spectral usage	Increased efficiency	Availability	99.999999%

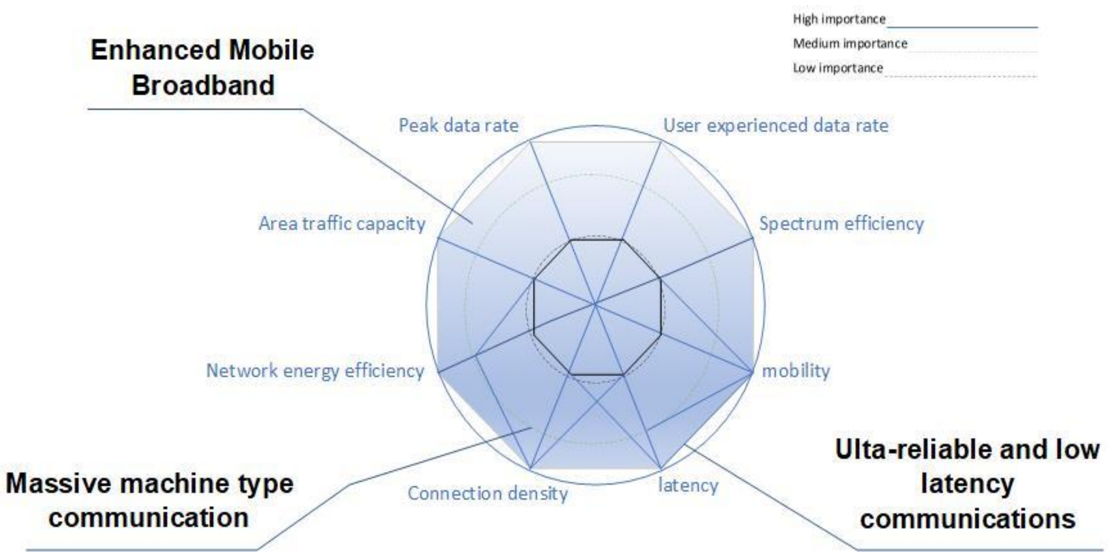

Figure 3. *Importance of key capabilities for IMT-2020 recommended by ITU-R [43]*

2.4 5G Network Architecture

5G has two network architecture modes: stand-alone (SA) mode and non-stand-alone (NSA) mode. In SA structure, 5G NR is directly connected to its own 5G core having a new 5G air interface. In NSA mode, 5G is operating under 4G/LTE evolved packet core (EPC). According to a GSM-Association (GSMA) report,192 operators were actively involved in testing and licensing for 5G operating band by November 2018. Two bands were mostly used in this purpose. One was band-n87 (3300 t0 3800MHz), widely known as sub-6GHz band and another was band-n257 (26.5 to 29.5 GHz) [6].

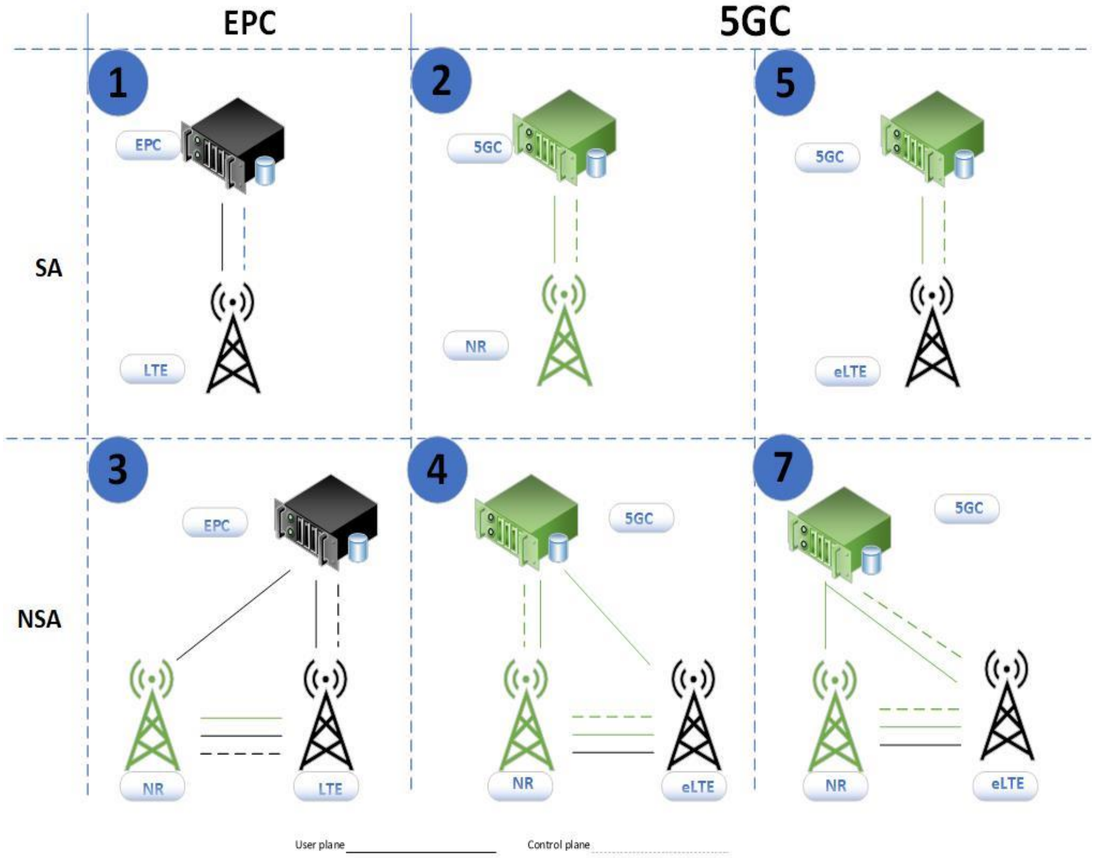

Figure 4. *3GPP defined deployment option for 5G [7]*

Fig. 4 depicts the deployment scenarios specified in 3GPP release-15. Most operators are going to use option 3 in order to exploit the full benefits of existing EPC core. Option 2 and 5 both having new 5G core were completed in June, 2018. Option 4 and 7 were completed in March, 2019 [7].

2.5 Beamforming

Beamforming is basically a special type of antenna radiation pattern. It is a method to concentrate the omni-directional radiated power of antenna into one or multiple specific directions. In 5G system beamforming is referred to transmission of a signal in a narrower shape from base station to receiver in such a way that only intended user can retrieve the information while rejecting interference from other directions. While transmitting, main lobe of the antenna pattern is directed towards a certain direction using phase and amplitude of each antenna element in an array. This phenomenon is called constructive interference in the wavefront. While receiving, individual response of each antenna element is combined to get the desired signal in desired direction. Fig. 5 depicts a typical beamforming scenario in case of cellular technology.

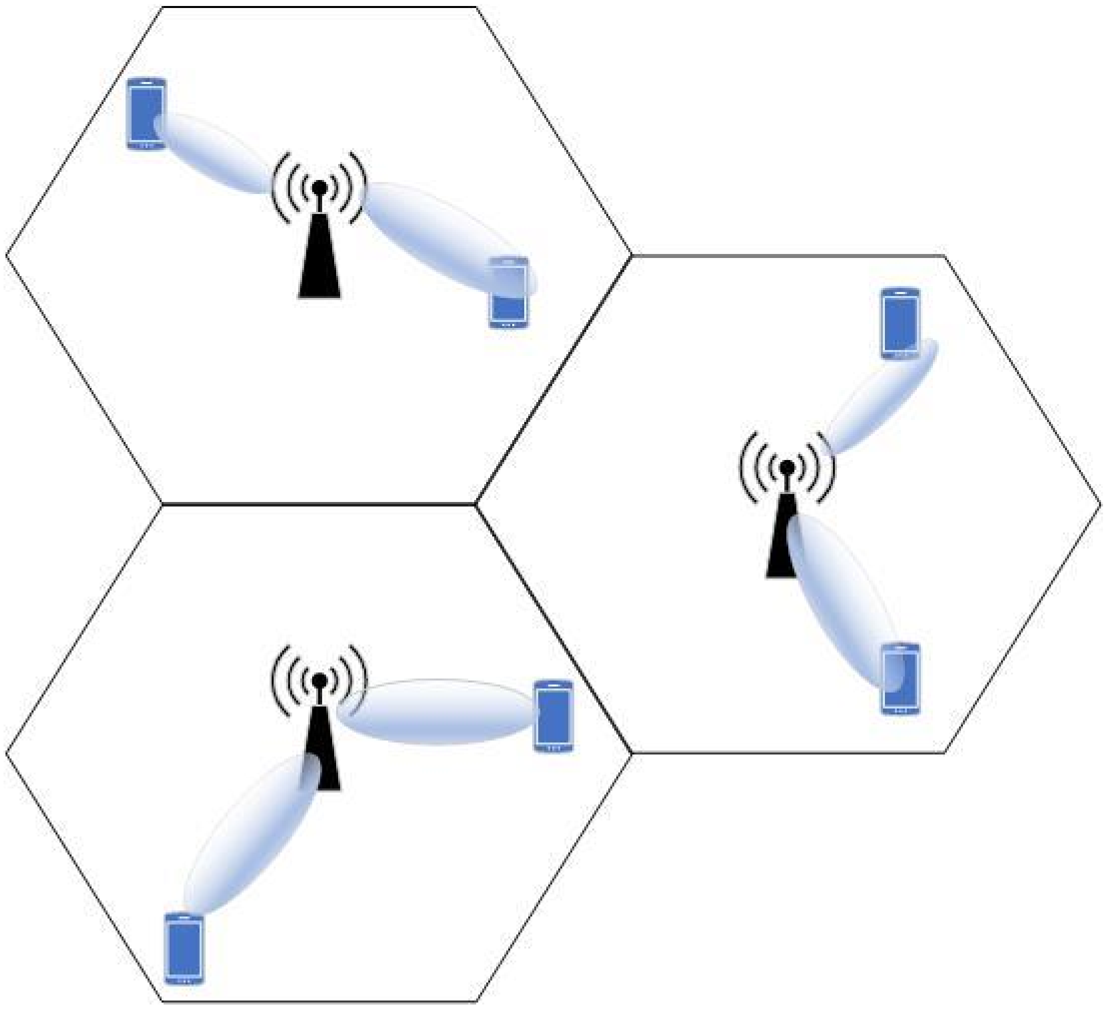

Figure 5. *Typical beamforming scenario inside a cell*

Beamforming can be done on both transmitter side and receiver side. when it is done in transmitter side it is called transmit beamforming and when it is done in receiver side it is called receive beamforming. Beamforming is a wide concept as it is associated with beamforming management and beam training which is discussed in later chapters. the main drawback of using millimetre wave in 5G is that these waves are highly susceptible to path loss in free-space, rain, fog and other atmospheric events [44]. Fig. 6 was generated using Friis' free-space path loss model [45] in order to compare free-space path loss in 5G and 4G. Two frequencies were chosen for 5G (28 GHz and 300GHz) and one for 4G (2100 MHz). If the distance between the transmitter and receiver is d (km) and the frequency is f (GHz) then the free-space path loss, $FSPL$ (dB) can be calculated as

$$FSPL(in\ dB) = 92.4 + 20\log(d\ in\ km) + 20\log(f\ in\ GHz). \quad (2.1)$$

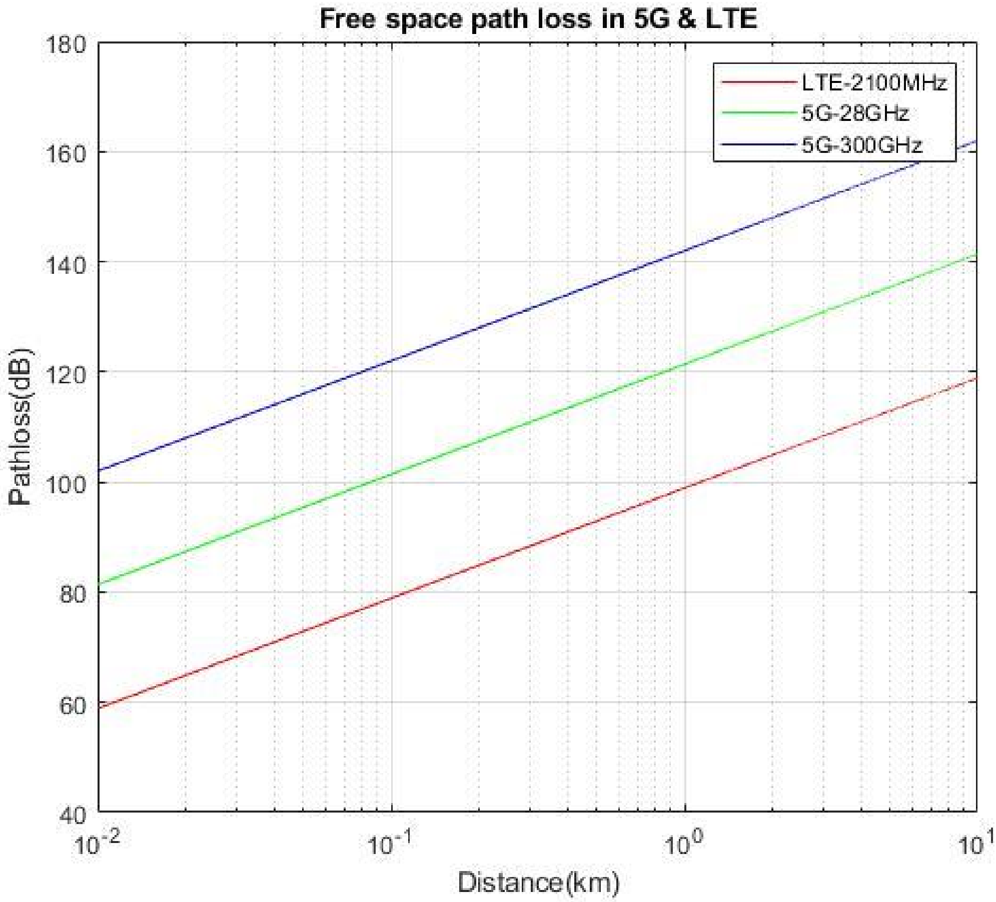

Figure 6. *Free-space path loss for different frequencies*

From fig. 6 it is visible that for a given range of distances (10m-10km), corresponding path loss increases (approx. 20 dB) with the higher frequency. To overcome this high path loss in 5G mmWave, high directional antenna gain is required and beamforming is the ultimate way to increase the directivity of the antenna. Antenna array of different sizes are used to provide beamforming gain in order to minimize path loss. Different kinds of arrays are used to exploit the best antenna geometry. Mostly used arrays are uniform linear array (ULA), uniform rectangular array (URA) and uniform circular array (UCA). The number of antenna elements used in array defines the array gain. For example, a 10 element ULA has an array gain of 10. Fig. 7 depicts different array geometry and size. Each antenna element in an array is separated by half of the wavelength of the transmitted frequency in order to avoid mutual coupling between antenna elements and grating lobes problems.

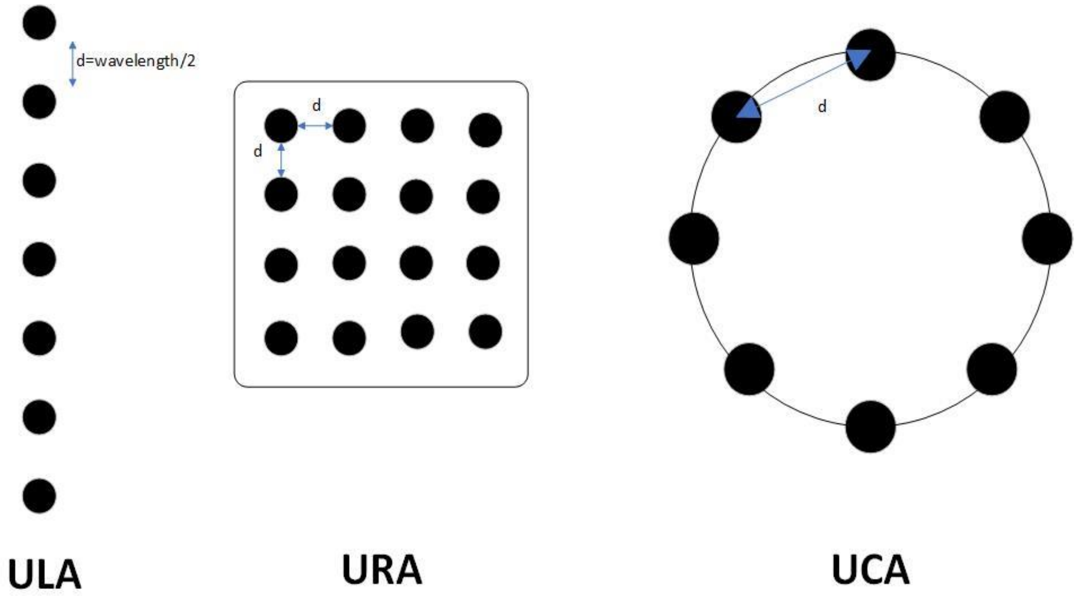

Figure 7. Different array geometry

In 5G mm Wave system, the area of an antenna array reduces in proportion to the wavelength of the operating frequency. As the frequency increases, the wavelength becomes shorter. This allows to manufacture antenna arrays in smaller size compared to other systems. For example, an antenna array of millimeter wave (i.e. 30 GHz) can be 100

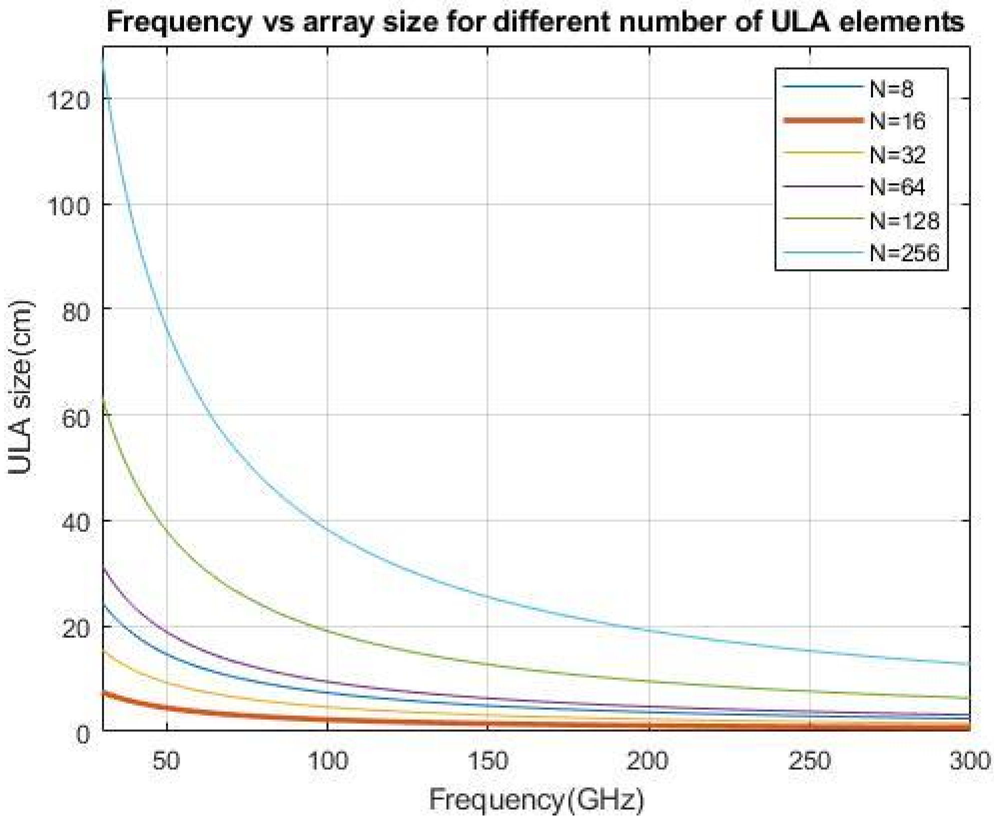

Figure 8. *Array size reduces with the higher frequency*

times smaller than the array of microwave (i.e. 300MHz). Fig. 8 shows that for different number of antenna elements (*N*), the area of a ULA (*D*) reduces as the frequency increase from 30GHz to 300GHz. The area of a ULA can be determined as

$$D = (N - 1) * \lambda/_2 \, , \tag{2.2}$$

where λ is the wavelength of respective frequency. Similar result can be obtained for URA also. This will allow to introduce large number of antenna elements in a smaller array geometry.

