5G Millimeter Wave – Beamforming Challenges and Techniques

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***Abstract*— The 5G network is planned to serve a high quantity of mobile data traffic and a significant number of wireless connections while improving communication delay, reliability, and security. Applications such as autonomous cars, remote surgery, augmented/virtual reality games demand an increase in data rates. Millimeter-wave (mmWave) is one of the critical innovations to get a better data rate in 5G communications. It is the under-utilized spectrum and is now used for 5G networks and beyond. But there are challenges with mmWaves as they are prone to high path loss, susceptible to blockages, and fading. Several cellular networks, base stations are required at very short distances to maintain the communication. There are several techniques proposed to mitigate the challenges. As we advance, Massive MIMO combined with beamforming will play a key role in 5G communication and is now a primary research area. Using beamforming, wireless signals can focus on a targeted device instead of spreading from a broadcast antenna in all directions. This will result in a stable, faster, and reliable connection. Fine beam alignment between user and antenna is very crucial for initial access and needs to be maintained owing to the channel fading and user mobility. This paper reviews classification of beamforming that includes analog, digital, and hybrid in detail and their applications in real-time. Also, this paper aims to study various beamforming methods, analyze challenges and identify the best-suited techniques that can be employed in massive MIMO frameworks.**

Keywords— mmWave, 5G, beamforming, MIMO, Deep Learning

I. Introduction

Recent times witnessed a tremendous surge in smartphones, laptops, and wearable gadgets. The increased use of IoT applications is expected to multiply tenfold in the next decade. Recent advancements in technology require high data rates with fewer disruptions for running applications, and the increased gadgets further alleviate the load on the network. Therefore, rigorous usage of the network may depreciate the quality of service. Moreover, the available spectrum will not satisfy the increased network demand and necessitates increased bandwidth. The current spectrum utilizes 1-6GHz, leaving a vast spectrum unused. Therefore, 5G proposes to utilize unused spectrum to meet the demands of various users. The main difference of 5G NR from 4G is that the 24-100GHz spectrum is utilized in addition to sub-6 GHz. The range of millimeter-wave (mmWave) is 30-300 GHz, and since the proposed spectrum for 5G is 24-100GHz, mmWave communication should be incorporated for data transmission.

Utilizing widely available mmWave bands can increase the number of users served along with enhanced data rates. The main advantages of utilizing the mmWave are, huge available bandwidth, increased data rates due to high frequencies, and massive MIMO.

The primary bottleneck in incorporating mmWaves is that obstacles easily block the high-frequency electromagnetic waves. As a result, they tend to lose energy quickly and incur huge path losses.

Massive MIMO can aid in overcoming the above challenges and is a promising technology to increase spectral efficiency. It uses many antennas to boost network performance and obtain high throughput in 5G networks [1]. MIMO stands for Multiple Input Multiple Output. A 1x1 MIMO can be defined as a transmitter sending a signal to the receiver. Fading of transmitted signals can be avoided by sending copies of a signal using multiple transceivers. Therefore, MIMO introduces signal transmission using multiple antenna transmitters and receivers and increases the chances of signal reception. Number of antennas at the transmitter will always be equal to the antennas at the receiver for every signal transmitted. For instance, if there are eight antennas transmitting signals and eight antennas receiving them, it can be termed as 8x8 MIMO. Anything beyond eight is considered a massive MIMO. Using too many small antennas at the transmitter and receiver will mitigate the poor propagation loss of mmWaves. But, having massive antennas sending signals increases interference between signals, and this can be avoided using a concept known as beamforming.

Beamforming is a widely used technique in wireless communication. Beamforming uses a phased array of antennas to steer signals in a particular direction and focuses the energy towards a receiver [2]. Signals experience constructive interference at specific angles and experience destructive interference at other angles. The strengthened directed signal formed with constructive interference is called the main lobe, and other small signals formed with destructive interference are called side lobes or nulls. This is how a directed beam is propagated towards a user, thus decreasing interference.

The advantages of using beamforming in massive MIMO systems are enhanced energy efficiency, spectral efficiency, increased system security, and applicability for mmWave bands

[3]. Beamforming methods are being used from different generations, and in 5G, it has got more importance because of the usage of massive MIMO.

II. Classification and Applications

There are different types of classifications of beamforming based on various factors such as physical characteristics, algorithms, signal processing, and bandwidth.

