Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 5, May : 2024

SURVEY OF BEAMFORMING TECHNIQUES IN ADVANCED 5G AND 6G WIRELESS TECHNOLOGIES

Allanki Sanyasi Rao[1], Dr. Sreeja Mole S S[2]

(Dept. of Electronics & Communication Engineering, Christu Jyothi Institute of Technology & Science, Jangaon - 506167, Jangaon, Telangana, India)

srao_allanki@cjits.org[1], sreeja@cjits.org[2]

ABSTRACT

, portable antennas meeting demands for voice over IP, on-demand bandwidth, and multimedia define the wireless communication landscape. Fifth-generation (5G) spans 6 GHz to 60 GHz, addressing spectrum shortages in various industries. Evolution from 4G to 5G signals a progression toward more advanced 6G capabilities. At the core of this evolution is beamforming, a key technology shaping network performance. This paper explores Beamforming techniques, tracing their evolution from 5G to potential 6G. It examines types, emphasizing practical benefits in wireless communication optimization. The paper systematically classifies Beamforming techniques, focusing on Hybrid Beamforming—an approach blending analog and digital strengths. It highlights the paramount importance of Hybrid Beamforming, addressing limitations in conventional techniques and offering insights into its unique advantages. In the context of 5G, beamforming addresses imperatives like higher data rates, increased device density, extended coverage, interference mitigation, and energy optimization. Looking to 6G, the discussion considers extreme data rates, terahertz frequencies, AI-driven beamforming, holographic techniques, and challenges in global coverage. This paper aims to provide a comprehensive overview of Beamforming techniques, serving as a valuable resource for researchers, practitioners, and enthusiasts in next-generation wireless networks.

I. INTRODUCTION

Wireless connectivity is integral to daily life, profoundly impacted by the emergence of 5G. This advancement facilitates a myriad of IoT applications categorized under enhanced mobile broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC) [1]. Objectives like Spectral Efficiency, Latency, Energy Efficiency, and Data rate become integral to Service-level Agreements. The Air Interface plays a vital role in achieving these objectives, with Beamforming standing out as a significant advancement in the 5G Air Interface domain. Notably, 5G extends beyond merely providing high spectrum availability via mmWave, building on the knowledge gained from

Long-Term Evaluation (LTE) studies but introducing several advancements tailored to New Radio (NR) requirements.

In contrast to the era of 4G or older networks, where consumers manually searched for the strongest signal by waving their phones, 5G revolutionizes this process. Through automatic beamforming, the antenna adjusts itself, illustrating a fundamental difference between older-generation mobile antennas and the sophisticated technology utilized in 5G networks. Beamforming, a critical 5G technique, leverages advanced antenna technologies on mobile devices and network base stations [2]. Its purpose is to concentrate a wireless signal in a specific direction, diverging from the conventional approach of broadcasting to a wide area. This nuanced technique enhances the efficiency and precision of wireless communication.

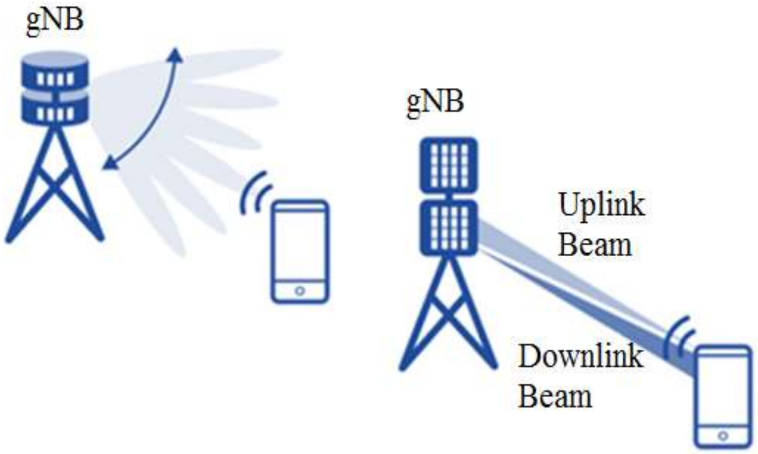

Figure 1: 5G Beamforming scenario.