As the number of antenna elements increases in an array, the directivity of the beam pattern produced by the respective array also increases. Fig. 9-11 shows a comparison between the beam patterns produced by 16×16, 32×32 and 64×64 URA in terms of directivity. The figures were generated using 'sensorArrayAnalyzer' tool in MATLAB. Operating frequency of 30 GHz and steering angle of 30^0 azimuth and 30^0 elevation were used to generate the beam pattern in all 3 cases. Fig. 9 represents 3D directivity pattern of a 16×16 URA steered at 30^0 azimuth and 30^0 elevation angles.

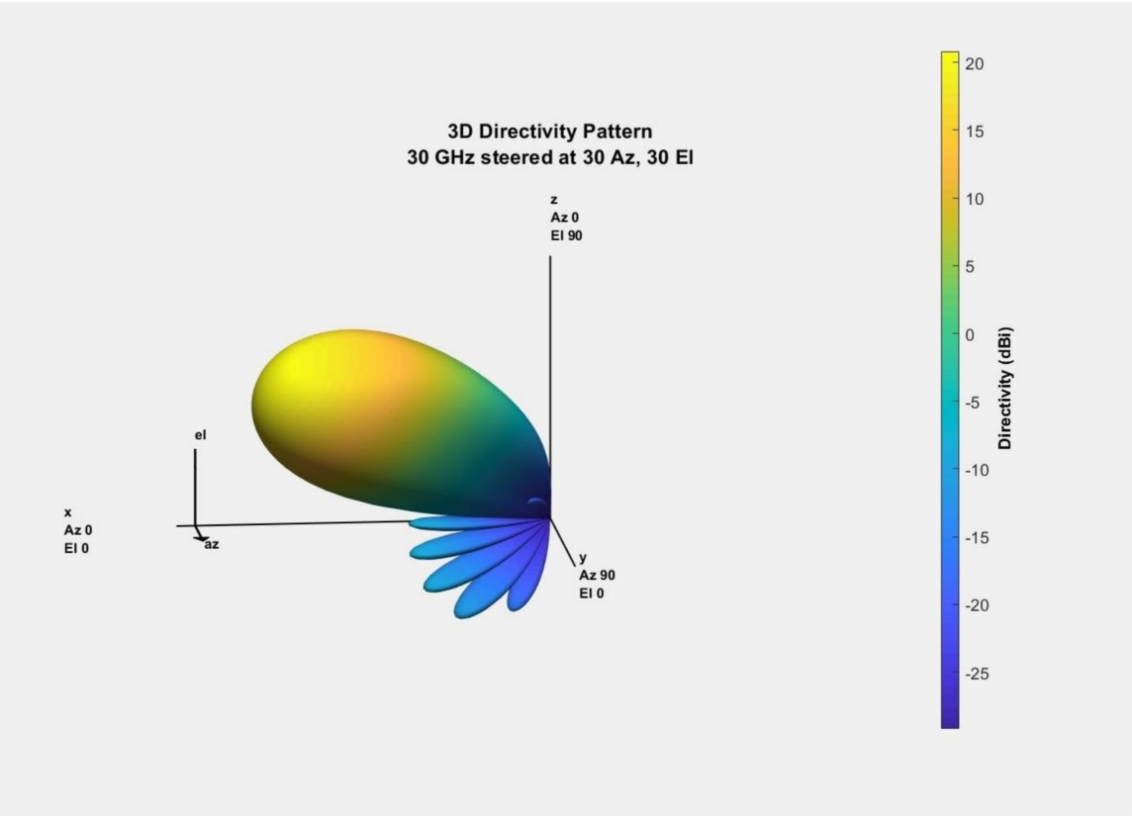

Figure 9. *Beam pattern of 16×16 uniform rectangular array*

Fig. 10 shows the 3D directivity pattern of 32×32 URA and fig. 11 shows the 3D directivity

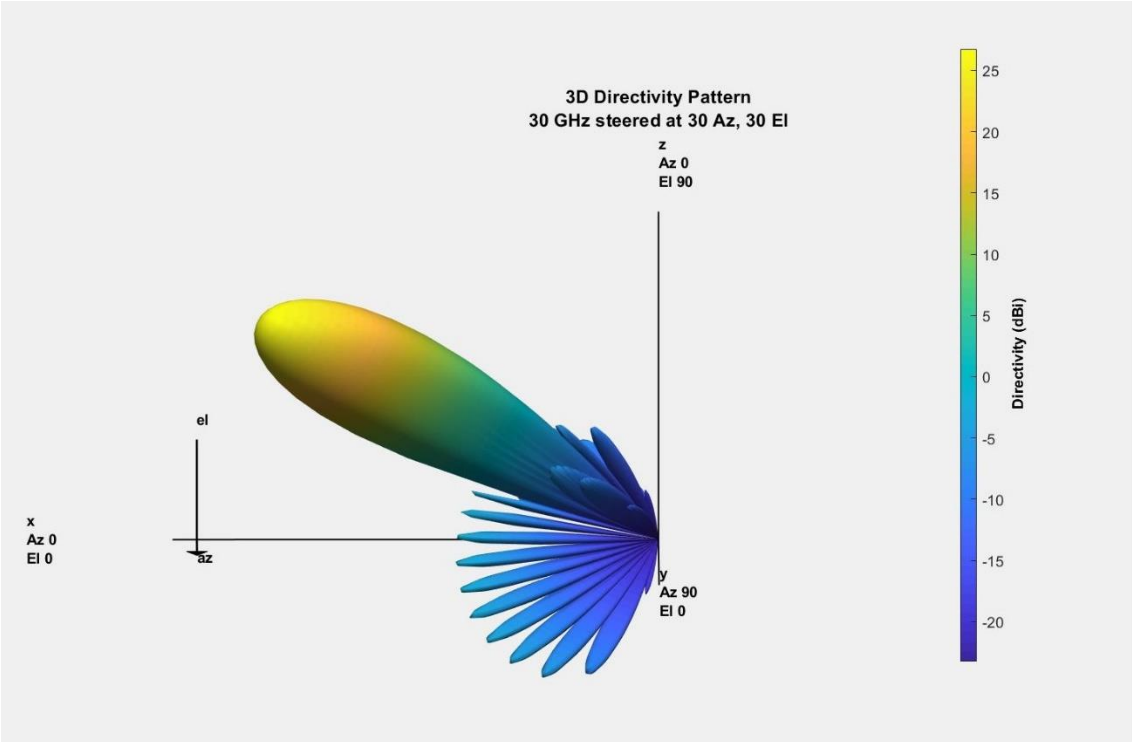

Figure 10. *Beam pattern of 32×32 uniform rectangular array*

pattern of 64×64 URA. For all 3 cases, spacing between the antenna elements was 0.0025 metre and Chebyshev tapering was applied to minimize side lobes. Cosine antennas were used to simulate the pattern.

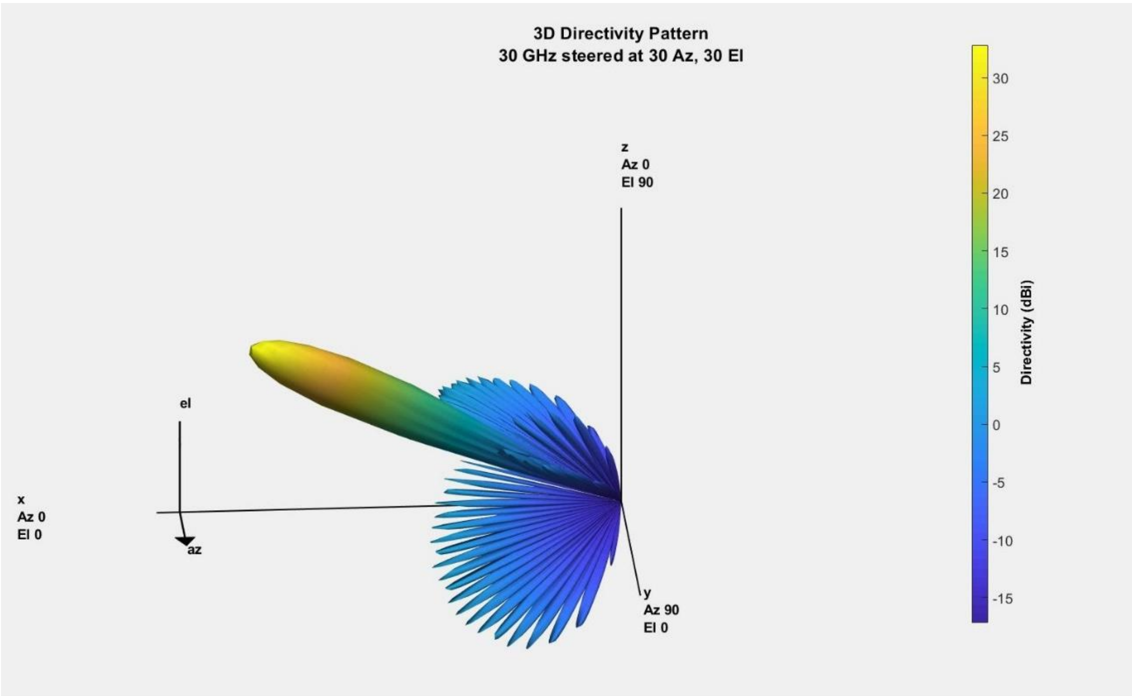

Figure 11. *Beam pattern of 64×64 uniform rectangular array*

2.6 Transmit beamforming

Transmit beamforming improves signal-to-noise-ratio (SNR) of a transmitter-receiver link by focusing energy towards a receiver. In this case a transmitter is called a beamformer and a receiver is called beamformee. A channel state information (CSI) of the channel between beamformer and beamformee is obtained by sounding of the channel. In order to do that, the beamformer sends a null data packet (NDP) to the beamformee. The beamformee then generate a feedback matrix by this measurement. The feedback matrix is then fedback to the beamformer. The beamformer then generates a steering matrix and transmit data to the beamformee. The whole process is shown in fig. 12.

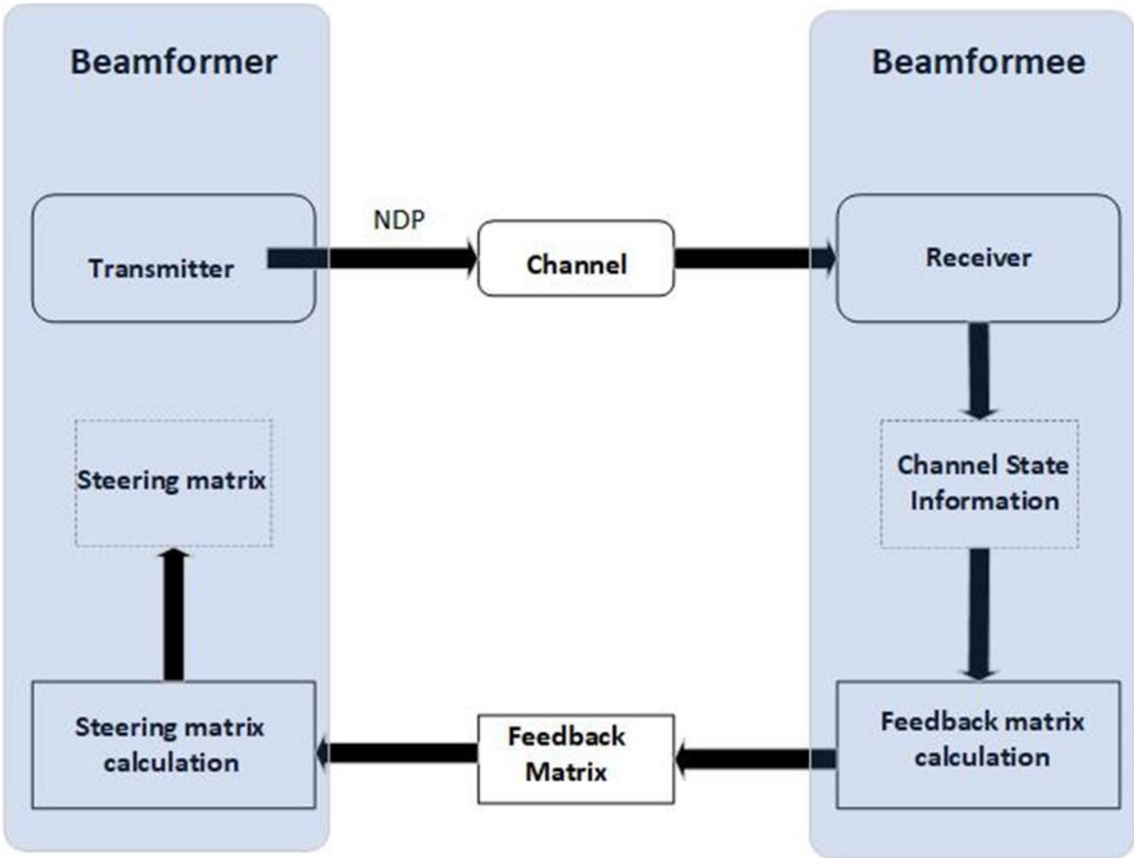

Figure 12. *Transmit beamforming*

2.7 Receive beamforming

Receive beamforming refers to steering the 'looking direction' of beams for any incoming signal. The conventional way to steer the beam towards the intended user is to use phase shift/time-delay and complex conjugate across all antenna elements. Fig. 13 represents a conventional beamformer known as delay-and-sum (DAS) beamformer which uses time delay and amplitude weight to the output of each element and sums the resulting signal. Consider an array of *M* number of antenna elements that are located in different positions in space $\overrightarrow{x_m} = [x_m, y_m, z_m]$ that measures a wavefront $f(\vec{x}, t)$. The wavefront sampled at each *m*th element is $y_m(t) = f(\overrightarrow{x_m}, t)$. Time delay, Δ_m and amplitude weight, w_m is applied to the output of each element and the resulting signal is summed as shown in fig. 13. By adjusting the delays, the array's direction of look can be steered towards the source and the waveforms captured by individual elements add constructively. Varying amplitude weight helps to maintain the gain or reducing side lobes of the beam. The output of DAS beamformer in a time domain is given as

$$z(t) = \sum_{m=0}^{M-1} w_m . y_m(t - \Delta_m). \qquad (2.3)$$

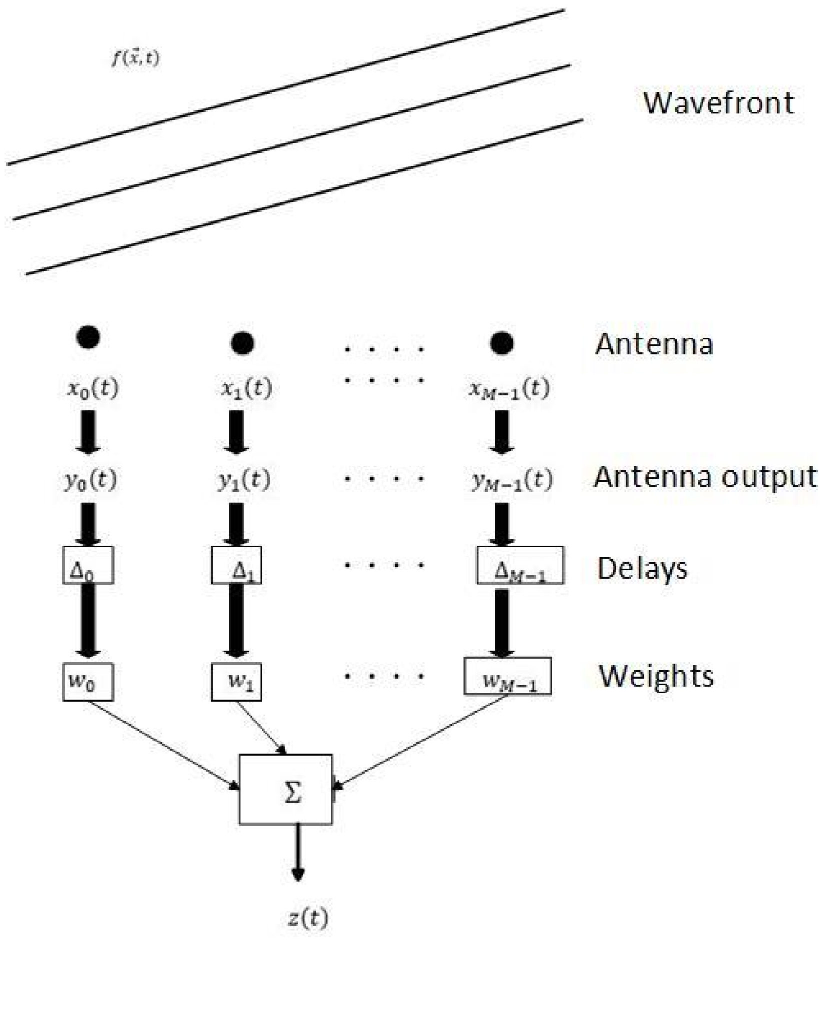

Figure 13. *Delay and sum beamformer [49]*

In terms of phase shifts, time delays can be expressed as

$$y_m(t - \Delta_m) = y_m(t). e^{-j\omega\Delta_m}, \qquad (2.4)$$

where $\omega = 2\pi f; f$ is the frequency of the signal. The output of the DAS beamformer can be stated again as

$$z(t) = \sum_{m=0}^{M-1} w_m . y_m(t) . e^{-j\omega\Delta_m}. \quad (2.5)$$

Eq. (2.5) can be written in vector form as

$$Z = W^H Y, \quad (2.6)$$

where Y is the vector of the received signal from each element with its individual phase delay, W^H is the complex conjugate transpose of weighting vector. The power, $P(z)$ or the variance, σ^2 of the output signal can be calculated as

$$P(z) = \sigma^2 = E\{|z|^2\} = W^H R W, \quad (2.7)$$

where $R = E\{YY^H\}$ is the correlation matrix of the incoming signal.