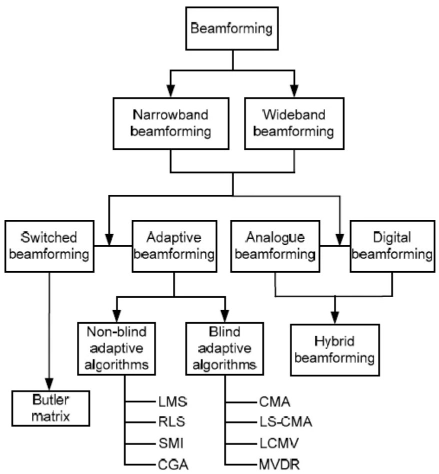

Fig.1. Beamforming Classification

A. *Narrow-band and Wide-band beamforming:*

This classification is based on the signal bandwidth. Narrowband beamforming is produced through an instantaneous linear combination of received array signals. To achieve wideband, we need additional processing dimensions such as tapped delay lines or Finite /Infinite Impulse Response filters. mm-wave beamforming is wideband and is used in 5G applications to establish high speeds and capacities to get an extremely high data rate [4].

B. *Switched Array Vs Adaptive Array beamforming:*

Based on physical characteristics, there are switched beamforming and adaptive-array beamforming. A switched beamforming uses a switching network to switch between multiple beams and chooses from predefined patterns to obtain a signal in the desired direction. It typically serves more than one mobile station. Butler matrix is the most popular type of switched MIMO beamforming network used as it is versatile and simple for multiple-beam antennas.

Whereas adaptive array beamforming formulates a single beam for each user with the help of weight vectors [3]. To optimize the results, the complex weights of the incoming signals are calculated and multiplied with the output elements of each array. Adaptive beamforming helps suppress the interferences and improves the desired signal and is, therefore, the preferred method for massive MIMO applications as it is reliable for 5G requirements [5].

A beamforming algorithm is used to create the antenna's beam towards the desired signal direction by calculating the complex weights. Adaptive beamforming algorithms have two types - Blind and non-blind adaptive algorithms: A reference signal is used to adapt the array weights after every iteration in non-blind adaptive algorithms. Examples are Least mean square (LMS) algorithm, recursive least square (RLS) algorithm, sample matrix inversion (SMI), etc. [3]. Blind adaptive algorithms do not use reference signals and therefore do not adjust the weights of the array. Examples are the constant modulus algorithm (CMA) and the least square constant modulus algorithm (LS-CMA).

C. *Analogue, Digital, and Hybrid beamforming:*

Based on signal processing, we can classify beamforming techniques into Analogue, Digital, and Hybrid beamforming. Let us see in detail about each of these classifications:

1) Analogue beamforming technique:

Analog or RF beamforming controls the phase of each transmitted signal by using low-cost phase shifters [3]. A selective radiofrequency (RF) switch is employed to operate the beam steering function (steering angle). The antennas in ABF consist of hybrid matrices and low-cost fixed phase shifters. the beamforming matrix weights are constrained with the phase shifter's constant amplitude [5]. Analog beamforming is implemented using phase shifters where all the antenna elements share a single RF chain, as shown below.

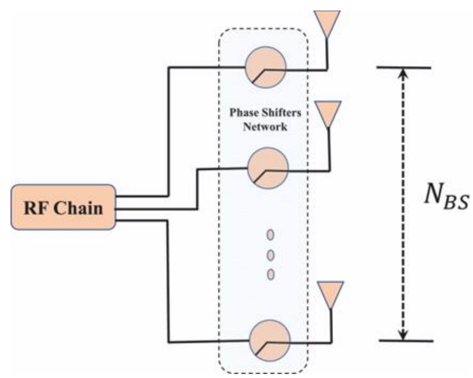

Fig.2. Analog Beamforming at BS

It did not function effectively when applied in MIMO communication systems using phase-shift networks. They cancelled the interfering signals in the analog domain and minimized the required analog-to-digital conversion resolution.

Advantages: 1) Inexpensive phase shifters can be used for Massive MIMO systems, 2) consume low power and has lower computational complexity, 3) the requirement for baseband processing is the least [4] [6].

Disadvantages: 1) It is difficult to reconfigure because it is less flexible compared to digital, 2) Only a single RF (radio frequency) is available with a large number of arrays for all antenna elements, 3) performance is low due to lack of amplitude control [4].

Applications: It can be applied well in short-range communication and radar systems

2) Digital beamforming technique:

Digital beamforming uses a digital signal processor to control the phase and amplitude of a signal beam with the help of RF chains, ADCs, digital circuits, and dedicated baseband. In this technique, the sum of the weights of the input signal vectors is used to generate the desired output.