The concept traces back to 1905, with recent applications in Wi-Fi and 5G networks. Illustrated by the 802.11 standard, Wi-Fi beamforming is implemented in routers. Electromagnetic waves naturally radiate in all directions from a single antenna, unless obstructed by a physical object. Multiple closely spaced antennas simultaneously transmit the same signal, creating a concentrated electromagnetic energy beam. Utilizing multiple antennas, 5G Beamforming directs a beam wave by adjusting the magnitude and phase of individual antenna signals within an array. This involves transmitting the same signal from several antennas spaced adequately apart. At the receiver's location, multiple copies of the signal are received, potentially canceling out or summing up constructively based on the varying phases of the signals relative to the receiver's position [3].

II. HOW DOES BEAMFORMING FUNCTION?

Imagine a world where sound waves can be precisely focused, just like light beams from a flashlight. In wireless communication, beamforming achieves this feat with radio waves, directing signals towards specific receivers instead of broadcasting them aimlessly. Think of multiple speakers working together to create a powerful, focused sound at a specific location. That's the essence of beamforming, where signals from multiple antennas are carefully adjusted to shape the radio beam like a sculptor molding clay. This precise control allows us to create zones of strong, clear signals for intended receivers, while simultaneously creating "silent zones" in unwanted directions. This magic trick, achieved by carefully adjusting the phase and amplitude of signals from each antenna, not only strengthens the signal for the intended receiver but also reduces interference for others, leading to faster data transfers, fewer errors, and a more efficient network overall. Beamforming is like the invisible conductor of the wireless orchestra, ensuring each instrument (antenna) plays its part in perfect harmony to deliver a clear and powerful signal, making it a cornerstone of modern communication technologies like 5G and Wi-Fi [4].

In the realm of Wi-Fi networking, beamforming is not a new concept, but its recent advancements have been significant. 5G networks heavily rely on beamforming as a crucial component. While a single antenna can transmit a wireless signal in various directions, the implementation of beamforming involves using multiple antennas positioned closely together. This technique facilitates the simultaneous transmission of multiple signal waves, which can either benefit or hinder depending on how effectively the signal waves are layered, leading to interference. Properly executed beamforming results in a robust signal precisely directed where intended, while incorrect implementation can lead to interference and signal loss. These represent some of the advantages and disadvantages associated with beamforming.

Through beamforming, wireless access points can focus their signals in specific directions, offering substantial benefits when receiving devices are aligned accordingly: increased throughput, reduced interference, and enhanced signal strength. If your devices support beamforming technology, concerns about signal capture or ensuring alignment with the signal path become less relevant [5].

III. VARIOUS TYPES OF BEAMFORMING

Beamforming is a signal processing technique applied prior to transmitting and receiving directional signals within a sensor array. Also referred to as spatial filtering, it involves utilizing angular arrangements to induce constructive or destructive interference at specific angles within the antenna array. This technique is employed at both transmission and reception terminals to achieve spatial directivity, ensuring accurate transmission and reception of radio or sound waves. Beamforming finds applications in various fields such as Sonar, radar, wireless communication, seismology, acoustics, radio astronomy, and biomedicine. Adaptive beamforming, a subtype, involves rejecting interference and filtering spatially to receive and estimate the desired signal at the sensor. Beamforming is categorized into different types based on the configuration of antennas.

Static Beamforming

An effective arrangement of multiple directional antennas results in a consistent radiation output directed outward from a central point, a process known as static beamforming. This term is typically used in reference to indoor, sectorized antenna arrays. Unlike dynamic beamforming, where parameters are adjusted dynamically, in static beamforming, all parameters remain fixed. This enables the distribution of an optimal quality signal to each connected device, as the radiation pattern remains constant per frame. Each station can receive either a strong or weak signal depending on the optimal power allocation achieved through this technique. However, projecting a beam towards a targeted receiver using a fixed array can pose challenges, making it a less commonly used technique. For instance, to cover a 360-degree area using 8 antennas, the area must be divided into 8 equal parts, with each antenna covering a 45-degree wide angle. An additional overlap of 5 degrees on the upper and lower sidebands of the bandwidth facilitates smoother roaming, resulting in each antenna covering a wider angle of 55 degrees. Indoor sectorized array solutions with 8, 12, or 16 unidirectional antennas can provide comprehensive 360-degree high-gain coverage.