2.8 Procedures of beamforming

3GPP has specified a set of basic procedures for sweeping, adjusting and reporting of the beams termed as beam management [9]:

1. Beam sweeping: it refers to the covering of the spatial area containing transmitter and receiver at regular interval and specific direction.
2. Beam measurement: it refers to the evaluation of the beams used in sweeping. The measurement is done based on reference signal received power (RSRP), reference signal received quality (RSRQ), received signal strength indicator (RSSI) or signal-to-interference-plus-noise-ratio (SINR) [10].
3. Beam Selection: Selection of the best beam to achieve optimum connectivity between transmitter and receiver.
4. Beam reporting: The acknowledgement from the transmitter to receiver on the beam selection.

2.9 Classification of beamforming

Based on architecture and hardware implementation, beamforming can be classified into mainly 3 categories: analog beamforming, digital beamforming and hybrid beamforming.

2.9.1 Analog beamforming

An analog beamformer is built with one RF chain and multiple phase shifters across the antenna elements. The phase of each element is controlled by advanced hardware and improved precoding algorithms. The phase shifters are responsible for steering the

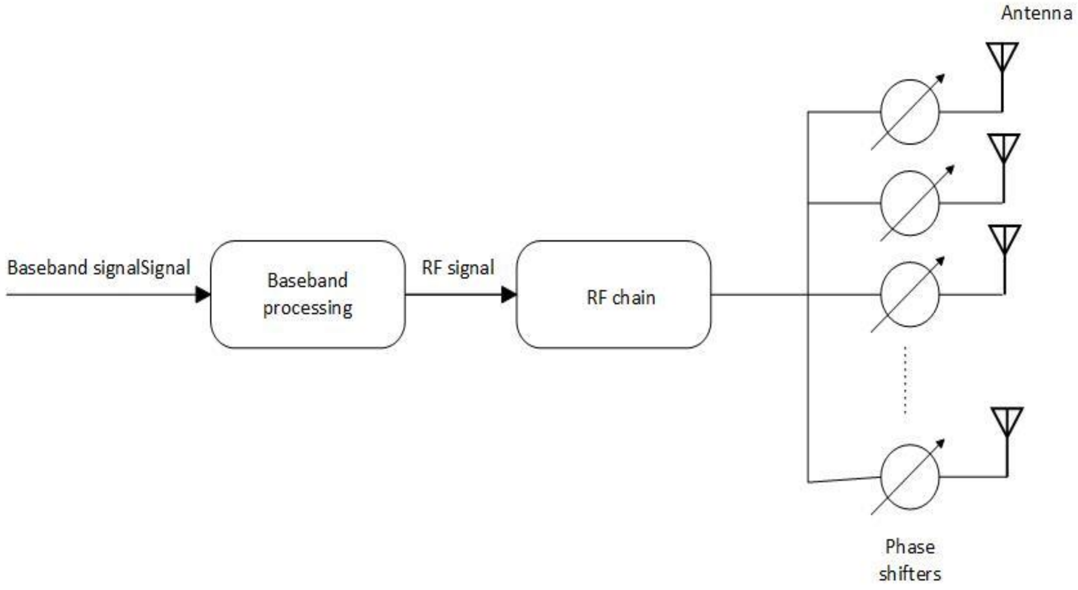

Figure 14. *Analog beamforming scenario [8]*

beam. Fig. 14 represents an analog beamformer with one RF chain. This type of beamforming is widely used in long range systems like radar and short-range communication system like IEEE 802.11 ad [8]. The advantage of analog beamformer is its simple implementation and cost reduction. On the other hand, one RF chain can transmit only one stream at a time.

2.9.2 Digital beamforming

In fully digital beamforming, the number of RF chains are same as antenna elements. That means each antenna element is equipped with a dedicated RF chain and phase shifter. Though theoretically digital beamforming is the best architecture for beamforming but in practical implementation of such higher number of RF chain and analog-to-digital

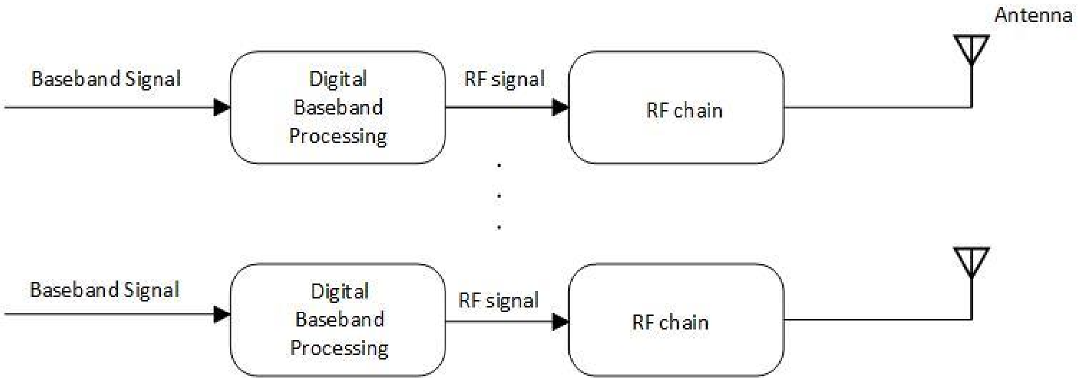

Figure 15. *Fully digital beamforming scenario [8]*

converter (ADC) is costly and complex task. Fig. 15 represents a fully digital beamforming structure. Multi-beam MIMO technique is possible with digital beamforming. However due to complexity and hardware cost it is best suited for base stations instead of mobile devices.

2.9.3 Hybrid beamforming

Hybrid beamforming is designed to exploit the advantages of both analog and digital beamformers. Hybrid beamforming architecture is designed by combining multiple arrays into sub-array module [11]. Thus, the trade-off between cost and flexibility is well maintained in hybrid beamforming and making it a suitable technique for 5G NR deployment. Hybrid beamforming structures are further divided into many categories such as full-connected hybrid beamforming, sub-connected hybrid beamforming, virtual sectorization, switched matrix and so on. Each structure has its own advantage and challenges. Fig.16 represents a full-connected hybrid beamforming structure. In full-connected hybrid beamforming, each RF chain is connected to a respective number of phase shifters and to all antenna. In sub-connected hybrid beamforming architecture, each RF chain is assigned to a sub-array of phase shifters. Full-connected hybrid structure has a higher beamforming gain compared to sub-connected hybrid structure, but its implementation is difficult due to complexity. Fig. 17 represent a sub-connected hybrid structure, where each RF chain is connected to set of phase-shifters or sub-array to perform multi-beam steering. This type of structure is useful for femto-cells to conserve power.

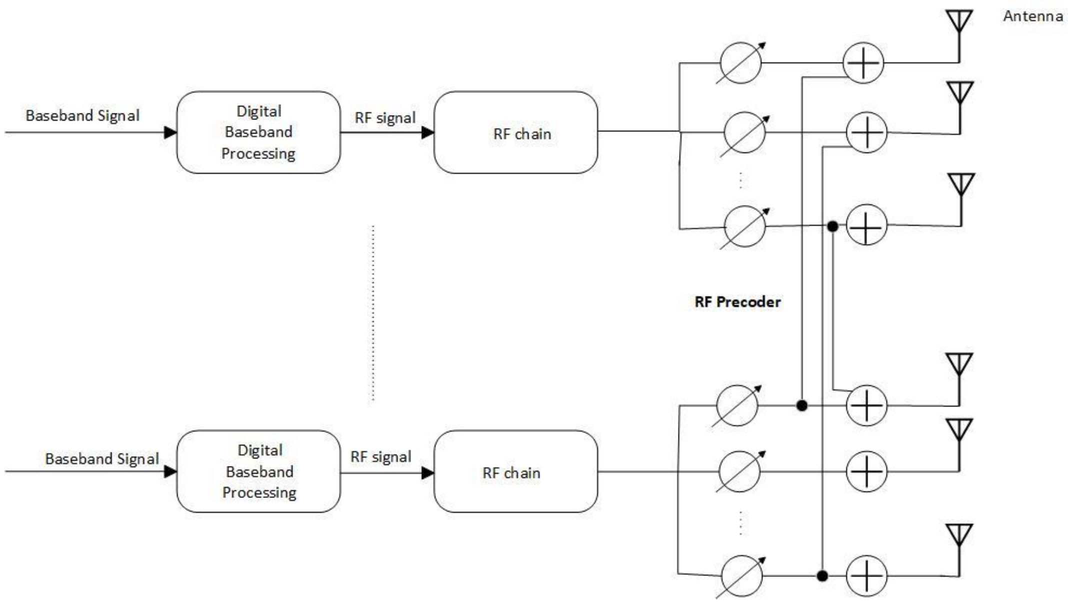

Figure 16. *Hybrid beamforming scenario, full-connected structure [8]*

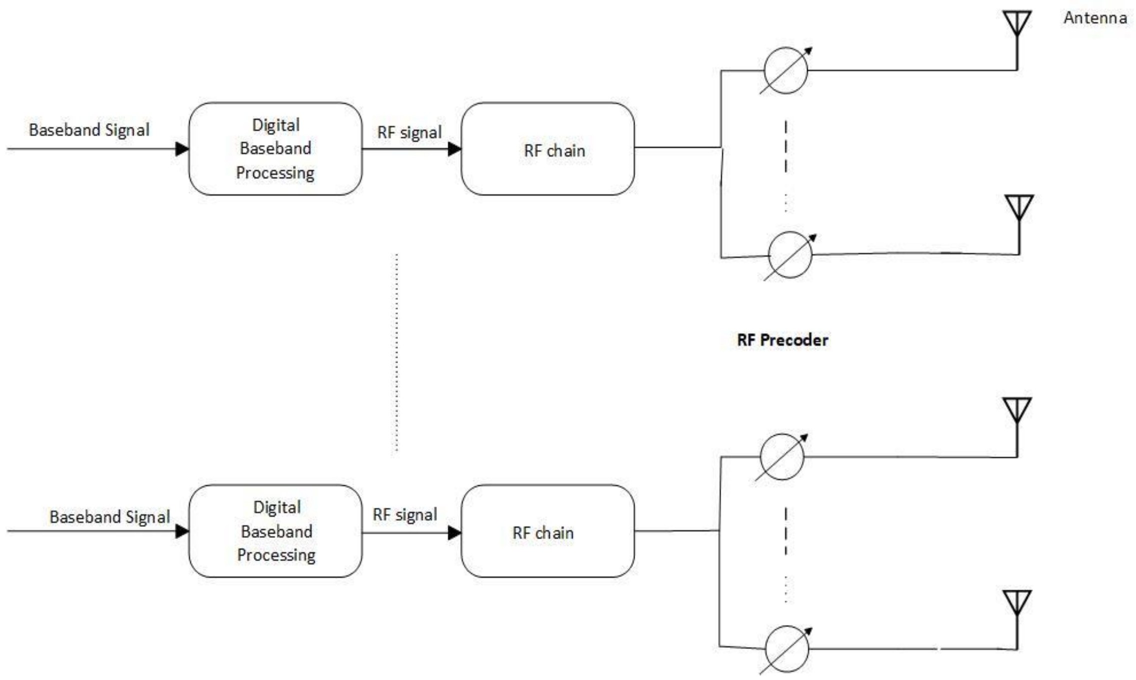

Figure 17. *Sub-connected hybrid beamforming [12]*

Another implementation of full-connected hybrid beamforming structure is virtual sectorization of digital baseband. Each sector can be used for baseband processing of a specific group of users. Thus, it reduces the signalling overhead and computational complexity. For 5G NR, this kind of hybrid structure can be well-suited. Fig. 18 depicts the hybrid virtual sector structure.

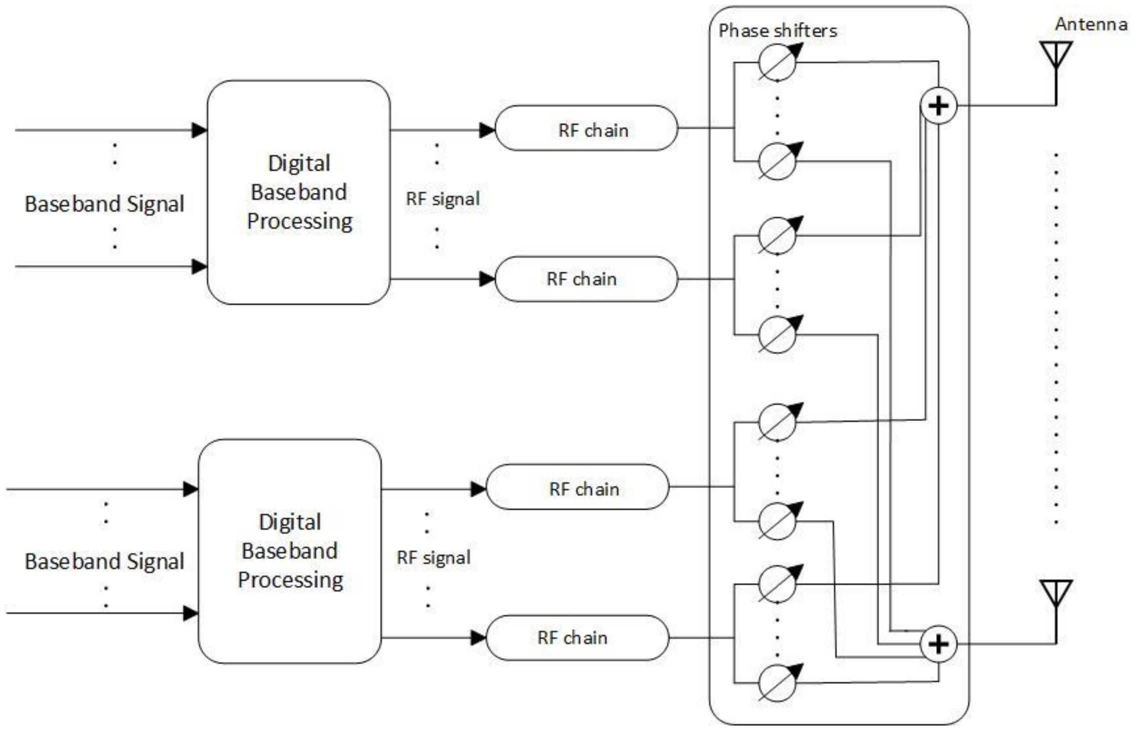

Figure 18. *hybrid beamforming structure with virtual sectorization [12]*

3. BENEFITS OF BEAMFORMING

Beamforming is an important tool for deploying 5G NR in different use case scenarios. There are many benefits of beamforming as a single option or combined with other techniques. This chapter includes such benefits as transmission diversity, beamforming gain, interference suppression, energy efficiency, system security, reduction in delay spread and overall spectral efficiency.

3.1 Transmission diversity

Massive MIMO refers to a MIMO system with large number of antennas. Massive MIMO will play a key role in 5G standardization with many benefits associated with it such as combating fading due to multipath propagation and providing diversity. For reliable data transmission over wireless channel, MIMO uses 3 techniques: precoding, spatial multiplexing and space-time coding. Precoding is a process to weight (phase and amplitude) the feeding data streams according to the channel matrix between transmitter and receiver. Spatial multiplexing is a technique used to divide an outgoing signal into multiple different streams and transmit them via different antennas parallelly. Precoding is similar to the concept of digital beamforming which enables multi-stream transmission. Spatial multiplexing and precoding are both necessary for 5G use cases to increase the data rate and throughput. Spatial multiplexing is more reliable with the complete CSI as a feedback from the receiver. If the receiver CSI is known at transmitter through feedback, then it is called a closed-loop system. If no CSI is available from the receiver as a feedback, then it is called an open-loop system [20]. Based on CSI and implementation perspective, precoding has also different categories to be employed in 5G system to achieve maximum channel capacity.

Fig. 19 (a) represents a 2×2 MIMO spatial multiplexing technique and fig. 19 (b) represents a 2×2 MIMO precoding technique. Both systems consist of two antennas at transmitter and two antennas at receiver side. In spatial multiplexing technique, two data symbols are transmitted by each transmission antenna over different propagation paths and received at receiver antenna as a sum of multiple streams. However, in precoding two data symbols are pre-coded as multi-layers according to the channel information and then fed to the transmitting antenna. This layering is done by using pre-defined codebooks for different number of MIMO antennas to achieve higher SINR [21]. In space-time coding, multiple coded copies of main signal are transmitted using multiple antenna to the receiver for decoding.

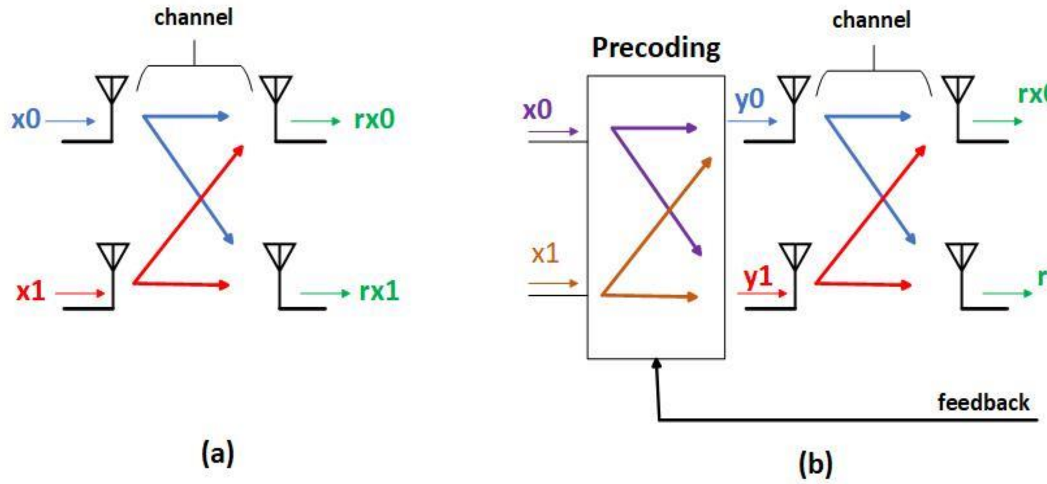

Figure 19. *(a) 2×2 MIMO with spatial multiplexing technique(b) 2×2 MIMO with precoding technique [21]*

In 5G, MIMO can be employed with one individual technique or with the combination of two or three techniques. However, requirements of these techniques are contradictory in terms of antenna spacing. For spatial multiplexing and space-time coding, the antenna spacing need to be sufficiently large compared to precoding. For example, if λ is the wavelength of transmitted signal, then the antenna spacing for spatial multiplexing and space-time coding requires more than 10λ whereas for precoding or beamforming the required space between antenna element is $\lambda/2$. In [37], the authors proposed a system model which combines spatial multiplexing and beamforming. The proposed scheme performs downlink beamforming using uplink direction-of-arrival (DoA). Fig. 20 depicts the proposed system model with *N* number of antenna elements in each array and *M* number of arrays in transmitter side with splitter option. It is shown through the calculation of channel matrix that the proposed scheme can improve spectral efficiency and system throughput. The combined scheme enhances the bit-error rate (BER) of the system by $10log_{10}(N)$ compared to traditional spatial multiplexing techniques such as vertical-Bell laboratories layered space-time (V-BLAST) technique and traditional beamforming technique. A combination of 3 MIMO techniques is proposed in [38] and it is shown that the proposed scheme provides better BER performance than other system benchmarks. It is suitable for rich scattering environment and provides diversity gain as well as beamforming gain. However, due to increased number of antenna size and sparse nature of channel in mmWave system, a hybrid precoding scheme is proposed in [25]. Through comparison with different system benchmarks, it was shown that this hybrid scheme can be well-suited for upcoming 5G deployment. Various authors have urged about the necessity of hybrid precoding in their work [13]-[17] for mmWave communication in terms of reduced complexity, low power consumptions and other system aspect. In summary, it can be said that hybrid precoding can leverage the trade-off between energy efficiency and spectral efficiency in 5G.