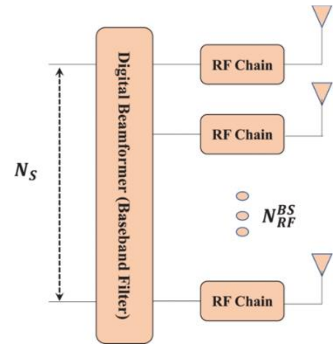

Fig.3. Digital Beamforming at BS

As shown in the above figure, a dedicated RF chain is needed for each antenna element in DBF systems, which helps process signals from all antennas simultaneously. Additionally, certain operations such as Direction of arrival estimation, adaptive beam steering, and antenna radiation patterns can also be controlled.

Digital beamforming can be further categorized into fixed and adaptive. The weights for the antenna array are predefined and kept unchanged in fixed DBF. In contrast, the weights alter as per surrounding conditions intending to improve the system's capacity in adaptive.

There are some difficulties in implementing digital beamforming in MIMO systems. This needs to be done at the baseband to control the phase and amplitude of the signal, and this requires several DAC converters, mixers, and power amplifiers. Each antenna element takes the responses from a dedicated RF chain, resulting in a massive number of antenna elements, which increases the power consumption, complexity in architecture, and the costs to implement digital beamforming in MIMO systems.

Advantages: 1) User signals have high resolution and are received with more accurate and rapid foundation results, 2) More cost-effective and flexible compared to analog, 3) there is a feasibility to change the number of beams or elements and programmable control of antenna radiation patterns, 4) there are many closely placed beams with flexible radar power [4].

Disadvantages: 1) Difficult to implement as it is complex and consumes huge amounts of power, 2) the number of RF paths required is higher than analog beamforming because there is a dedicated RF chain for each antenna element, 3) Low signal-to-noise ratio (SNR), 4) Due to a large number of antenna elements, digital beamforming is not suitable for implementation of massive MIMO systems at mmWave frequencies as it is expensive [4] [6].

Applications: Digital beamforming works well for base stations. It is typically used when multiple beams with high gains are required without decreasing the SIN ratio.

3) Hybrid beamforming technique:

Hybrid beamforming is based on the concept that the number of antenna elements limits the diversity and beamforming gains. In contrast, the number of transmitted data streams is limited by the number of RF chains.

Hybrid beamforming is implemented in both digital and analog domains. At first, in the digital domain, the transmitting signal is processed using a digital precoder as there is no requirement for dedicated RF chains here. Subsequently, RF phase shifters are employed as per the traditional analog beamforming approach to direct the digital out to antenna arrays.

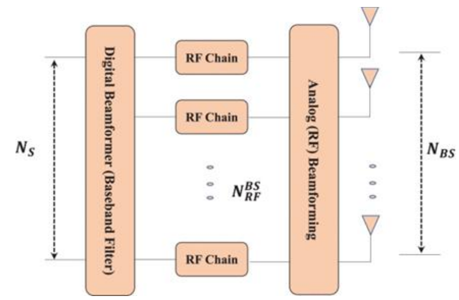

Fig.4. Hybrid Beamforming at BS

Hybrid beamforming works very well in Massive MIMO mmWave systems because mmWave signals are susceptible to high path loss. They cannot penetrate deep surfaces and are quickly scattered or absorbed in the atmosphere. The design of antenna arrays and the hybrid beamforming technique overcome this problem.

Advantages: Hybrid beamforming technique has the advantages of both analog and digital beamforming: 1) consumes less power and reduces hardware costs, so it is cost-effective, 2) has greater flexibility when compared to analog beamforming, 3) Supports multi-stream and multi-user transmission by leveraging additional degrees of freedom, 4) The Hybrid beamforming ensures there are capacity improvements in effectively using massive MIMO mmWave systems [4] [6].

Disadvantages: 1) There is excessive loss at combining power, 2) flexibility compared to digital beamforming is less.

Applications: Given its advantages from combining analog and digital positive aspects, it is best suited for massive MIMO systems.

III. Challenges

Today, many major cities and towns are already deployed with the fifth-generation telecommunication technology, but it is still in the initial phase. We merely saw the least capabilities of 5G, and the actual potential is yet to be seen and used. Devices that are compatible with 5G are already available in the market, yet we do not see the actual deployment of 5G in reality because of the challenges underlying it. Challenges in this section are discussed considering different perspectives.