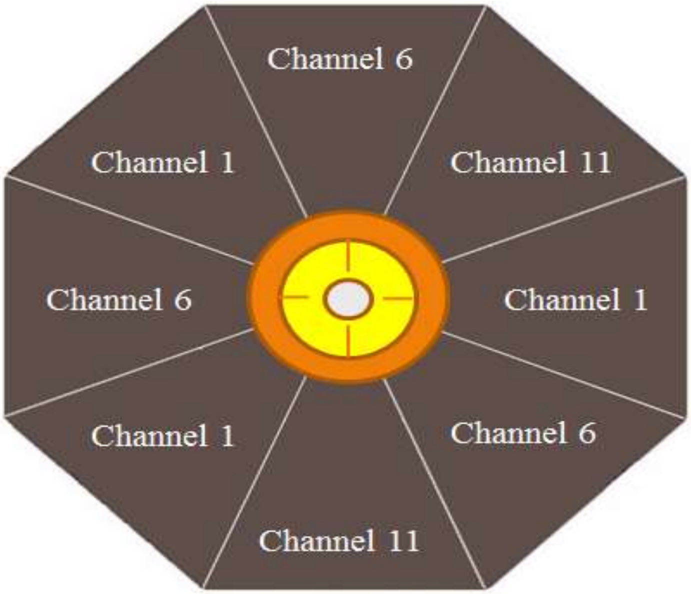

Figure 2: Static beamforming-indoor sectorized array

Dynamic Beamforming

Similar to static beamforming, dynamic beamforming differs in that it allows for the adaptive adjustment of radiation patterns and directivity capabilities. This enables the distribution of the highest quality signal to each connected device, as the radiation pattern changes with each frame. Through this technique, optimal power allocation ensures that each station receives a strong signal. Employing an adaptive array, this method efficiently handles signals projected towards a targeted receiver. This technology is also known as Beam steering or smart antenna technology, and it is a feature exclusive to the transmitting station.

Figure 3: Visualization of dynamic signal steering with an Intelligent Antenna Network

Transmit Beamforming

Unlike dynamic beamforming, where antennas physically steer a focused signal beam, transmit beamforming utilizes digital signal processing to enhance transmission towards specific users. This versatile technique involves transmitting multiple copies of the signal from the antenna array, each with slightly adjusted phases. These adjusted phases work together to constructively interfere at the intended receiver location, resulting in a stronger signal compared to traditional omnidirectional transmission. This amplification occurs without physically changing the antenna pattern, making it a software-based solution embedded within the transmission device. The two main forms of transmit beamforming further refine this technique by employing different strategies to optimize signal strength and directionality.

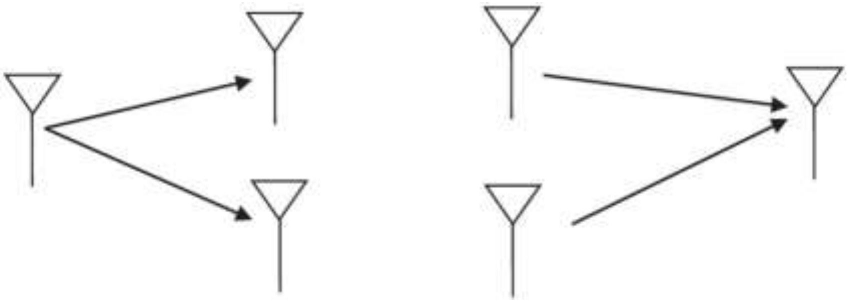

Figure 4: Depiction of Dynamic Beamforming Signal Patterns in Adaptive Antenna Arrays

Fixed Beamforming

Unlike its dynamic counterpart, fixed beamforming plays it straight. It uses pre-determined antenna weights, like aiming a fixed flashlight, to shape a signal pattern that amplifies towards a specific target. This simplicity makes it computationally efficient and cost-effective, finding applications in cellular networks, Wi-Fi, radar, and even satellite communication. However, its rigidity holds it back in dynamic environments where targets move or interference pops up, as it lacks the adaptability to adjust its beam pattern on the fly. While not the most flexible option, fixed beamforming offers a reliable and efficient way to aim our radio signals when we know where they need to go.

Switched Beamforming

The functionality relies on a static beamforming network designed to generate predefined beams. In this network, which typically has more beams (P) than antenna elements (N), signals from N antenna elements are processed to produce P beams. A specific type of beamforming network known as the Butler matrix generates P beams when P equals N.