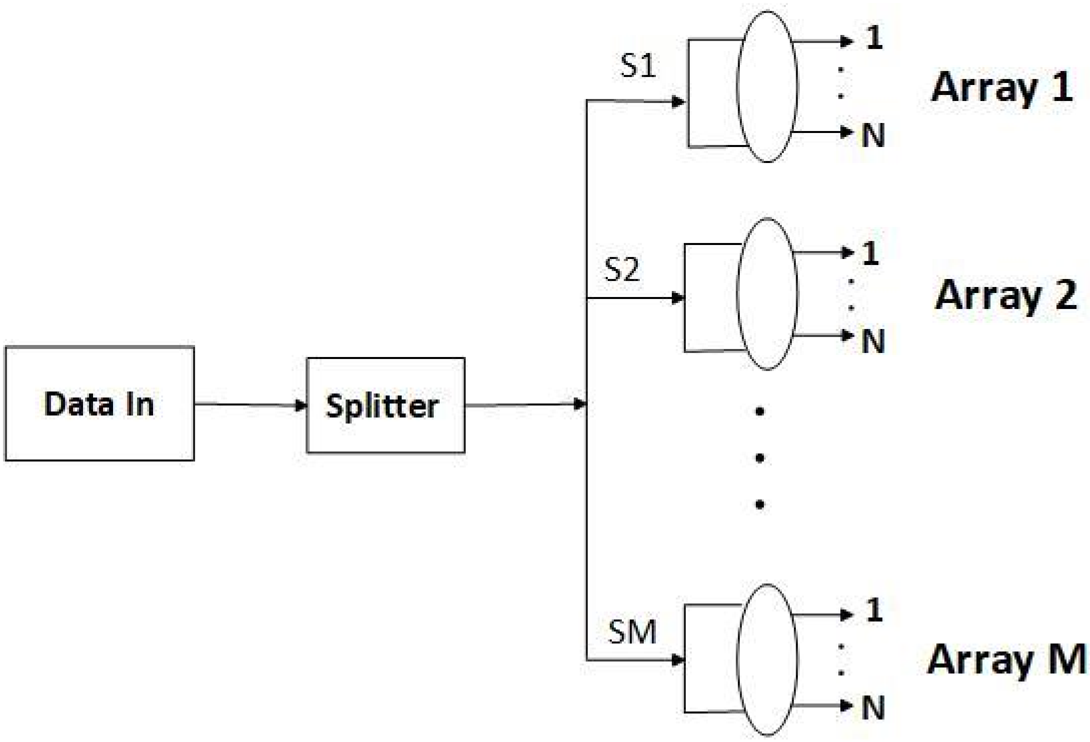

Figure 20. *Transmitter structure of the proposed system model in [37]*

3.2 Beamforming gain

There are two types of gains associated with beamforming techniques: array gain and diversity gain. Array gain is defined as increase of average output SNR depending on the antenna elements. If there are *M* number of antenna elements in an array, then array gain is a maximum of *M*. A 30 element ULA will provide better SNR than a 10 element ULA. For example, a rectangular signal arrives at a ULA of 10 isotropic elements from an angle of 45^0 azimuth and 0^0 elevation. A phased shift beamformer was used to collect the signal with noise and the output is shown in fig. 21. The signal becomes much stronger compared to the noise as the number of elements increases in the array. The noise floor decreases with the increment of antenna elements providing a better SNR. Diversity gain is observed in multipath propagation. Average over fading, for a given BER, the decrease of average received SNR is called diversity gain [25].

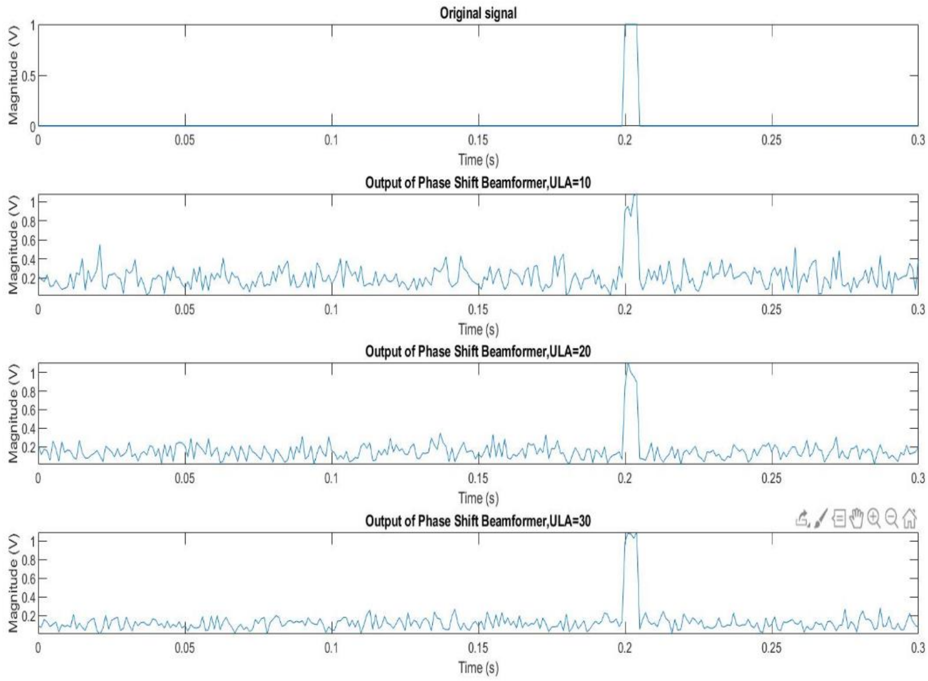

Figure 21. *SNR improves with the number of antenna element*

Friis' law defines the relation between the transmit power P_t and receive power P_r in free space which can be described as

$$P_r = G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 P_t \, , \tag{3.1}$$

where all the powers are in linear scale, d is the distance between transmitter and receiver, λ is the wavelength and G_t and G_r are the transmitter and receiver antenna gain respectively. With a given amount of P_t, $\lambda, d,$ the received power P_r depends on the antenna gains G_r and G_t. Moreover, higher frequencies in 5G like 30-300GHz yields lower λ compared to conventional lower frequencies. So, from Friis' Law it is easily imaginable that without high directional antenna gains, the average received power will be lower in any propagation path. Therefore, beamforming with high-dimensional array can help increasing antenna gain and thus improving the received power.

A diversity order of single beamforming (transmitting one symbol from all transmitting antenna at the same time using best sub-channel) and multiple beamforming (transmitting *S* symbols, *S*>1) was derived in [39]. The sub-channels were separated from MIMO channel using singular value decomposition (SVD) method. If the number of transmit antenna is *M* and number of receive antenna is *N* in a MIMO system, then it is showed that single beamforming can achieve maximum spatial diversity as an order of (*M.N).*

For multiple beamforming using S number subchannel or symbol the diversity order becomes *(M-S+1).(N-S+1).*

In [50], a shared-aperture antenna (SAA) is proposed for 5G system with high gain and pattern diversity. The concept of SAA is to combine one or more antenna in a shared aperture for multi-functionality without affecting the performance of other antennas shared on same platform.

Beamforming gain was measured in a 5G testbed in [18] with respect to mobility reference signal received power (M-RSRP) of user equipment (UE). Different indoor and outdoor environments were chosen to measure and log the M-RSRP. Analog grid-of-beams (48 fixed beams) with equal power on all beams were used at the base station (BS). The measured gain was compared with a wide beam reference antenna. It was shown that the measured beamforming gain for different environment is higher than the reference gain. Assuming perfect phase coherent transmission on *N* number of strongest beams, hybrid beamforming gain was also measured with two transmit power option: (1) equal power distributed over the beams and (2) optimized power proportional to received power in UEs. For analog beamforming upper bound was set to 15 dB and for hybrid beamforming upper bound was set to 16 dB according to system parameters. Table 2. summarizes the measurements.

Table 2. *Measured gain in different environment*

Environment	Analog grid-of-beam gain(dB)	Hybrid beamforming gain(dB) with required N
Outdoor environment inJapan	11-13	14;N=2
Indoor environment Japan	5-11	14;N=8
Outdoor environment non-LoS propagation in Sweden	7-12	14;N=5
Outdoor environment LoS propagation in Sweden	9-13	14;N=3

3.3 Interference suppression

Beamforming use the spatial dimension to suppress interference by increasing SINR. A typical array with *M* antenna element has a (*M-1*) degree of freedom to null (*M-1*) interfering user while providing gain towards the desired user [25]. The basic way of getting rid of the interference problem is using zero-forcing (ZF) beamformer, which is of lower complexity. In ZF beamforming, weight vectors are carefully chosen from the user's inverted composite channel matrix to avoid interference between user streams [40]. Fig. 22 shows a general phased-array transmitter, where a beam is formed in a desired direction by varying relative delay in each element. If the input signal *S(t)* is delayed at each element is a multiple of time delay τ, then the final signal that add up constructively in a direction α is given by

$$S(t) = \sum_{k=0}^{N-1} s\left(t - k\tau - (N-1-k)\frac{dsin\alpha}{c}\right), \quad (3.2)$$

where c is the velocity of light, d is the distance between antennas, N is the number of antennas and $\tau = (dsin\alpha/c)$. Similarly, the incoherent addition is directed towards the unwanted signal to supress interference. It can be seen from (3.2) that, if P (watts) is the omnidirectional radiation power of each antenna element, then the effective isotropic radiated power (EIRP) towards the main beam direction can be calculated as N^2P (watts). For example, if each transmitter in an 8-element array radiates 14 dBm, then the EIRP in the beam direction increases followingly,

$$\mathrm{EIRP} = (20\log_{10}8) + 14dBm = 18dBm + 14dBm = 32dBm.$$

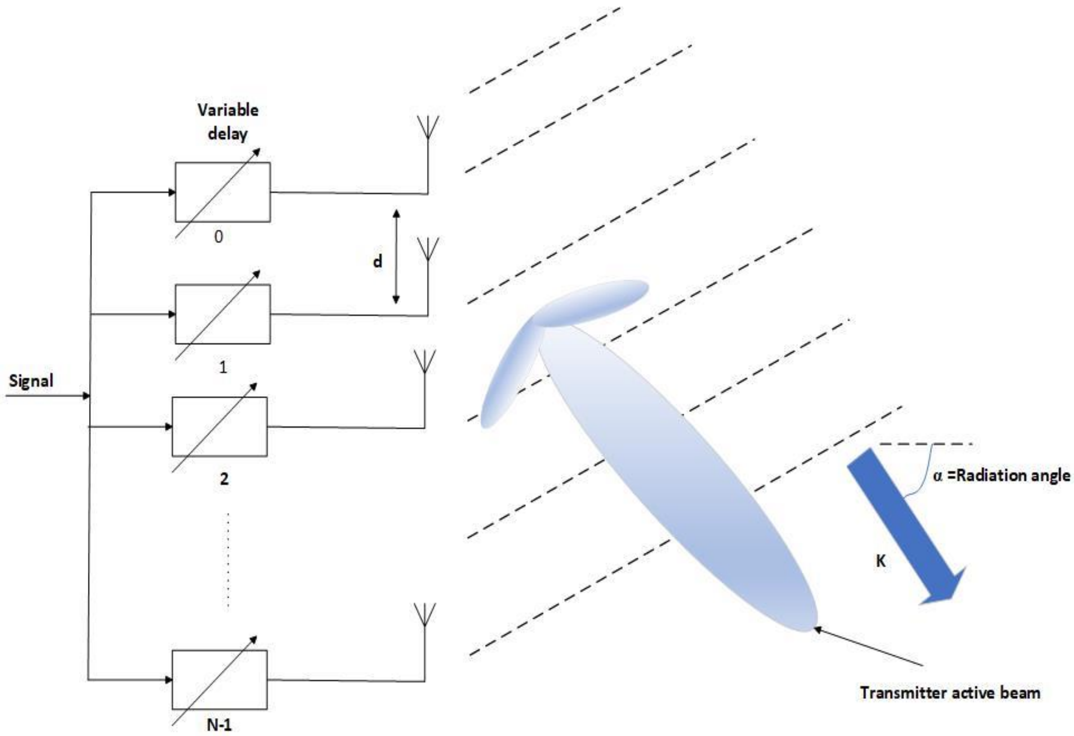

Figure 22. *N-element phased array transmitter [19]*

Higher frequency reuse is possible because of higher directivity of phase-array transmitter. Better interference suppression and rejection helps to increase network capacity [19].

Most of the beamformer like ZF requires full information of CSI but in [22], it is showed that eigen and orthogonal beamforming technique can improve SINR and help mitigating intercell interference even with partial information of CSI to get high system throughput.

3.4 Energy efficiency

Energy efficiency is one of the desired system aspects for upcoming 5G to be deployed globally. Among many phase-1 projects of 5GPPP, one is to establish an energy-efficient wireless communication (Green communication) in order to reduce manufacturers operational cost and CO_2 emission [51]. Most of the power consumed in wireless communication is associated with BS, almost 80% [23]. In active mode the power consumption of a BS is calculated by

$$P_{active} = \frac{\omega B(P_1+P_{bp})N_{bs}+N_{bs}P_2+P_{tx}/\eta_{pa}}{(1-\beta_d)(1-\beta_m)} \quad , \tag{3.3}$$

where ω is the ratio of bandwidth, *B* is the bandwidth of the network, N_{bs} is the number of antennas at BS. P_1, P_2, P_{bp} denotes power consumed by ADC, filters and other transceiver part respectively. η_{pa} denotes efficiency of power amplifiers and P_{tx} denotes transmit power of BS in the network. β_d and β_m denotes loss factor due to direct power supply and main power supply respectively. Hybrid beamforming can reduce the consumed power by employing optimal number of ADC, power amplifiers (PA) and other devices in baseband processing in BS according to the system requirement of 5G. Beamforming can also minimize the total power consumption of a BS by determining the optimal quantity of antenna elements [24]. Multi-level beamforming can improve the cell capacity and reduce consumed power. Multi-level beamforming is done using a multi-level codebook suitable for a given scenario for example, urban or rural. Energy efficiency of a network is a comparative concept and can be expressed as

$$Energy\ efficiency = \frac{Total\ data\ rate\ (bit/s)}{Total\ power\ consumption\ (watt)} \,. \tag{3.4}$$

Even with beamforming, it is possible to reduce 50% energy consumption while providing 10 times more capacity [31]. Beamforming can reduce the required number of BSs employed individually or in collaboration with cell discontinuous transmission (Cell-DTX) in a rural area [30]. Cell-DTX is a hardware implementation that disables some functions of BS to conserve energy in idle stage or sleep mode when there is no transmission. A rural area model of non-uniformly distributed users was generated by Lloyd algorithm. Two carrier frequencies were chosen: 0.8 GHz (LTE) and 28GHz (5G). The Idea was to determine the number of required BS to serve 95% of that users at busy hour at 50Mbps data rate. The simulation result shows that in both cases (LTE and 5G) beamforming (with DTX/without DTX) reduces average consumed power to a great extent. Moreover, beamforming also reduces the number of required BSs which increase the signal strength and suppress the interference which allows the system to conserve energy. Table 3 depicts the results obtained in [30].

Table 3. *Energy consumption in different conditions*

System (Frequency)	Area power consumption when there is no beamforming or cell-DTX (KW/Km^2)	Area power consumption when there is only cell-DTX (KW/Km^2)	Area power consumption when there is only beamforming (KW/Km^2)	Area power consumption when there is both beamforming and cell-DTX (KW/Km^2)
LTE (0.8GHz)	115.60	34.90	6.70	3.10
5G (28GHz)	4.10	2.20	0.70	0.60

3.5 System security

Secure transmission over wireless channel is another feature that can be added to beamforming's benefit list. Many systems consider secrecy and energy efficiency as one performance index as secrecy energy efficiency (SEE) which can be expressed as secrecy bits per joule [35]. Beamforming can increase system security by steering main lobe towards desired UE and nulls towards interferer UE. This is a common problem-solving feature when the interferer is not in line-of-sight (LOS) with desired UE. But there are other problems which can deteriorate the transmission between BS and UE. For example, an eavesdropper can steal the information or listen to the signal not being in the LOS. A jammer can jam the signal to reach destined UE. Robust beamforming algorithm and multi-layer precoding can solve this kind of problems. A hybrid beamforming scheme was proposed in [33] with artificially generated noise to combat eavesdropper problem in a relay system. Two stage (Phase 1: source-to-relay and phase 2: relay-to-source) hybrid algorithm was used to improve physical layer security of MIMO. Having full CSI between BS and UE, beamforming vectors can be designed to transmit interference towards eavesdropper while transmitting main signal towards respective UE in case of channel variation or user mobility [34]. Under static channel, secrecy rate, R_s of a UE and an eavesdropper can be calculated in terms of SINR as

$$R_s = \log(1 + SINR_u) - \log(1 + SINR_e), \tag{3.5}$$

where $SINR_u$ and $SINR_e$ are the respective SINR of UE and eavesdropper. It is shown in [33]-[35] that associated with other techniques and computational procedures, beamforming can solve the eavesdropper and jamming problems in time-varying channels in wireless communication and can enhance overall system secrecy.

3.6 Reduction in delay spread

Due to multipath propagation, a signal travels different distances to reach receiver which causes delay. This causes delay spread. By focusing the energy in a certain direction, beamforming can reduce the multipath reflection and hence delay spread. In receiver side, the delay is compensated by optimal combining of the vectors. Uncompensated delays are cancelled by steering nulls towards their direction.