In Massive MIMO, we form arrays of antennas at each BS to send a signal and use beamforming techniques to direct the signal towards a particular user. Challenge lies within the development of the antenna arrays. The designing of antenna arrays is straightforward, and the best techniques are already defined and are in place for lower frequency signals. As 5G now focuses on the unused higher frequency spectrum, there are challenges concerning the array design. First, based on the required gain, the available technology at low frequencies is well matured, and it is quite easy to develop arrays for beamforming. It is more challenging as frequency increases. Second, the gain required to mitigate the path loss increases as frequency increases. For example, the path loss for a radio frequency (RF) signal at a frequency of 2 GHz is ~80 dB; it will be ~114 dB at a frequency of 100 GHz. This would increase the number of antennas, too, thus increasing the overall electronics cost.

To discuss the challenges with beamforming, we must also consider beamformers on fixed transceivers and beamformers on mobile transceivers. This is because requirements and engineering specifications differ for both scenarios. The challenges that exist are, 1) as antenna size grows, additional antenna components cost and associated RF electronics also grow, 2) processing load in mobile beamformers increase due to the beam selection and management overheads, 3) additional antennas and electronics further increase pressure on power management units and mobile user device batteries.

There are specific atmospheric effects also on beamforming. These effects are different for different frequency bands. The refractive index of the propagation medium and the corresponding propagation loss has to be considered. Hence, atmospheric conditions are also a challenge and must be regarded to enhance the system's accuracy.

There are health concerns while using the mmWave beamformers. In the sub-6 GHz, the power used by radio signals is less because the signals can be excited at lower power. But in mmWave radio signals, power usage is high, and the increase in power would cause health issues. Also, beamforming focuses a signal towards a particular user, again a problem for the user. Specific absorption rate (SAR) is the most prominent parameter used to measure the impact of radio exposure on human tissue. This parameter also has to be considered, and careful measures must be taken while designing the antennas [7].

We must also consider the whole process of beam management, and beamforming is just a part of it. The beam management process consists of at least 6 phases: beam sweeping, beam measurement, beam reporting, beam determination, beam maintenance, and beam recovery. Every phase has its challenges, and every challenge has to be addressed [1].

IV. TECHNIQUES

The paper titled "Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research" [3] discusses state-of-the-art beamforming techniques that can be deployed to the massive MIMO systems. It discusses the issues underlying the deployment of massive MIMO systems and the importance of beamforming techniques in solving those issues. Also, various classifications are discussed, and an optimal beamforming technique that can provide good performance with massive MIMO systems has been suggested.

The introduction talks about how demand for wireless connectivity has increased, leading to the need for massive MIMO. The concept of smart antennas was discussed. This paper reviewed various papers and talked about beamforming and its necessity in the current 5G systems. The background of various important topics like massive MIMO, benefits of beamforming in massive MIMO systems - improved spectral efficiency, applicability for mm-wave bands, enhanced energy efficiency, and increased system security, Massive MIMO precoders and detectors were discussed, providing an overall necessary detail.

Classification of various beamforming techniques was discussed. Smart antennas are categorized into three types – beamforming, spatial multiplexing, and diversity. Classified into adaptive and switched beamforming based on physical characteristics. They are also classified into analog, digital and hybrid beamforming based on signal processing. Some algorithms improve adaptive beamforming performance and are classified as blind and non-blind algorithms. Examples of these algorithms are mentioned. There are subsections within section 3 where each classification mentioned above was briefly explained. Comparisons were made between them, and the advantages and disadvantages were discussed.

Millimeter-wave beamforming in massive MIMO is then discussed. The mmWave characteristics, benefits of using mmWave in 5G, issues present with mmWave, and how beamforming can help solve those issues are mentioned. It also reviews digital and hybrid beamforming techniques and discusses digital beamforming techniques. It concludes that digital beamforming is not well suited for massive MIMO systems because of the RF chain. It will be complex and expensive to address digital beamforming with massive antennas. It concludes in this section that hybrid beamforming is the best as it provides improvements to both spectral efficiency and power consumption.

Finally, the paper focuses on unresolved issues and future trends. The taxonomy of articles based on classification was appropriately tabulated. The paper concludes that broadband is more applicable than narrowband beamforming, adaptive is more suitable than switched beamforming. Finally, a combination of analog and digital, i.e., hybrid beamforming in addition to optimal algorithms, is the best-suited beamforming technique that can be deployed in massive MIMO systems. The optimal algorithm is 'minimum variance distortionless response (MVDR).'