For every user, the signal-to-noise ratio (SNR) is computed for each beam, enabling the selection of the beam with the highest SNR for further processing. All users within the coverage area of the array have access to all channels allocated to the cell it serves. Consequently, multiple users can utilize the same beam simultaneously [6].

Delay and Sum Beamforming

Delay and sum beamforming is a traditional spatial filtering method employing analog techniques, where delays are utilized instead of phase shifters [7]. While primarily applied in narrowband transmissions, this approach can also accommodate broadband signals. By introducing delays, the antenna array segregates signals corresponding to specific directions. However, due to the absence of amplitude weighting, interference mitigation is not effectively addressed in this technique.

Adaptive Beamforming

An adaptive beamformer employs an array of transmitters or receivers to execute adaptive spatial signal processing. This technique operates under the assumption that the base station (BS) continuously updates the mobile station's location. However, in scenarios with numerous real-time mobile stations, this algorithm can face challenges, complicating accurate localization.

In wireless communication systems, accurately determining the Direction-of-Arrival (DOA) of incoming signals on an antenna array poses a significant challenge. Implementing an adaptive beamforming system is notably more complex compared to a switched-beamforming system. The objective of perfect adaptive beams is to minimize user interference and significantly enhance available power resources.

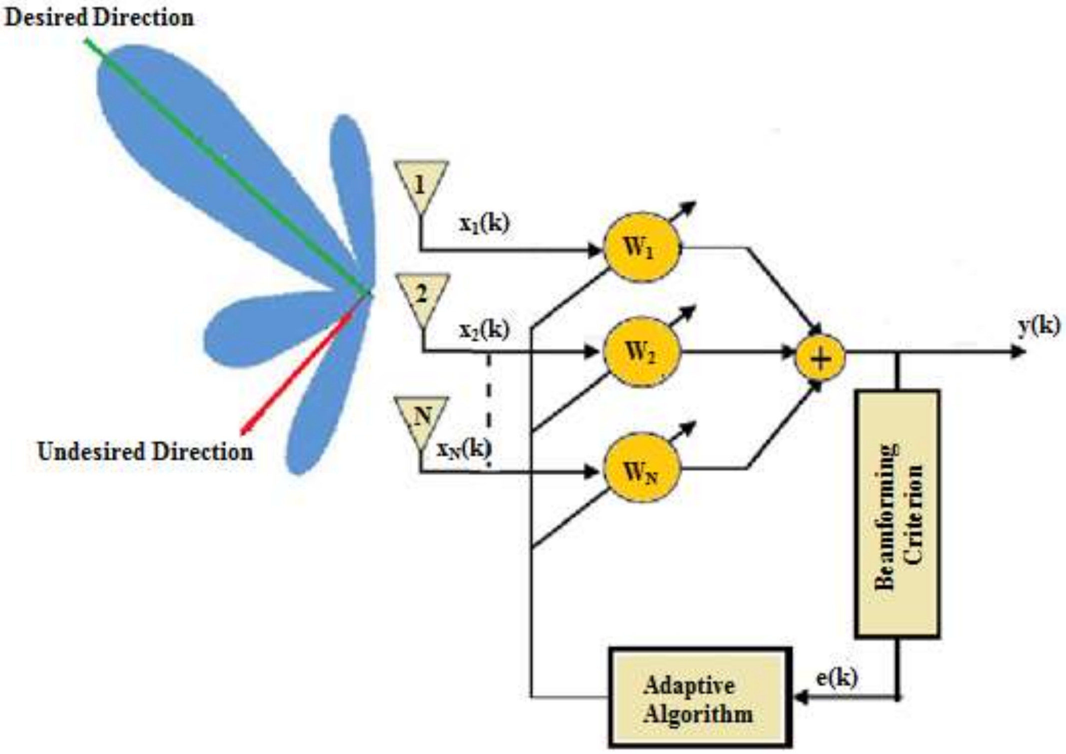

Figure 5: Adaptive Beamforming System

Narrowband Beamforming

Narrowband beamforming is achieved through instant linear combination of received array signals. However, wideband signals require additional processing dimensions to operate efficiently, such as tapped delay lines or sensor delay lines, as recently proposed, to create a wideband beamforming system.

Despite advancements, narrowband beamforming remains prevalent in most wireless communication applications. The mapping matrix adjustments for narrowband signals exhibit a straightforward form, as temporal shifts closely resemble changes in signal phase. This characteristic enables high-resolution beamforming and accurate determination of direction-of-arrival using the resulting equations.