Beamforming also control the spread of Doppler frequencies occurring at the UE side due to smaller angular spread. In an urban case, when the receive signal is the superposition of multiple waves at random direction, Jake's Doppler spectrum can be calculated by [52]

$$S_r(f) = \left\{ \begin{array}{ll} \frac{1}{\pi f_m \sqrt{1-\left(\frac{f}{f_m}\right)^2}} , & f \leq f_m \\ 0 , & f > f_m \end{array} \right\}, \tag{3.6}$$

where f is the doppler shift and f_m is the maximum doppler shift. However, for directional antenna at the base station, if $|f| < f_m$, then the Doppler spectrum is given by [47]

$$S_r(f) = \frac{A_0^2}{\pi f_m \sqrt{1-(f/f_m)^2}} \cdot [f_\theta(\phi_v + |cos^{-1}(f/f_m)|) + f_\theta(\phi_v - |cos^{-1}(f/f_m)|)], \tag{3.7}$$

where A_0 is the mean transmitted power, ϕ_v is the angle between the direction of motion of UE with respect to the direction of BS and $f_\theta(.)$ is the probability density function (PDF) of the DoA of the multipath components at the UE as given by

$$f_\theta(\theta) = \begin{cases} \frac{R^2}{I} , & -\theta_1 < \theta < \theta_1 \\ \frac{(Dtan(\alpha))^2}{I(sin(\theta)+cos(\theta)tan(\alpha))^2} , & \theta_1 < |\theta| \leq \theta_2 \\ \frac{R^2}{I} , & \theta_2 < \theta < -\theta_2 \end{cases} , \tag{3.8}$$

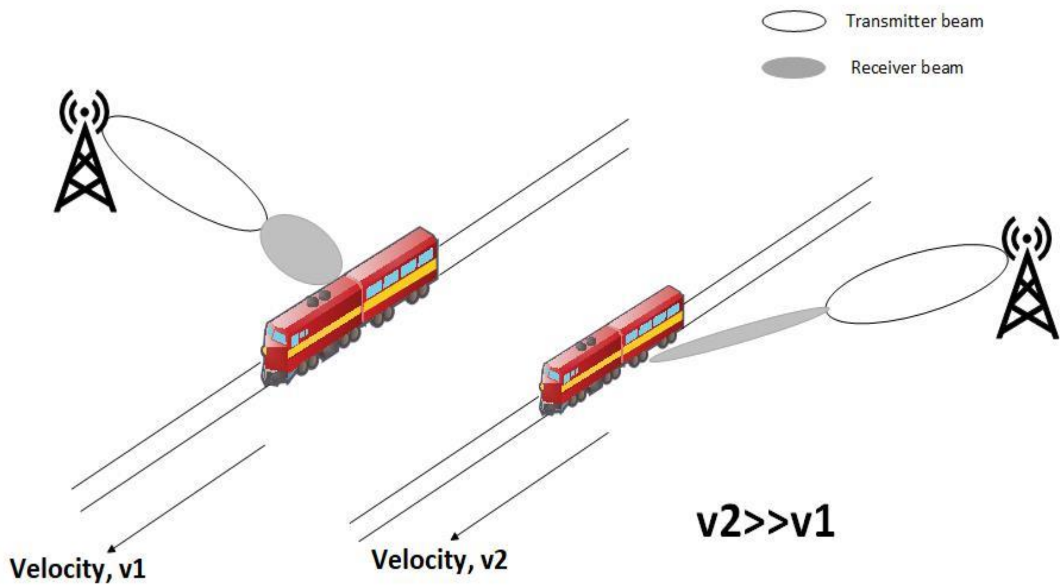

Figure 23. *Maximum Doppler spread can be controlled by adjusting receiver beam-width [53]*

where

$$I = 2R^2(\pi + \theta_1 - \theta_2) + 4Dsin(\alpha)\sqrt{R^2 - D^2 sin^2(\alpha)}\,. \tag{3.9}$$

Here R is the radius of the circular area containing all the scatters, D is the distance between the BS and the UE, α is the half beamwidth of directional antenna. θ_1 and θ_2 are constants. Fig. 23 represents an illustrative example of beamforming employed in Vehicle-to-infrastructure (V2I) system. By adjusting the receiver beamwidth it is possible to control maximum Doppler spread [53]. Receiver beamwidth is given by

$$\theta_H^{RX}(°) = \frac{1.4 \times 10^4}{f_c(GHz).v(km/h)}\ , \tag{3.10}$$

where $\theta_H^{RX}(°)$ is the receiver beamwidth, f_c is the carrier frequency in GHz and v is the velocity of UE in km/h. For a low-speed train (50 km/h), the receiver beamwidth can be 10^0 but for a high-speed train (500 km/h), the receiver beamwidth should be 1^0 in order to control the maximum Doppler spread.

3.7 Overall spectral efficiency

Spectral efficiency of a wireless system is defined as the amount of information delivered or user served under a given bandwidth in each area. It is usually expressed as (bits/s)/Hz. [32] [41]. If a system has net data rate of 15Mbps and bandwidth of 2MHz, then the spectral efficiency of that system is measured as follows

$$Spectral\ Efficiency = \frac{Net\ data\ rate\ in \frac{bits}{s}}{Bandwidth\ in\ Hertz} = \frac{15Mbps}{2MHz} = 7.5\frac{bits}{s}/Hz.$$

Beamforming improves the spectral efficiency of a channel between BS and UE in various way [24]. Such as:

- Controlling the power of uplink and downlink signals based on AoA/DoA
- Utilizing the information of the training sequence
- Improving signal quality by beamforming antenna by suppressing interference and thus providing better SNR
- MIMO system with beamforming antennas at BS can improve system capacity and spectral efficiency with coherent precoding.
- The data rate of a system can be improved by beamforming as the download and upload speed depends on antenna gain.

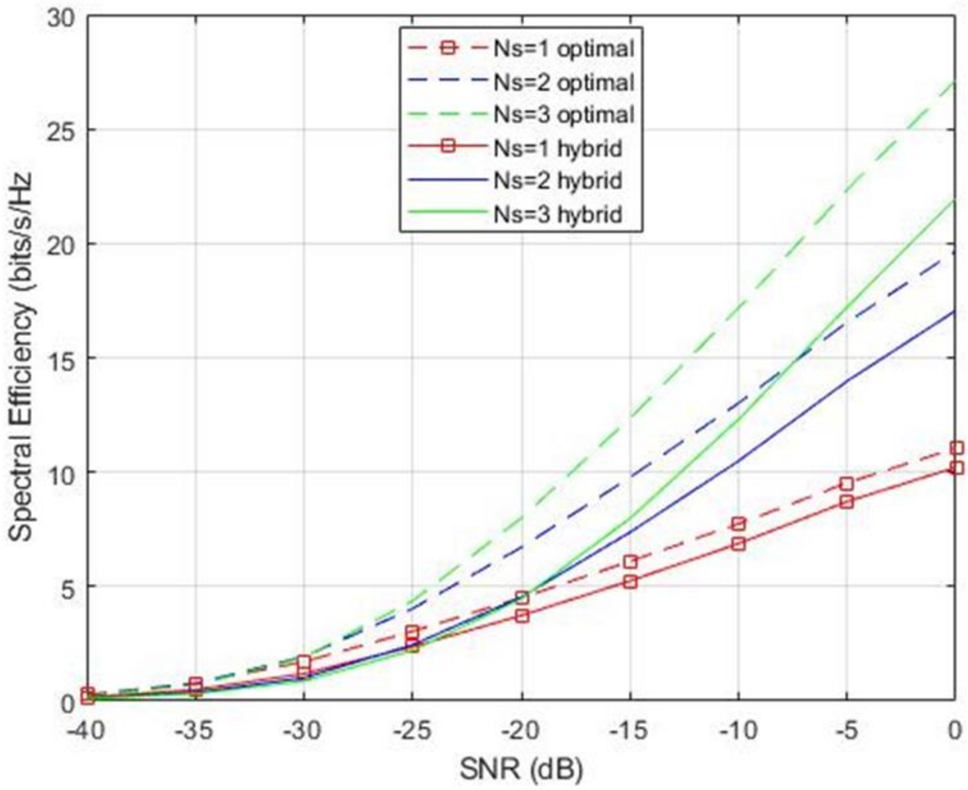

Figure 24. *Spectral efficiency measurement of hybrid beamforming*

With necessary requirements met, beamforming can perform better than other transmit diversity techniques. Beamforming is able to achieve channel capacity and maximum spectral efficiency under certain conditions like user handoff scenario, smaller angular spread and better feedback quality with channel state information reference signal (CSI-RS) [26]-[28]. One of the system metrics of 5G is spectral efficiency. Fig. 24 shows the spectral efficiency as a function of SNR in case of hybrid beamforming and optimal beamforming. In optimal beamforming the weighting vectors were chosen to achieve optimum performance by diagonalizing the channel matrix. A network consists of 64×64 MIMO with 4 RF chain both at transmitter and receiver can support up to 4 data streams. Carrier frequency was set to 30 GHz and AoD from transmitter is 60^0 azimuth and 20^0 elevation angles. Receiver can collect the wave from any direction. A scattering environment is considered using 8 clusters and, in each cluster, there are 10 scatterers with 6.5^0 angle spread. The path gain of each scatterers was computed using complex circular symmetric Gaussian distribution. Spectral efficiency was calculated in the SNR range of -40:5:0. 3 data streams and 50 monte-carlo iterations were used for the simulation. It can be seen from the fig. 24 that hybrid beamforming can achieve close spectral efficiency compared to optimal beamforming with less hardware required.

4. BEAMFORMING MANAGEMENT

Management of beamforming usually refers to choosing the best beam-pair between BS and UE for the best connectivity and adjust the beam-pair when necessary. It also has beam recovery protocol if the established beam-pair is broken due to any incident and tracking protocol for mobile UEs. Due to obstacles, the best connectivity path between a BS and UE can be non-line-of-sight (NLOS) instead of a line-of-sight (LOS) path. Beamforming management is done in both uplink (UL) and downlink (DL) transmission to ensure the connectivity. The process of beamforming management can be divided into many parts which are described thoroughly in this chapter.

4.1 Initial beam-pair establishment

The first step of beamforming management is to establish a beam-pair during initial access. 5G NR uses synchronization signal (SS) blocks for initial access. When a UE enters a cell, it receives a SS-block from BS. Multiple SS blocks can be transmitted in different downlink beams.

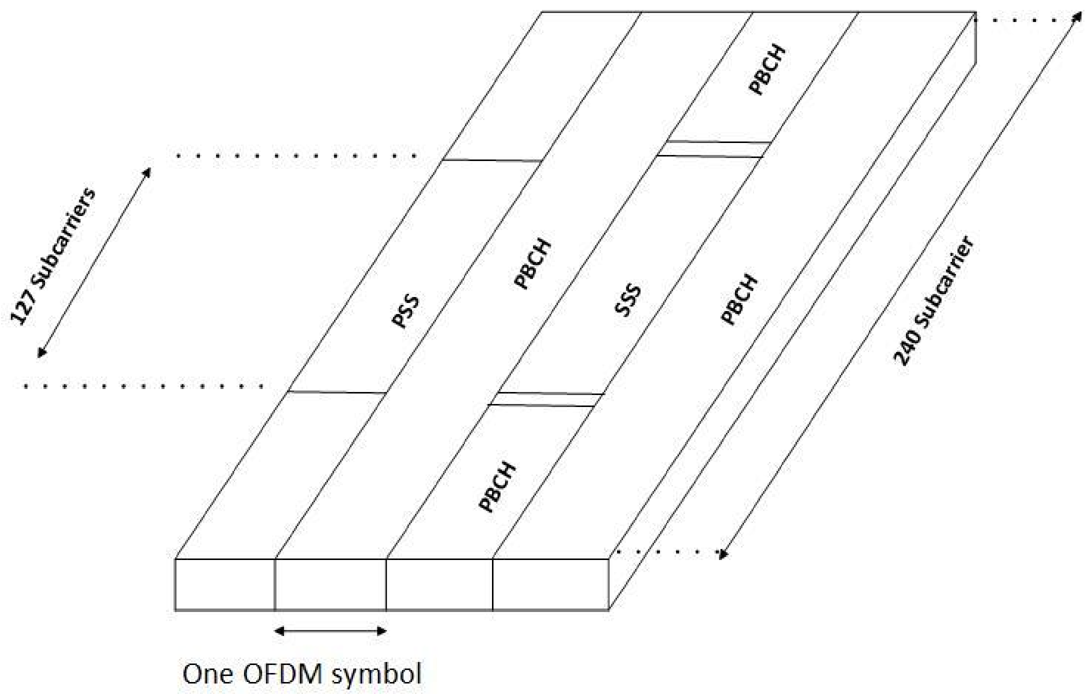

Figure 25. *SS block structure [1]*

A SS block contains physical broadcast channels (PBCH), primary synchronization signals (PSS) and secondary synchronization signals (SSS). The SS block is transmitted

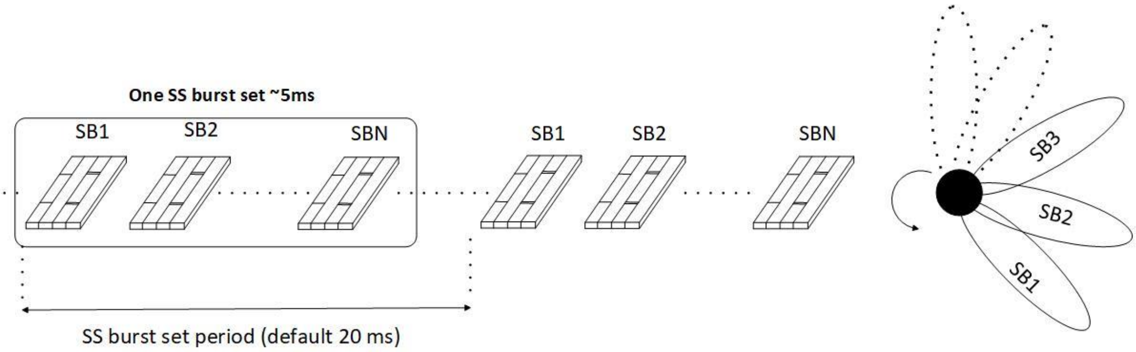

Figure 26. *SS block burst set period*

by orthogonal frequency division multiplexing (OFDM) technique to the UE. Fig 25 shows a SS block structure consist of 4 OFDM symbols. In 1st OFDM symbol, PSS uses 127 subcarriers. During initial beam-pair establishment process, BS sends a burst of SS block in each beam with a minimum interval time of 5ms in a sweeping manner as shown in the right side of fig 26. The beam sweeping is done in a time-multiplexed fashion and all transmitted SS blocks are called a SS burst set. Each SS burst set has a default period of 20 ms. BS side beam sweeping also helps in UE side beamforming in uplink. Depending on frequency range of sub-carriers, 64 beam-sweeping is possible [1].

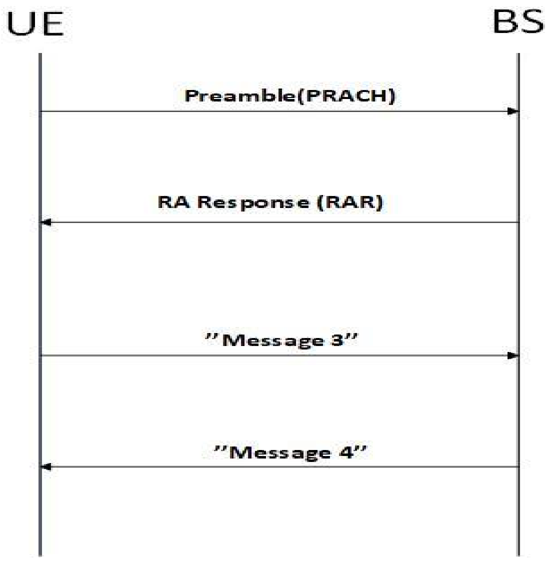

Figure 27. *Random access process*

As a key feature of 5G NR hardware implementation, a desired beam-pair can be established during initial access stage. It is possible by enabling UE side analog-beam-sweeping for preamble reception and merging different SS-block time indices with different random-access channel (RACH) occasions. Based on the received preamble, the BS can identify the downlink beam of the UE to use as an initial beam. With the help of digital beamforming technique, UE can sweep over the area in synchronization with the downlink beam for uplink beam establishment. Fig. 27 shows the initial beam establishment stage between UE and BS.

4.2 Beam tracking

Beam tracking refers to keeping the track of UE due to mobility. It is a measure to align beamforming vectors according to the changing characteristics of a channel between BS and UE. Beam tracking is the next phase of beam training and it is done to improve connectivity. Sectors are grouped into high resolution beam clusters to detect the best beam with higher resolution. Beam tracking is also done to detect the change in the beam former and combiner vectors. The vectors value can change due to channel characteristics over time. These vectors need to be adjusted for achieving optimal link. The selection of clusters is done quasi-periodically. The best beam and its adjacent beams are treated as best cluster. The second-best beam and its adjacent beams are selected as second-best cluster. Beam tracking also helps in handover situation between beams. Handover frequency of a UE can be set according to their speed. For example, a high-speed UE can experience least number of handovers between beam boundaries due to shorter time compared to a low-speed UE [54].

4.3 Adjustment of beam-pair

The connectivity path can face problems when an obstacle is placed between the established beam-pair consisting of BS-side beam and UE-side beam. Beam adjustment helps to overcome these kinds of situations. Beam adjustment also refers to the reshaping of the beams. For example, wider beam to narrower beam. As a beam pair is consists of BS-side beam and UE-side beam, so beam adjustment must be done in both way:

- Adjustment of BS-side beam, when UE-side beam is fixed in its direction
- Adjustment of UE-side beam when BS-side beam is fixed in its direction

4.3.1 Adjustment of DL BS-side beam

In DL BS-side beam adjustment, BS generates a set of reference beams and the UE selects the best beam based on best report quantity. As shown in fig. 28, the BS side reference beams sweeping is done by keeping the UE side beam fixed. The report quantity of reference beams includes rank indicator (RI), channel quality indicator (CQI), precoder matrix indicator (PMI). These 3 quantities are called channel state information (CSI). Another quantity is very important to measure the signal strength of the reference signals in wireless communication which is known as reference signal received power (RSRP). 5G NR uses Layer-1 RSRP (L1-RSRP) as a report quantity in beamforming management [1]. The measurement of L1-RSRP is carried out on either channel state information reference signal (CSI-RS) or SS block. If CSI-RS is used, then it should be limited to single or dual port CSI-RS. For SS blocks, the measured L1-RSRP is the linear average of the individual ports. The receiver can report up to 4 reference signals corresponding to 4 beams which includes:

- The measured L1-RSRP for the best beam
- The difference of measured L1-RSRP between best beam and remaining beam.

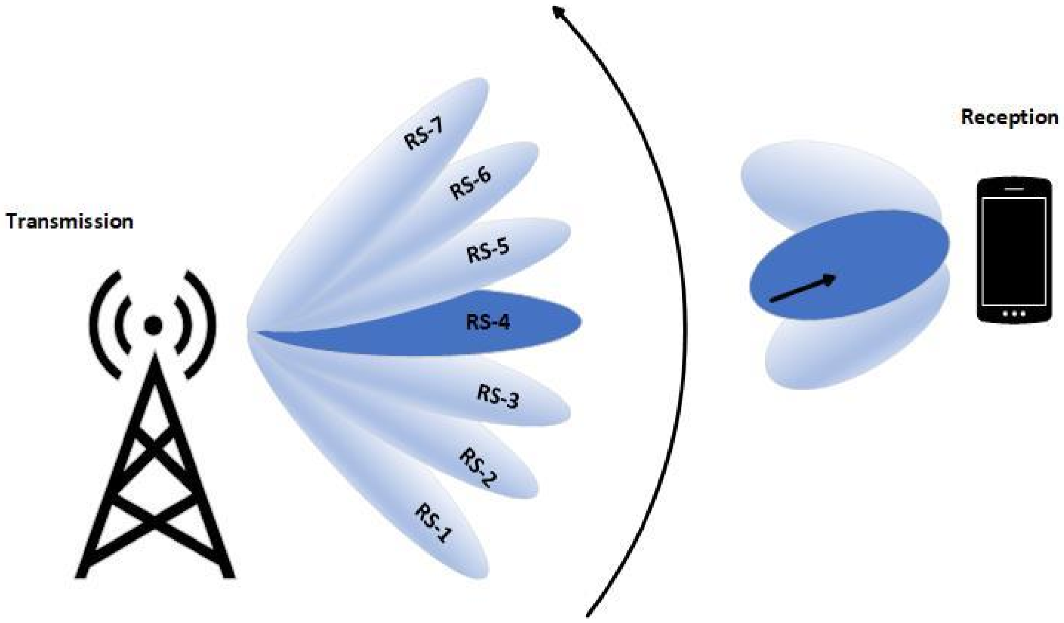

Figure 28. *BS-side beam adjustment in downlink*

4.3.2 Adjustment of DL UE-side beam

To adjust the UE-side beam in DL, the UE follows the same technique as discussed in 4.3.1 to find the best beam-pair. Fig. 29 represents the DL UE-side beam adjustment procedure where the BS-side beam is fixed. The only difference is that there is no report quantity as the adjustment is done within the UE [1]. The UE has internal resource set to adjust the beam according to the BS-side beam. The resource set sweep the UE beams over the reference signals to detect best beam-pair.