We have considered what was concluded in this paper, i.e., we have performed a literature review on the hybrid beamforming technique and how machine learning can be leveraged with this technique to obtain the best results.

The second paper that we reviewed is “Deep Learning-Based Hybrid Precoding Technique for Millimetre-Wave Massive MIMO Systems,” published in 2021. This paper presents a hybrid beamforming design that leverages deep learning to join optimization of combiners and precoders in massive MIMO systems. It uses Convolutional Neural Network for this purpose and MATLAB to simulate the scenario [8].

The paper starts with introducing 5G, the need for 5G, and its uses compared to 4G. 5G is way faster than 4G providing up to 10 Gb/s; the spectral efficiency is greater multiple times, several hundred times higher cost, and energy-efficient. Techniques to improve spectral efficiency like MIMO and the advantages of millimeter waves were detailed. By combining the phased antenna arrays with precoding technologies, millimeter-wave transmission loss can be mitigated.

Hybrid precoding techniques are divided into baseband/digital precoding and radiofrequency/analog precoding. Conventional digital precoding uses too many RF chains, and hence hybrid architectures are preferred where lesser RF chains are used. The hybrid beamforming architecture has two types - RF chains, fully connected with antennas, and RF chains, partially connected with antennas. Different papers which proposed various algorithms, optimization approaches based on these two fully and partially based techniques are presented. However, these solutions focused on the optimization problem of hybrid beamforming have to fix computation time.

Deep learning provides solutions with less computational complexities and extrapolates functions from given limited features. This paper explores hybrid precoding with low complexity and studies the design of MIMO systems using Convolutional Neural Networks. They named it HBDL, hybrid beamforming based on deep learning.

The preliminaries and system model were discussed with the required antennas and RF chains. Several equations representing the channel matrix and spectral efficiency are formulated.

Two CNNs are proposed, one for combiner and one for precoder. The network parameters like the number of filters, hidden layers, dropout layers, input size, output size are defined. The channel Matrix ‘H’ is given as input to the neural network, and the model is trained for optimal parameters; this is the training stage. When a channel matrix is given as input in the prediction stage, the model outputs an optimal precoding matrix.

MATLAB has been used to simulate, and the results are presented and are compared with various fully and partially connected techniques like OMP, PE-Alt-Min, SDR-Alt-Min, and SIC. Parameters like the number of RF chains, data streams are changed, and graphs are plotted for various parameters to study its effect on spectral efficiency. HBDL has provided the best results and performance of every technique compared here degraded as the number of each parameter increased. Also, the spectral efficiency of this proposed technique can be improved by increasing the number of antennas. This technique is for single-user MIMO systems, and the paper concludes by stating it can be extended to multi-user massive MIMO systems.

In the paper titled “Beamforming Design for Large-Scale Antenna Arrays Using Deep Learning” by Tian Lin, Yu Zhu (2019), the objective is to use Deep Learning to design beamforming neural networks (BFNN) that are trained to optimize hybrid beamforming techniques to improve spectral efficiency (SE) despite challenges with imperfect channel state information (CSI) and hardware limitations [9].

For easy representation, the analysis in this paper is performed with a large-scale antenna array with only one RF chain. However, a few challenges arise with the input to the Deep Learning algorithm because DL-based design usually takes the received baseband signal as input. Still, here, the signal itself is optimized through the analog precoder. Another challenge is in finding an appropriate label for the beamforming design.

These challenges are overcome by formulating a new design approach. To tackle the input of DL, the analog phase shifters cannot be replaced by a digital neural network directly. Instead, Deep Learning is used to develop a beamforming neural network that gives an optimized analog BF vector output using the input of estimated CSI. In this new design, there is no need for labels; instead, the BFNN is trained with a loss function closely related to spectral efficiency performance.

Tian Lin, Yu Zhu (2019), designed the BFNN architecture in two stages: In the offline training stage, after generating samples via simulation, a classic mmWave channel estimator is applied to the base station that estimates the channel from the received signal. Now the channel estimate and SNR estimate are given as input to BFNN. Finally, the BFNN generates optimized analog vector output by using perfect CSI in the loss function that is minimized [9].

Secondly, in the online deployment stage, fixed parameters for BFNN are used, and the same mmWave channel is given as input to the base station to get the partial CSI. This channel estimate is applied to BFNN to generate an optimized beamformer. To summarise, the BFNN learns to get to an ideal SE with only reasonable channel estimates as input in the offline training stage. Subsequently, in the online deployment stage, the BFNN achieves robust performance to channel estimation errors and adapts itself to imperfect CSI.