Wideband Beamforming

Wideband beamforming employs spatial filtering techniques to process wideband signals. Given the demands of 5G for high-frequency band transmissions to achieve remarkably high data rates, wideband beamforming has emerged as a critical aspect for future wireless communication applications.

mm-wave beamforming stands out as a prime example of wideband beamforming poised to enable ultra-fast speeds and vast capacity in 5G networks. The evolution of wideband beamforming has been facilitated by advancements in ultra-wideband (UWB) technology and the expansion of wireless communication bandwidth. Both fixed designs, such as frequency invariant beamformers, and adaptive designs are utilized in wideband beamforming techniques to handle the characteristics of wideband signals.

IV. CLASSIFICATION OF BEAMFORMING

The terms massive MIMO and beamforming are sometimes used interchangeably. To clarify, beamforming can be considered a subset of massive MIMO or a technique used within it. Essentially, beamforming involves controlling the direction of a wave by appropriately adjusting the magnitude and phase of signals from an array of multiple antennas. This method enables the same signal to be transmitted from several antennas, with a guard wavelength between them. Consequently, the receiver will pick up the same signal from multiple sources in various directions.

Analog Beamforming

Analog beamforming is a fundamental technology in 5G and will continue to influence 6G networks. It focuses radio signals in a desired direction by adjusting their phase using phase shifters, which coordinate the timing of signals from each antenna element to create a concentrated beam.

This method is cost-effective due to its simpler hardware and requires minimal processing, allowing for faster beam steering. It is relatively straightforward to implement, facilitating deployment and management within mobile networks. However, analog beamforming offers less precise control over the beam's shape and direction compared to digital techniques. Its performance can be affected by dynamic environments where user locations or signal conditions change rapidly.

In 5G networks, especially at millimeter wave frequencies, analog beamforming is often used for initial beam steering, providing a quick and efficient connection setup. It can work alongside digital beamforming, with analog methods providing initial coarse steering that digital processing can refine.

Looking towards 6G, operating at higher frequencies will demand even more precise beamforming. While digital beamforming offers superior control, advancements in analog beamforming, such as improved phase shifters and advanced antenna designs, will ensure its continued relevance in future wireless communications.

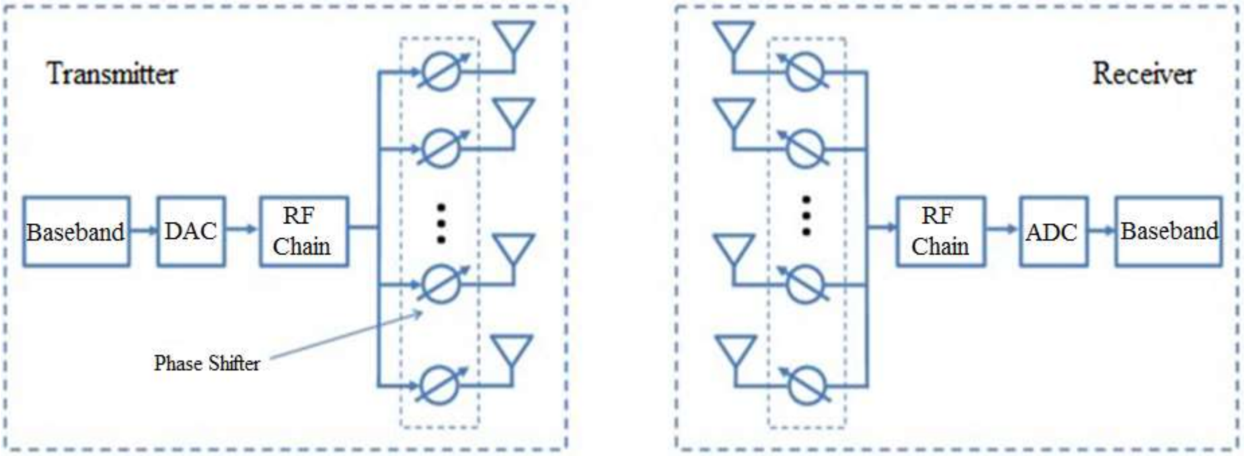

Figure 6: Architecture of Analog Beamforming

Digital Beamforming

Digital beamforming significantly enhances the ability to focus radio waves in 5G and sets the stage for advanced control in 6G networks. Unlike analog beamforming, it uses digital signal processing (DSP). Each antenna element's signal is converted to digital form via an ADC, allowing the DSP to adjust both phase and amplitude. This precise control creates customized beams and can nullify unwanted signals, enabling multi-user beamforming where one base station can serve multiple users simultaneously. Despite its advantages, digital beamforming requires more complex and costly hardware, leading to higher power consumption. However, its benefits, such as high capacity and precise signal delivery, often outweigh these drawbacks.