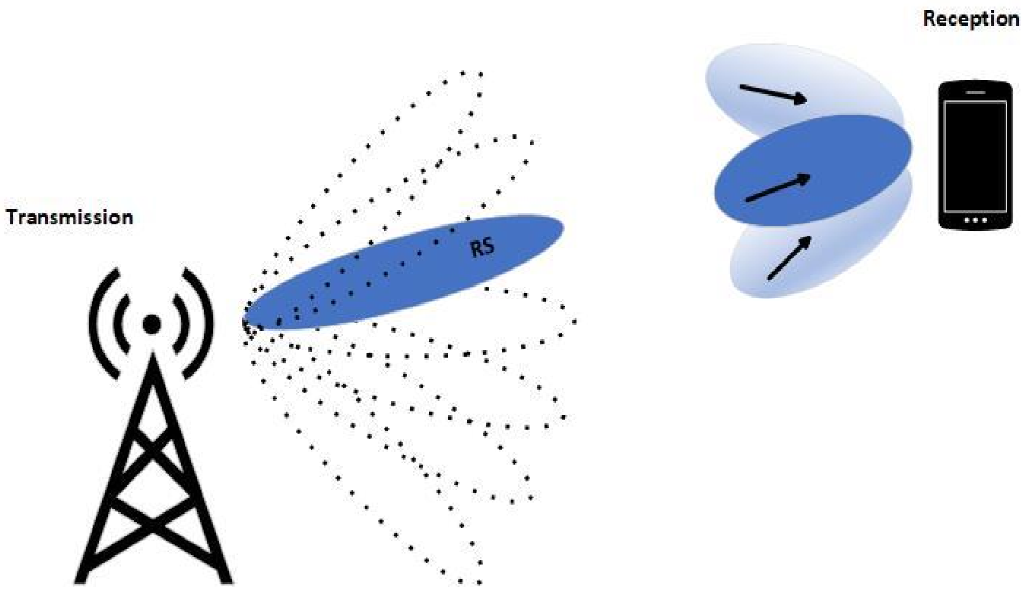

Figure 29. *Downlink receiver side beam adjustment*

4.3.3 Adjustment of UL BS-side beam and UL UE-side beam

The uplink beam adjustment also take place as the same manner as downlink beam adjustment. The transmitter (BS) and receiver (UE) changes side and continue the whole process as uplink beam management. However, once a downlink beam adjustment is done there is no need for explicit uplink beam adjustment. In the similar way, if uplink beam adjustment is done before and maintained then there is no need for explicit downlink beam adjustment. If explicit uplink beam adjustment is required, then it can be done in the similar way as the downlink beam adjustment is done. The report quantity in that case is configured sounding reference signal (SRS) instead of CSI-RS or SS blocks.

4.4 Beam-pair recovery

Due to rapid movement of UE or other uncertain events in the environment, the established beam-pair could be blocked or hampered without giving enough time for beam adjustment. The specific procedures that helps to overcome this kind of situation is called beam recovery and consists of following steps:

1. Beam failure detection: UE detects a beam failure.
2. New beam-pair identification: UE tries to identify a new beam-pair to restore connectivity.
3. Recovery request: UE sends a recovery request to the BS.
4. BS Response: BS response to the request made by the UE.

4.4.1 Detection of beam-pair failure

Device detects an ‘beam failure instance’ has occurred if-

- Error probability of physical downlink control channel (PDCCH) exceeds a certain value
- Measured L1-RSRP of the signal is under a certain value

If such ‘beam failure instances’ exceeds a configured value, then the UE declares beam failure and initiates beam recovery procedure.

4.4.2 Selection of new beams

In this state, the UE tries to find a new beam-pair from candidate beam-pairs in order to restore connectivity. A set of CSI-RS or SS blocks as reference signal is configured within a UE. This reference signals are treated as candidate beams and transmitted within a specific downlink beam. The best beam-pair is selected based on the measured L1-RSRP of the candidate beams. The BS and UE then follows the same beam establishment process discussed in 4.1.

4.4.3 Requesting recovery

If the beam failure is detected and the UE has found a new beam-pair to restore connectivity based on measurement, then it sends a beam recovery request to the BS. The request consists of preamble transmission and random-access response (RAR). The preamble transmission is carried out using specific preamble configuration such as RACH occasions and preamble sequence. Random access is done with power ramping parameters.

4.4.4 Response

After sending a beam recovery request, the UE monitors the downlink from the BS. The monitoring starts after 4 slots of sending request. If the BS does not response within a configured time, the UE sends the request again after adjusting power ramping parameters.

5. BEAM TRAINING PROTOCOL AND ALGORITHM

In order to illustrate potential beam training protocol for 5G, the one used in IEEE 802.11.3c [42] works as a concrete example and can be an option for 5G. In this chapter, beam training protocol and algorithms to train the beams are discussed.

5.1 Beam training region

Beam training region is the 360^0 angular area of a transmitter or receiver. It is divided into 3 parts- Quasi-omni regions, sectors and beams. Beams can be further divided into high-resolution beams and low-resolution beams.

5.1.1 Quasi-omni region and sectors

The quasi-omni pattern is a lower resolution area around the beamformer which covers a broader region than sector level and beam level. A sector covers relatively small area than quasi-omni region. A sector consists of multiple beams. During initial beam sweeping, the beamformer divides the radiating region into quasi-omni pattern of different sectors. After selecting the right quasi-omni region the beamformer then selects the appropriate sector from the multiple sectors of selected quasi-omni pattern. Fig. 30 (a) shows 2 quasi-omni pattern region and fig. 30 (b) shows 8 sectors around a BS/UE. Sectors are narrower region than quasi-omni regions.

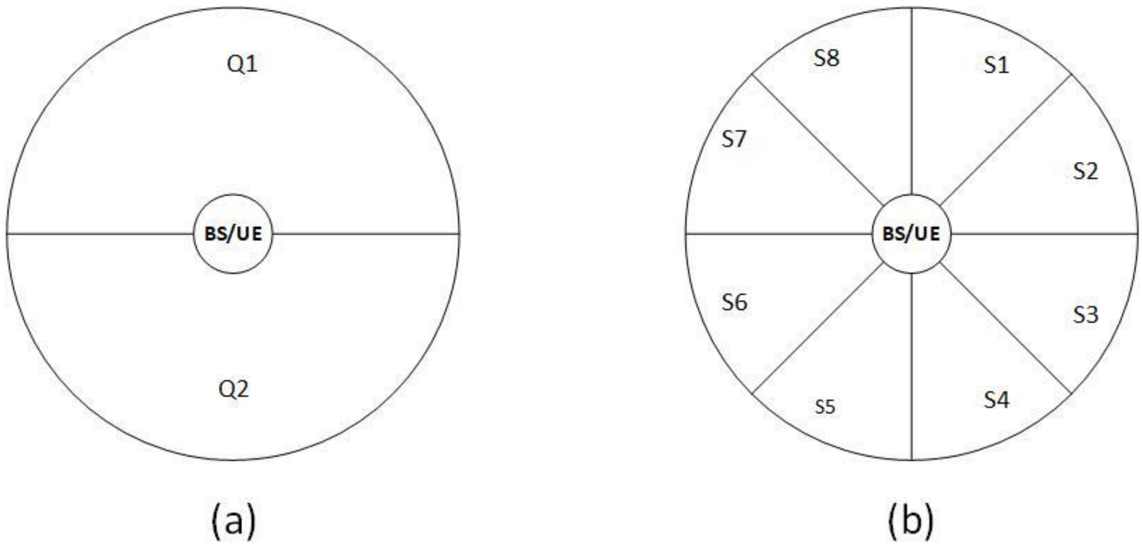

Figure 30. *(a)quasi-omni regions; (b)multiple sectors*

5.1.2 Beams

The sectors are further divided into multiple low-resolution beams and high-resolution beams. Among those beam the transmitter and receiver selects the best beam pair. From fig. 31, the division based on the resolution or number of beams can easily understood.

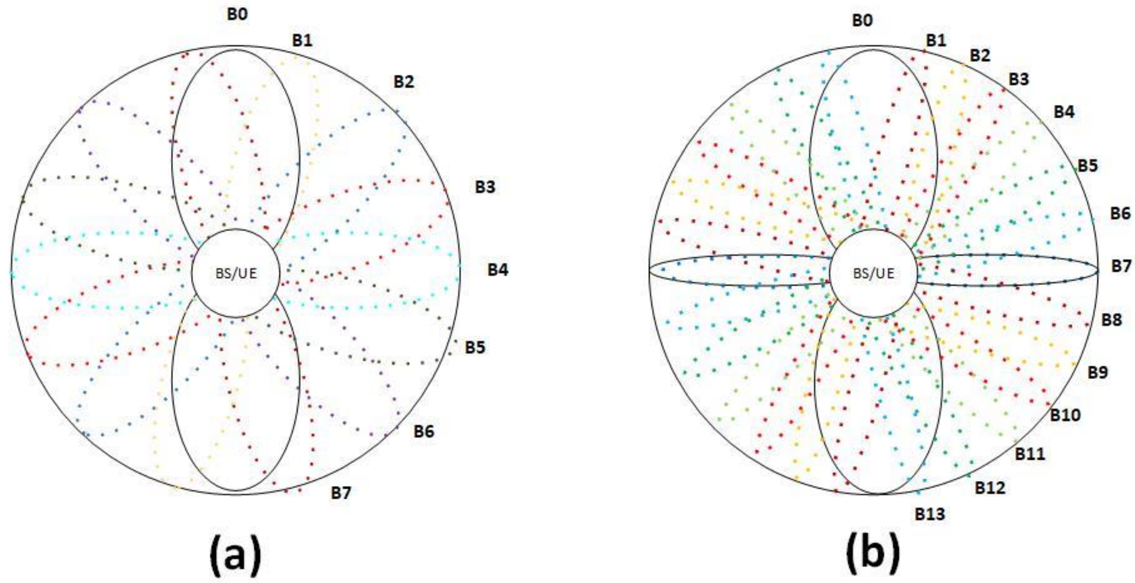

Figure 31. *(a)Low-resolution beams (b)High-resolution beams*

A codebook is a *M*×*M* matrix containing beamforming vector or combining vector, where *M* is number of antenna element of an array. If the desired number of beam pattern is *K,* then the codebook beam vectors can be derived from the column vectors of the matrix shown in following equation [42]:

$$\text{when } k \ge M\ ; \quad W(m,k) = j^{fix\left\{\frac{m\times mod[k+(\frac{k}{2}),k]}{k/4}\right\}} \quad \text{for } m = 0{:}M-1 \text{ and } k = 0{:}k-1. \qquad (5.1)$$

$$\text{When } k = \frac{M}{2};\ W(m,k) = \begin{cases} (-j)^{mod(m,k)} & m = 0{:}N-1 \text{ and } k = 0 \\ (-1)^{fix\left\{\frac{m\times mod[k+(\frac{k}{2}),k]}{k/4}\right\}} & m = 0{:}N-1 \text{ and } k = 1{:}K-1 \end{cases} . \quad (5.2)$$

The function fix(.) returns the biggest integer smaller than or equal to its argument. It is similar to round(.) function which returns the closest integer to the input argument. Beam level training helps to achieve the optimal beam pair for transmitter and receiver. Beam level training is done by using a set of beam former and combiner vectors from the code-book.

A frame structure similar to 5G NR is proposed in [55] for beam training. Fig. 32 describes the establishment of beam training via a handshake or acknowledgement after downlink beam training and uplink beam training. Each beam is trained by using unique tone for their pilot frequency. A frame is divided into subframes and subframes are further divided

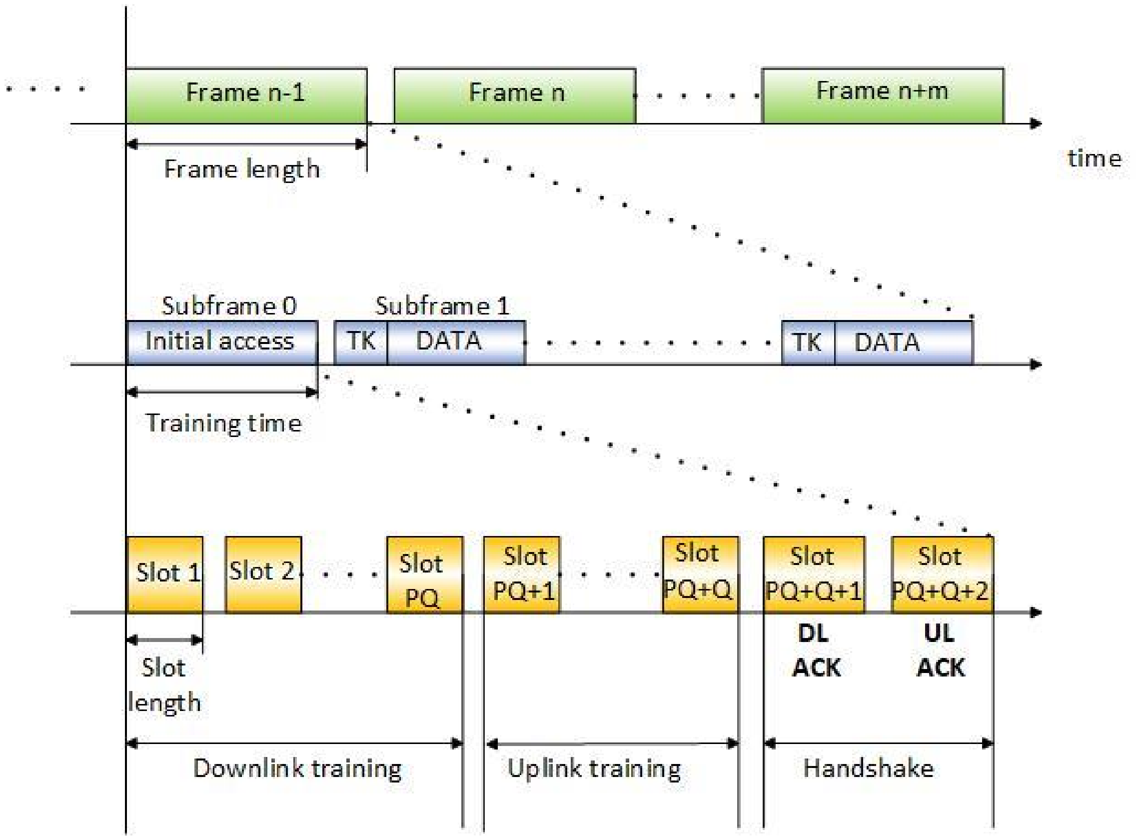

Figure 32. *Proposed frame structure [55]*

into slots. First subframe is used for beam training as initial access and rest are used for tracking (TK) and data transmission. Slots are the smallest unit of time and based on frequency can be adjusted in duration. In downlink training *PQ* time slots are used where BS sequentially sweep over *P* direction and UE sequentially sweep over *Q* directions. In uplink time slot expand to *PQ+Q* slots. Downlink acknowledgment and uplink acknowledgement are done in two time slots.

5.2 Approaches

There are various types of approaches used in training and tracking the beam. Two of the most popular approaches are: Brute force (sequential) method and Tree-based (adaptive) method.

5.2.1 Brute force (sequential) method

This method performs an exhaustive beam searching according to a predefined codebook. The beamforming vectors are chosen according to the codebook to sequentially scan the 360^0 angular space. The best beam-pair are determined on the basis of highest

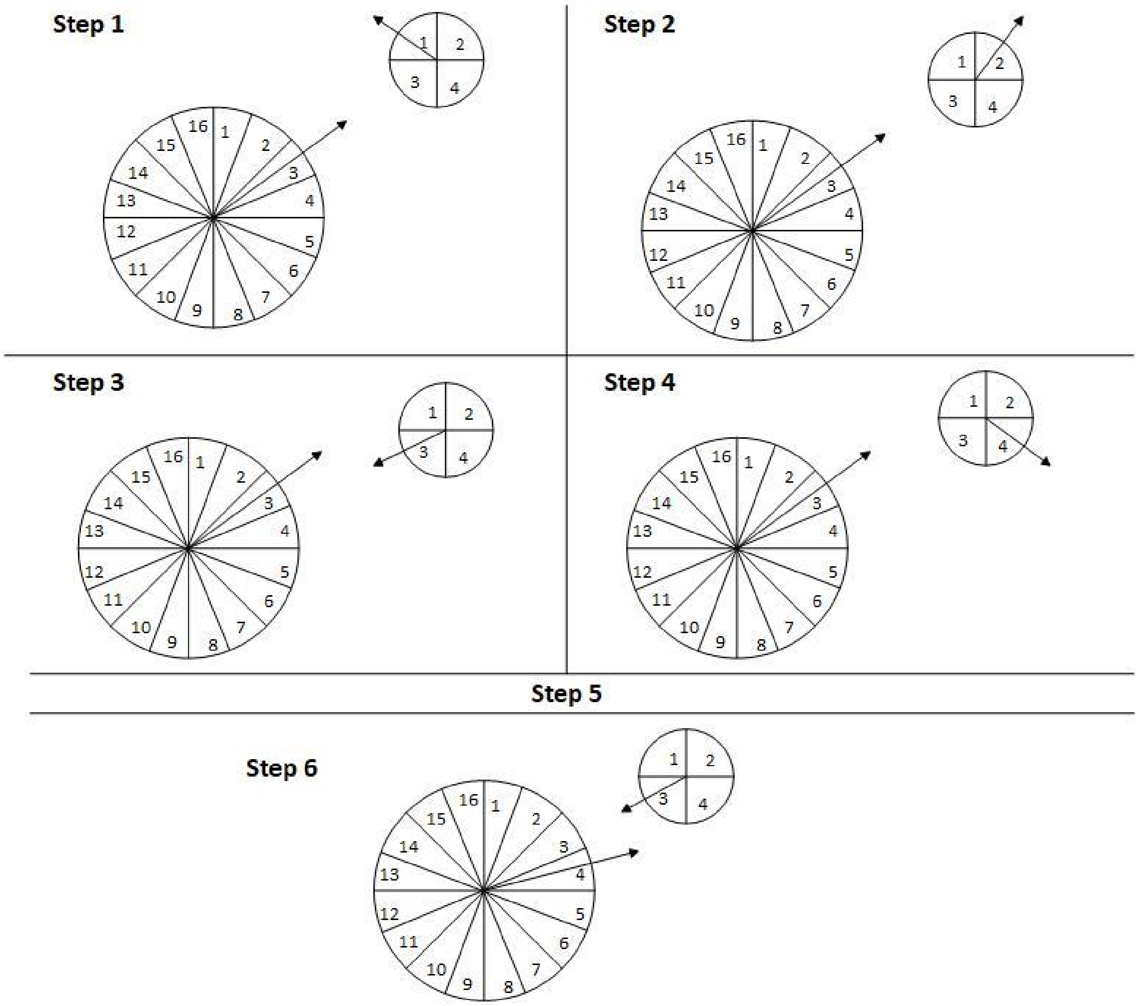

Figure 33. *Exhaustive search training*

received SNR [56]. Having 8×8 antennas at BS, 16 narrow beam direction can be created and using 2× 2 antenna at UE 4 wide beam direction can be created. Fig. 33 depicts such scenario where 4 PSS signals are sent towards UE in 4 DL slots to match with the 4 receive direction (step 1-4). Then in UL training UE sends back its PSS and decides which beam to select for connectivity (step 5). These 4 DL slots and 1 UL slot makes one Initial access macro-element, *k*. Same process is repeated for all 16 directions. Step 1-5 denotes a procedure for *k*=3/16. Step 6 indicates the starting of procedure for *k*=4/16.