The paper discusses certain limitations, such as BFNN has competitive computational complexity compared to traditional algorithm Hybrid beamforming design in terms of the number of floating/point operations (FLOPs). Additionally, the creation of BFNN requires many matrix multiplications and additions, whereas hybrid beamforming is limited to serial iterations and cannot perform parallel computing.

Also, suppose the accuracy of the channel estimate is low. In that case, the performance gap is larger because the main advantage of BFNN is that through many iterations, it can train itself to learn the characteristics of mmWave propagation channels and understand the relationship between imperfect CSI and ideal SE with perfect CSI.

Furthermore, the paper discusses that the BFNN design illustrated can be extended to other scenarios, such as hybrid beamforming with multiple RF chains by making small changes.

In the paper titled “Hybrid Beamforming for Multiuser MIMO mmWave Systems Using Artificial Neural Networks,” a research study by S Aljumaily, Li (2021) focuses on machine learning-based design for hybrid beamforming that can be applied in mmWave and MIMO systems [10].

This paper highlights that beamforming plays a huge role in achieving reliable 5G communication using massive MIMO systems. Beamforming is used to send narrow directed beams towards the receiver by altering the weights of baseband and RF precoder components of MIMO systems so that signals from multiple antennas convolute constructively in the pre-defined desired direction destructively in other directions.

The paper agrees that hybrid beamforming is better for 5G communications. Many researchers have developed hybrid beamforming designs intended to improve spectral efficiency and tackle channel limitations. However, the challenge is to balance the trade-off between high spectral efficiency and simple, realistic hardware architecture. Hence, the basis for this research is that machine learning algorithms are beneficial to train the beamforming systems to understand the surrounding environment and thus result in a better design for the weights of the digital baseband and analog RF precoder. This paper mainly focuses on multiple users being served at the base station simultaneously.

The system design of the hybrid beamforming design proposed in this paper has two parts. In addition to the first onsite part, which has the digital baseband and analog RF precoders, the second remote part within the central processing unit is implemented with convex optimization and a machine learning algorithm. Well-known machine learning aided designs are evaluated on three primary parameters: hardware and computational complexity and spectral efficiency [10].

The processing begins by gathering channel information from multiple users for sufficient samples and is given as input to a convex optimizer. The results are then vectorized, which is the main difference between this design and those designs of a single user. The critical assumption in this design is that the base station knows the total number of users for each beamforming process.

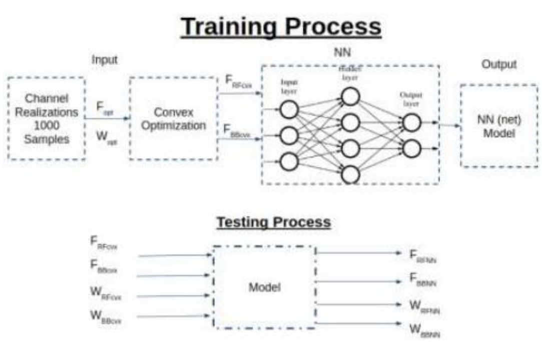

Fig.5. Proposed Architecture

After comparing the simulation results of this design with other popular architectures, we can conclude that this ML-aided architecture is less time-consuming as it is partly deployed in the cloud and calculations are performed offline. This design gives accurate beamforming for both static and mobile users and requires less channel training data to train the model quickly. Furthermore, this architecture can be used in applications that require high flexibility, fast beamforming, and mobility management.

V. Conclusion

This paper presents various Beamforming classifications primarily concentrating on Analog, Digital, and Hybrid. Millimetre-Wave beamforming is wideband. For massive MIMO in 5G applications, adaptive array beamforming is preferred. Hybrid beamforming is the best technique suitable for implementing massive MIMO systems for higher frequencies like mmWaves. Various challenges encountered with beamforming, for example, atmospheric conditions, antenna design, were discussed that affect the deployment of massive MIMO frameworks.

Various techniques for effectively implementing the hybrid beamforming method for 5G communications were reviewed. These hybrid beamforming architectures are developed using Machine Learning (ML) and Deep Learning (DL) that provide the best results. With the use of DL and ML, these architectures ensured that factors like power consumption, computational complexity, channel limitations were further decreased, and spectral efficiency has increased. These ML and DL techniques will improve the performance of the Massive MIMO frameworks, which would satisfy the requirements needed for 5G communication and beyond.

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