5.2.2 Tree-based (adaptive) method

This method divides the region from wider beams to narrower beams in an iterative manner. In each iterative phase, the previously selected angular region in again divided into smaller region. Fig 34 depicts division of region based on AoA and AoD. Red marker denotes the selected region which is divided further for beam refinement. Beamforming vectors are updated accordingly to perform scan in selected angular region after each successful iteration. A parallel-adaptive scheme showed that sector level training can be achieved in 6 slots [57]. Thus, adaptive beam training can be done in reduced number

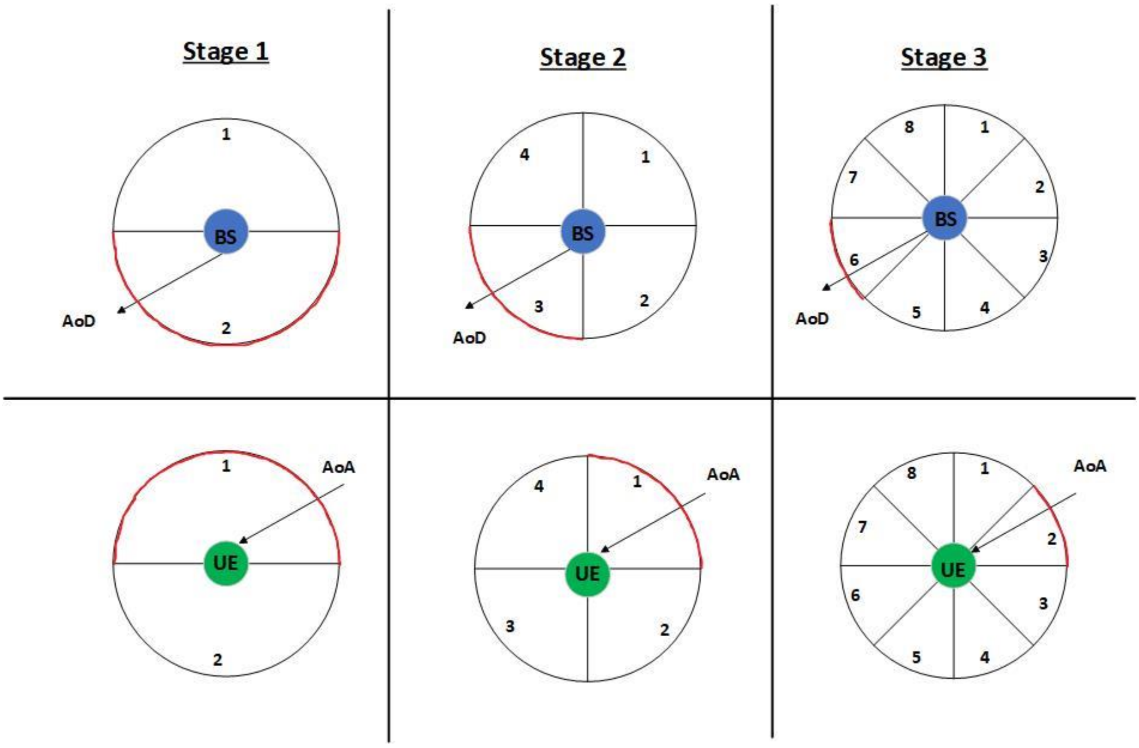

Figure 34. *Parallel-adaptive beam training method*

of time slots compared to sequential training. Misdetection probability refers to the probability of undetected UEs in the discussed approaches. Due to broader division of regions, UE often remain undetected in adaptive method compared to sequential training. Table 4 shows a comparison between sequential method and adaptive method.

Table 4. *Comparison between sequential method and adaptive method*

Parameters	**Sequential method**	**Adaptive method**
Training time	High	Low
Misdetection probability	Low	High

5.3 Beam training algorithm

The beam training algorithm refers to achieving optimal cost function in terms of designing the beamforming vectors. Beamforming techniques can be generally classified into two categories:

1. Conventional (switched) beamforming: In conventional or switched beamforming, a fixed set of weight and phase-shifters are used to steer the beam towards desired direction. Location of antenna elements in the array and desired direction of angle is enough for the calculation. One popular example can be stated as Butler Matrix.
2. Adaptive beamforming: Adaptive beamforming uses different information to update its beamforming weight to adapt with the situation and perform accordingly. Multiple signal classification (MUSIC), iterative sparse asymptotic minimum variance (SAMV) are some example of adaptive beamforming.

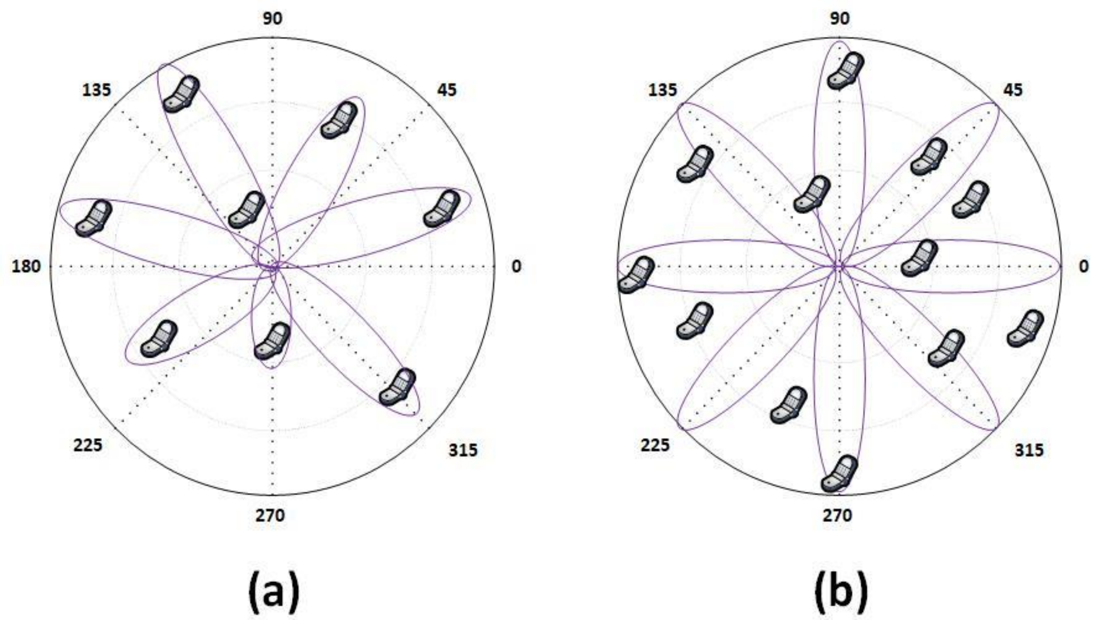

Figure 35. *(a) Adaptive beamforming (b) switched beamforming*

Fig. 35 shows an illustrative difference between switched and adaptive beamforming. A switched beamformer is typically made of phase shifters, hybrid coupler and crossovers. One popular algorithm for switched beamforming is Butler matrix. The objective of Butler matrix algorithm is to choose a suitable beam to obtain the desired signal. In a Butler matrix, majority of the beams may not be pointing towards desired direction, which causes waste of energy. A classic butler matrix can be $N \times N$ input-output port where N is a power of 2. Thus, a butler matrix can be order of 2×2, 4×4 or 8×8. Fig. 36 (a) shows a

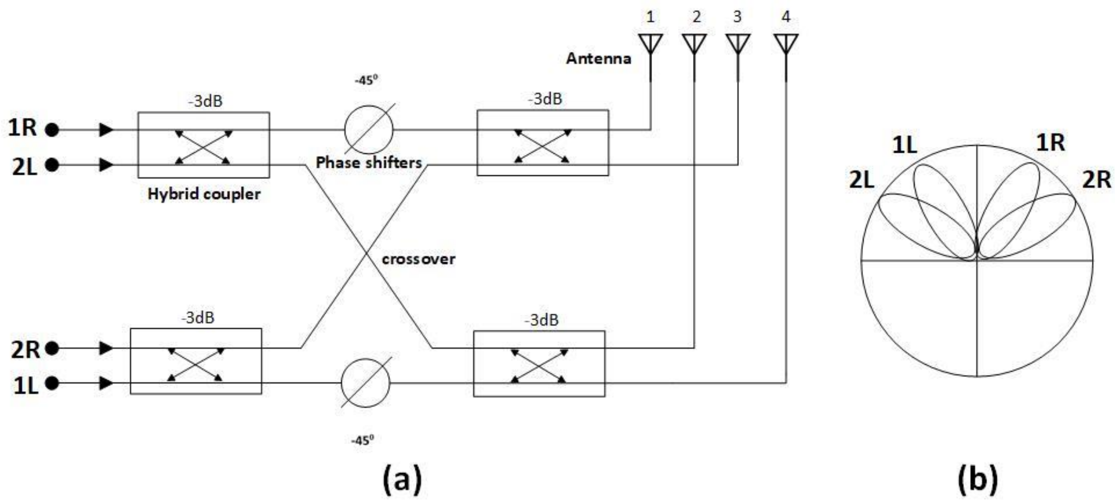

Figure 36. *(a)4x4 Butler matrix (b)beam pattern produced by 4x4 Butler matrix*

butler matrix of order *4×4* and fig. 36 (b) shows the produced 4 symmetrical beams. Exciting one port can result into 4 symmetrical fixed-directional beams using phase shifters and couplers. The degree of freedom is very limited in classic butler matrix. However recent research shows that asymmetrical beam with limited steering and even 3×*5* Butler matrix is also possible [58][59].

Adaptive beamforming algorithm can be mainly classified into 2 categories- blind algorithm and non-blind algorithm. Fig. 37 shows a detailed classification of beamforming algorithms. Non-blind algorithms require to know the statistics of the transmitted signal or some reference in order to calculate the weighting vector. This reference can be classified into 2 categories:

1. Spatial reference such as AoA or DoA.
2. Temporal reference such as training signal.

A training signal is used along the communication link to detect the user. The goal is to maximize the desired signal and minimize the unwanted interference between transmitter and receiver. If $x(t)$ is the desired signal and w^H is the complex conjugate transpose of the weighting vector, then the output signal is given by

$$y(t) = w^H x(t). \tag{5.3}$$

In non-blind algorithm, a reference signal is used to update the weighting vector after each iteration in order to minimize the error and get as close as the desired signal. If $d(t)$ is the reference signal, then the error signal is described as follows

$$e(t) = d(t) - w^H x(t). \tag{5.4}$$

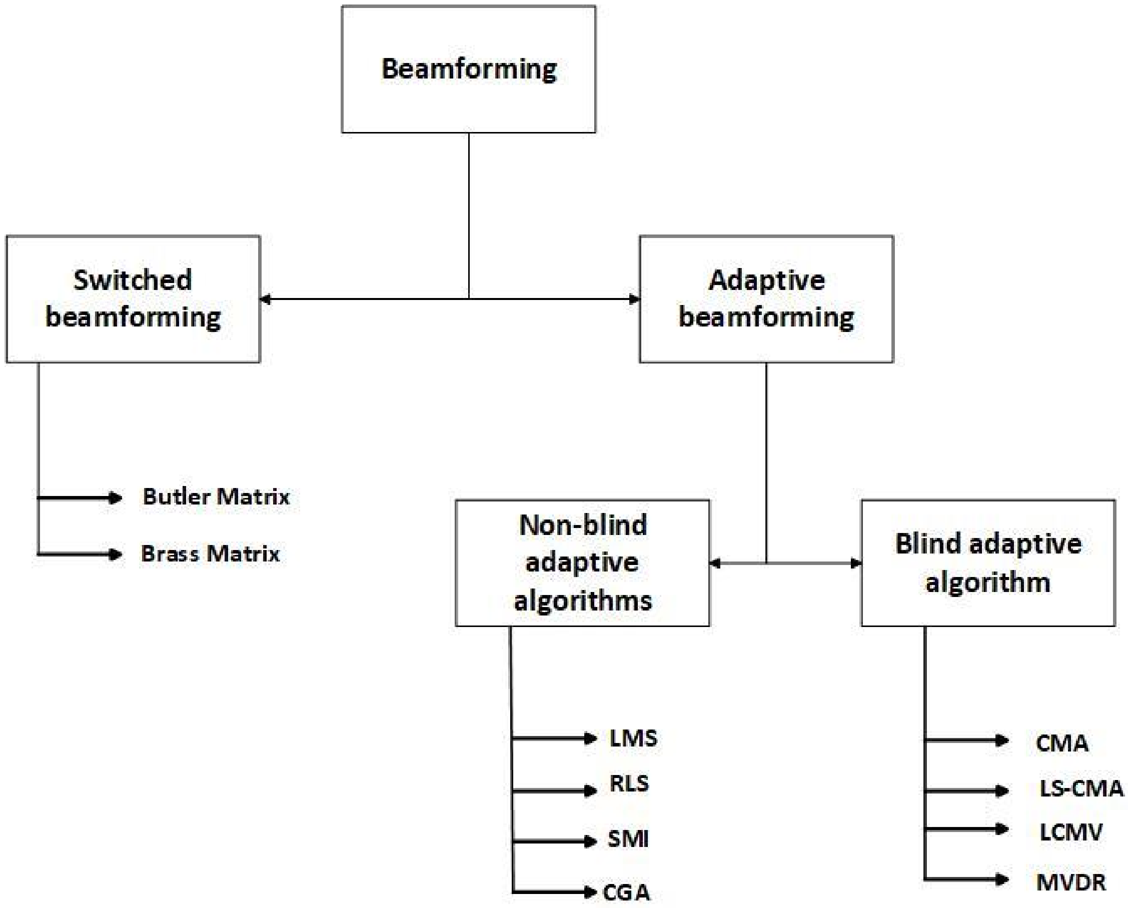

Figure 37. *Beamforming algorithm Classification [24]*

Blind algorithms don't require any information beforehand to train the beams. The main objective of blind algorithms is to re-establish the physical characteristic of downlink signal. Blind algorithm uses some known properties of a signal such as constant modularity. The authors in [24] provide some examples of adaptive algorithms such as the least-mean-square (LMS) algorithm, the recursive-least-square (RLS) algorithm, sample matrix inversion (SMI) and conjugate gradient (CG) algorithm are some widely known non-blind algorithms. Among blind algorithms, the constant modulus algorithm (CMA), least square constant modulus (LS-CMA) algorithm, linearly constrained minimum variance (LCMV) and minimum variance distortion-less response (MVDR) algorithm are widely popular. LCMV and MVDR shows improved performance in terms of improved SINR at receiver and steering nulls towards interferer. Due to self-nulling issue, LCMV beamformer are preferred over MVDR beamformer. A system model was generated using 'pashed.LCMVBeamformer' function to compare performance analysis of a LCMV beamformer with conventional beamformer. A signal containing two rectangular pulse is incident on a 10 element ULA from 30^0 azimuth and 0^0 elevation angle. A complex-valued white gaussian noise was added to the signal and a barrage jammer was created as an

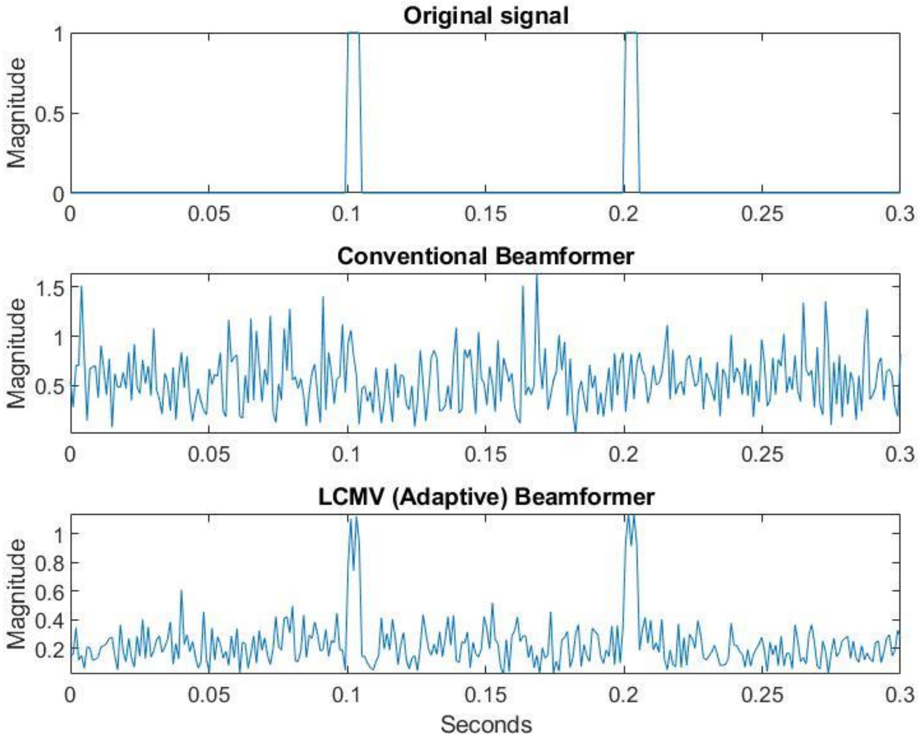

Figure 38. *Performance analysis of a LCMV beamformer*

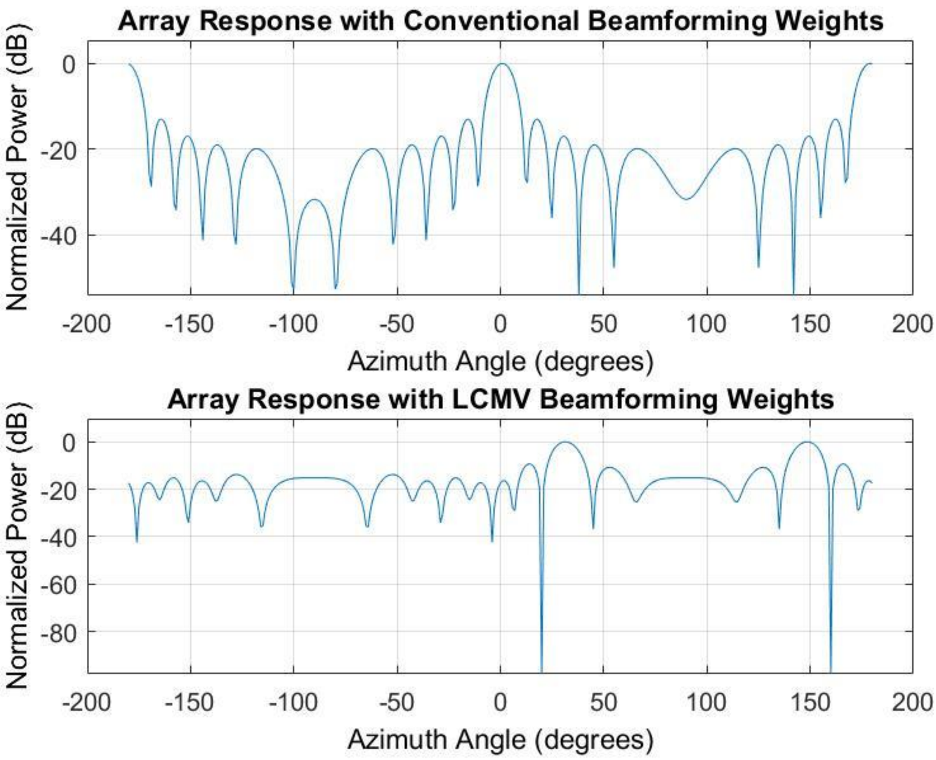

Figure 39. *Steering null towards interferer at 160^0 azimuth*

interference source. The interference is incident on the ULA from an angle of 160^0 azimuth and 0^0 elevation. Fig. 38 shows that LCMV beamformer can retrieve the signal with a better SNR than conventional beamformer. Additionally, LCMV beamformer successfully steer the null towards the interference at 160^0 azimuth angle as shown in fig. 39.

The main driving factors of these algorithms depend on their speed of conversion rate, number of iterations performed and accurate resolutions in terms of SNR. New techniques and algorithm are invented and incorporated with the existing algorithm to achieve better performance. For example, particle swarm optimization (PSO), dynamic mutated artificial immune system (DM-AIS) and gravitational search algorithm (GSA) were incorporated into LCMV to improve its weight [24].

Machine learning is integrated with coordinated beamforming to serve high-speed users. In coordinated beamforming, a UE transmit an uplink pilot sequence and the BSs receive the sequence using omni or quasi-omni pattern. BS predicts the beamforming vectors from the received sequence using a deep learning method [60].

The position of the UE can be also used to update transmit beamforming vector instead of acquiring CSI as feedback. Global positioning system (GPS) data of a UE can be used in that case [46]. GPS positioning accuracy (up-to 20m in most cases) can affect the angular precision of beamforming. The maximum angular error can be calculated by

$$\alpha_{max} = \arctan\left(\frac{20}{R}\right), \tag{5.5}$$

where R is the distance between BS and UE.

6. CONCLUSIONS

Operating at mmWave, it was shown that beamforming can allow implementation of massive number of antennas in a smaller array. This huge number of antenna elements increases the directivity of the beam pattern, which can be used to compensate high path loss in 5G mmWave system. Additionally, it allows more degree of freedom as narrower beam can be formed from the BS to the UE ensuring the maximum throughput and spectral efficiency. It was shown that beamforming technique along with other MIMO techniques can provide spatial diversity as well as combat fading due to multi-path propagation. In terms of array gain and diversity gain, beamforming can provide better SNR at receiver and decrease BER as a function of SNR. Different beamformer can successfully supress interference in unwanted direction by steering nulls towards them. Beamforming helps to conserve energy at BS not only in active mode but also in sleep mode compared to other techniques. It was shown that beamforming can also solve secrecy issue in wireless communication. Varying receiver beamwidth it is possible to control maximum Doppler spread. By enhancing such different system benchmark, beamforming ultimately increases the data rate and spectral efficiency of a system. Considering all the benefits associated with beamforming, it can be said that beamforming is an ultimate deployment option for 5G both in SA and NSA mode.

Beamforming management discusses about the directional initial access and sustainable connectivity in 5G. It also provides different protocol for different situation like user mobility, beam-pair failure (etc.). Beam tracking helps to overcome difficult handover situations. Comparing sequential and adaptive beam training approaches, it was shown that there remains a trade-off between training time and misdetection probability in both cases. Different algorithms are designed using different system parameters in order to achieve optimum weighting vectors. Comparing different types of beamforming algorithms, it can be said that adaptive beamforming algorithms are the most suitable option for 5G system.

Though beamforming solves most of the existing problems related to 5G wireless communication, yet there are some challenges to overcome. Trade-off between selection of RF chain for each antenna (in full-digital beamforming) and hardware complexity with power consumption is still not fixed fully. Pilot signal overhead is another challenge in beam training scenario to reduce time slots. Designing efficient algorithm to exploit maximum channel capacity is a subject to research. Another challenge can be addressed as acquiring CSI between transmitter and receiver which uses considerable amount of spectral resources.

Future trends can be the incorporation of different system enhancement techniques with beamforming. With the advancement of technology, the hardware or software collaboration with beamforming is increasing day by day. For example, using machine learning for predicting the accurate beamforming vectors and using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) beamforming for better coverage during mobility. Photonic assisted chips are used to design beamforming architecture for faster data processing and conversion rate. Research and development can be done in other areas related to beamforming such as designing the efficient network structure and acquiring perfect channel conditions.

This thesis can be helpful in research purposes in such a way that the reader can get a detailed overview of beamforming management and beam training techniques in 5G system. Comparing different parameters of beamforming, in conclusion, it can be suggested that optimally designed hybrid beamforming structure with robust adaptive beamforming algorithm can help 5G NR to achieve its performance benchmark in near future.

REFERENCES

[1]. E. Dahlman, S. Parkvall, and Johan Sköld, *5G NR: the next generation wireless access technology*. San Diego: Elsevier Ltd, 2018

[2]. N. Gupta, “5G Technology and Requirement,” *Medium*, 30-Mar-2019. [Online]. Available: https://medium.com/swlh/5g-technology-and-requirement-d163434a5c45.

[3]. “This is 5G,” *www.ericsson.com*. [Online]. Available: Available at: https://www.ericsson.com/4a3114/assets/local/newsroom/media-kits/5g/doc/ericsson_this-is-5g_pdf_v4.pdf.

[4]. K. Flynn, “Release 15,” *3gpp.org*, 2018. [Online]. Available: https://www.3gpp.org/release-15. [Accessed: 08-Oct-2019].

[5]. Ghosh, “5G New Radio (NR): Physical Layer Overview and Performance,” 2018.

[6]. S. Teral, “5G best choice architecture IHS Markit Technology | White Paper,” 2019.

[7]. “Operator Requirements for 5G Core Connectivity Options - Future Networks,” *Future Networks,* 2019. [Online]. Available: https://www.gsma.com/futurenetworks/wiki/operator-requirements-for-5g-core-connectivity-options/.

[8]. Rohde & Schwarz GmbH & Co KG, “Millimeter-Wave Beamforming: Antenna Array Design Choices & Characterization,” *Rohde-schwarz.com*, 2016. [Online]. Available: https://www.rohde-schwarz.com/fi/applications/millimeter-wave-beamforming-antenna-array-design-choices-characterization-white-paper_230854-325249.html.

[9]. M. Giordani, M. Polese, A. Roy, D. Castor and M. Zorzi, "A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 173-196, Firstquarter 2019.

[10]. 3GPP, “NR - Physical layer measurements - Rel. 15,” TS 38.215, 2017.

[11]. G. Zucchelli, H. Chen and R. Gentile, "Hybrid-Beamforming Design for 5G Wireless Communications", *Electronic Design*, 2019. [Online]. Available: https://www.electronicdesign.com/communications/hybrid-beamforming-design-5g-wireless-communications. [Accessed: 31- Oct- 2019].

[12]. I. Ahmed *et al.*, "A Survey on Hybrid Beamforming Techniques in 5G: Architecture and System Model Perspectives," in *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3060-3097, Fourthquarter 2018.

[13]. A. F. Molisch et al., "Hybrid Beamforming for Massive MIMO: A Survey," *in IEEE Communications Magazine*, vol. 55, no. 9, pp. 134-141, Sept. 2017.

[14]. T. E. Bogale, L. B. Le, A. Haghighat, and L. Vandendorpe, “On the number of RF chains and phase shifters, and scheduling design with hybrid analog-digital beamforming,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3311–3326, May 2016.

[15]. L. Liang, W. Xu, and X. Dong, “Low-complexity hybrid precoding in massive multiuser MIMO systems,” *IEEE Wireless Communications Letters,* vol. 3, no. 6, pp. 653–656, 2014.

[16]. Z. Li, S. Han, and A. F. Molisch, “Hybrid beamforming design for millimeter-wave multi-user massive MIMO downlink,” in *IEEE ICC*, 2016, accepted

[17]. A. Alkhateeb, G. Leus, and R. Heath, “Limited feedback hybrid precoding for multi-user millimeter wave systems,” *IEEE Trans. Wireless Commun*., vol. 14, no. 11, pp. 6481–6494, 2015.

[18]. A. Simonsson et al., "Beamforming Gain Measured on a 5G Test-Bed," *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, Sydney, NSW, 2017, pp. 1-5.

[19]. A. Natarajan, A. Komijani, and A. Hajimiri, “A fully integrated 24- GHz phased-array transmitter in CMOS,” *IEEE Journal of Solid-State Circuits*, vol. 40, no. 12, Dec. 2005.

[20]. S. Sun, T. S. Rappaport, R. W. Heath, A. Nix and S. Rangan, "Mimo for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?" in *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110-121, December 2014.

[21]. R.T. Becker, "Precoding and spatially multiplexed MIMO in 3GPP long-term evolution". *High Freq Electron*. 2009.

[22]. Y. Ju, X. Qiu, Y. Chen, K. Huang, Q. Yin and H. Wang, "Beamforming design for interference management in millimeter wave cellular networks with partial CSI," *2017 9th International Conference on Wireless Communications and Signal Processing (WCSP),* Nanjing, 2017, pp. 1-6.

[23]. P. Gandotra, R. K. Jha and S. Jain, "Green Communication in Next Generation Cellular Networks: A Survey," in *IEEE Access*, vol. 5, pp. 11727-11758, 2017.

[24]. E. Ali, M. Ismail, R Nordin and N.F. Abdulah, "Beamforming techniques for massive MIMO systems in 5G: Overview, classification, and trends for future research," *Front. Inf. Technol. Electron. Eng.,* vol. 18, no. 6, pp. 753-772, Jun. 2017.

[25]. H. Bölcskei, D. Gesbert, C. B. Papadias, and A.-J. van der Veen, *Space-Time Wireless Systems: From Array Processing to MIMO Communications*. Eds. Cambridge: Cambridge University Press, 2006

[26]. S. A. Jafar, Sriram Vishwanath and A. Goldsmith, "Channel capacity and beamforming for multiple transmit and receive antennas with covariance feedback," *ICC 2001. IEEE International Conference on Communications. Conference Record (Cat. No.01CH37240),* Helsinki, Finland, 2001, pp. 2266-2270 vol.7.

[27]. B. Friedlander and S. Scherzer, "Beamforming versus transmit diversity in the downlink of a cellular communications system," in *IEEE Transactions on Vehicular Technology*, vol. 53, no. 4, pp. 1023-1034, July 2004.

[28]. S. A. Jafar and A. Goldsmith, "On optimality of beamforming for multiple antenna systems with imperfect feedback," *Proceedings. 2001 IEEE International Symposium on Information Theory (IEEE Cat. No.01CH37252)*, Washington, DC, USA, 2001, pp. 321-.

[29]. F. E. Salem, A. Tall, Z. Altman and A. Gati, "Energy consumption optimization in 5G networks using multilevel beamforming and large scale antenna systems," *2016 IEEE Wireless Communications and Networking Conference*, Doha, 2016, pp. 1-6.

[30]. A. Karlsson, O. Al-Saadeh, A. Gusarov, R. V. R. Challa, S. Tombaz and K. W. Sung, "Energy-efficient 5G deployment in rural areas," *2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, New York, NY, 2016, pp. 1-7.

[31]. S. Tombaz, P. Frenger, F. Athley, E. Semaan, C. Tidestav and A. Furuskar, "Energy Performance of 5G-NX Wireless Access Utilizing Massive Beamforming and an Ultra-Lean System Design," *2015 IEEE Global Communications Conference (GLOBECOM)*, San Diego, CA, 2015, pp. 1-7.

[32]. “Spectral Efficiency: 5G-NR and 4G-LTE - Techplayon,” *Techplayon,* 18-Jul-2018. [Online]. Available: http://www.techplayon.com/spectral-efficiency-5g-nr-and-4g-lte/. [Accessed: 31-Oct-2019].

[33]. S. Wang, X. Xu, K. Huang, X. Ji, Y. Chen and L. Jin, "Artificial Noise Aided Hybrid Analog-Digital Beamforming for Secure Transmission in MIMO Millimeter Wave Relay Systems," in *IEEE Access*, vol. 7, pp. 28597-28606, 2019.

[34]. Heejung Yu and W. Khalid, "Secure communication with beamforming and jamming in time-varying channels," *2016 Eighth International Conference on Ubiquitous and Future Networks (ICUFN)*, Vienna, 2016, pp. 218-221.

[35]. N. T. Nghia, H. D. Tuan, T. Q. Duong and H. V. Poor, "MIMO Beamforming for Secure and Energy-Efficient Wireless Communication," in *IEEE Signal Processing Letters*, vol. 24, no. 2, pp. 236-239, Feb. 2017.

[36]. H. Kim and Joohwan Chun, "MIMO structure which combines the spatial multiplexing and beamforming," *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring (IEEE Cat. No.04CH37514)*, Milan, 2004, pp. 108-112 Vol.1.

[37]. S. Fang, L. Li, X. Tao, and P. Zhang, “A spatial multiplexing mimo scheme with beamforming for downlink transmission,” *in Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*, 2007, pp. 700–704

[38]. J. Xu and J. Zhang, "A spatial multiplexing MIMO scheme with beamforming and space-time block coding for downlink transmission," *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, London, 2013, pp. 1271-1275. doi: 10.1109/PIMRC.2013.6666334

[39]. Ersin Sengul, E. Akay and E. Ayanoglu, "Diversity analysis of single and multiple beamforming," in *IEEE Transactions on Communications*, vol. 54, no. 6, pp. 990-993, June 2006.

[40]. Taesang Yoo and A. Goldsmith, "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming," in *IEEE Journal on Selected Areas in Communications,* vol. 24, no. 3, pp. 528-541, March 2006.

[41]. "Spectral efficiency," *En.wikipedia.org*. 2019. [online] Available at: https://en.wikipedia.org/wiki/Spectral_efficiency [Accessed 8 Oct. 2019].

[42]. "IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 15.3: Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension," *in IEEE Std 802.15.3c-2009 (Amendment to IEEE Std 802.15.3-2003)*, vol., no., pp.1-200, 12 Oct. 2009

[43]. “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond,” *Recommendation ITU-R M.2083-0*, 2015.

[44]. P. Nagaraj, “Impact of atmospheric impairments on mmWave based outdoor communication,” *arXiv.org*, 2018. [Online]. Available: https://arxiv.org/abs/1806.05176. [Accessed: 31-Oct-2019].

[45]. Harald T. Friis, "A Note on a Simple Transmission Formula*," Proceedings of the I.R.E. and Waves and Electrons*, May 1946, pp 254–256.

[46]. R. Maiberger, D. Ezri and M. Erlihson, "Location based beamforming," 2010 IEEE 26-th Convention of Electrical and Electronics Engineers in Israel, Eliat, 2010, pp. 000184-000187.

[47]. P. Petrus, J. H. Read, and T.S. Rappaport, ‘Effects of Directional Antennas at the Base Station on the Doppler Spectrum’*, IEEE Communications Letters*, vol. 1, pp. 40-42, March 1997.

[48]. "History of smart antennas".," *En.wikipedia.org*. 2019. [online] Available at: https://en.wikipedia.org/wiki/History_of_smart_antennas#cite_note-7 [Accessed 23 Oct. 2019].

[49]. J. Grythe and A.S. Norsonic,"Beamforming algorithms-beamformers, ". *Technical Note*, Norsonic AS, Norway.

[50]. K. Gulur Sadananda, M. P. Abegaonkar and S. K. Koul, "Gain Equalized Shared-Aperture Antenna Using Dual-Polarized ZIM for mmWave 5G Base Stations," in IEEE Antennas and Wireless Propagation Letters, vol. 18, no. 6, pp. 1100-1104, June 2019.

[51]. 5GPP, "5G PPP Phase 1 Projects ‹ 5G-PPP," 5g-ppp.eu, 2018. [Online]. Available: https://5g-ppp.eu/5g-ppp-phase-1-projects/. [Accessed: 31-Oct-2019].

[52]. J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed., New York: McGraw-Hill, 2008.

[53]. J. Lorca, M. Hunukumbure and Y. Wang, "On Overcoming the Impact of Doppler Spectrum in Millimeter-Wave V2I Communications*," 2017 IEEE Globecom Workshops (GC Wkshps),* Singapore, 2017, pp. 1-6.

[54]. J. S. Kim, W. J. Lee and M. Y. Chung, "A multiple beam management scheme on 5G mobile communication systems for supporting high mobility," *2016 International Conference on Information Networking (ICOIN),* Kota Kinabalu, 2016, pp. 260-264.

[55]. H. Zhou, D. Guo and M. L. Honig, "Beam Acquisition and Training in Millimeter Wave Networks with Narrowband Pilots," in *IEEE Journal on Selected Areas in Communications.*

[56]. M. Giordani, M. Mezzavilla, C. N. Barati, S. Rangan and M. Zorzi, "Comparative analysis of initial access techniques in 5G mmWave cellular networks," *2016 Annual Conference on Information Science and Systems (CISS),* Princeton, NJ, 2016, pp. 268-273.

[57]. D. De Donno, J. Palacios and J. Widmer, "Millimeter-Wave Beam Training Acceleration Through Low-Complexity Hybrid Transceivers," in *IEEE Transactions on Wireless Communications,* vol. 16, no. 6, pp. 3646-3660, June 2017.

[58]. A. Tajik, A. Shafiei Alavijeh and M. Fakharzadeh, "Asymmetrical 4×4 Butler Matrix and its Application for Single Layer 8×8 Butler Matrix," in *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 8, pp. 5372-5379, Aug. 2019.

[59]. H. Zhu, H. Sun, C. Ding and Y. J. Guo, "Butler Matrix Based Multi-Beam Base Station Antenna Array," *2019 13th European Conference on Antennas and Propagation (EuCAP)*, Krakow, Poland, 2019, pp. 1-4.

[60]. A. Alkhateeb, S. Alex, P. Varkey, Y. Li, Q. Qu and D. Tujkovic, "Deep Learning Coordinated Beamforming for Highly-Mobile Millimeter Wave Systems," in IEEE Access, vol. 6, pp. 37328-37348, 2018.