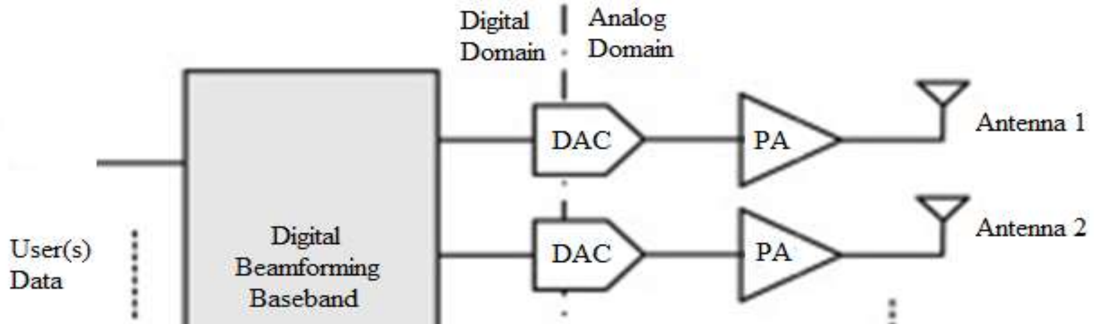

Figure 7: Architecture of Digital Beamforming

In 5G, digital beamforming is essential for millimeter wave (mmWave) communication, overcoming signal attenuation at high frequencies and supporting Multi-User MIMO, where a base station communicates with multiple users without interference.

For 6G, the expected higher frequencies, possibly in the Terahertz range, will make precise beamforming even more critical. Digital beamforming will likely evolve with AI and machine learning, leading to intelligent, adaptive beamforming that optimizes signal transmission based on real-time conditions, crucial for managing ultra-dense networks and dynamic 6G environments.

V. HYBRID BEAMFORMING

Currently, wireless technologies operate within the frequency range of 300MHz to 3GHz, heavily reliant on spectral efficiency and bandwidth to meet the increasing demands for wireless communication services. However, as the system bandwidth approaches the Shannon capacity, further exploration is needed. One potential solution lies in utilizing the bandwidth between 3GHz to 300GHz, known as the mmWave band. Employing multiple antennas at both transmitter and receiver ends can enhance spectral efficiency (SE) [8]. This enhancement can be achieved through MIMO technology, which involves either multiple antennas at the base station or utilizing multiple data streams between user equipment (UE) and base station (BS).

Massive MIMO offers significant advantages by leveraging thousands of antennas in a base station. Through beamforming gain, both transmission energy and small-scale fading can be minimized in a massive MIMO system. However, mitigating high path losses and optimizing beamforming gain are crucial to achieving a moderate Signal-to-Noise Ratio (SNR) for massive MIMO in mmWave bandwidths. Consequently, exploiting mmWave frequencies presents an opportunity to boost SE, particularly in the 30-300 GHz bands, by integrating massive MIMO communications [9].

mmWave massive MIMO and 5G networks find primary applications in device-to-device internet connectivity, machine-to-machine communication, and sector-wise vertical virtual division. These technologies face pressure to deliver high data rates while maximizing capacity, energy, and spectral efficiency [10]. However, mmWave frequencies suffer from increased path loss, which can be mitigated through proper line-of-sight selection and a multi-tier system to reduce multiple paths to the receiver [11]. Beamforming in massive MIMO compensates for path losses through directional transmission with large antenna arrays. Yet, hybrid beamforming, which combines analog and digital RF beamformers, aims to reduce power consumption and costs. This technique employs RF in analog form and multiple sets of beamformers connected to ADCs and DACs, optimizing data rates, particularly in mmWave architectures.

The effectiveness of beamforming hinges on the antenna arrays' directivity, ensuring that transmitting antennas concentrate signals toward the intended direction. In beamforming, transmitting antennas emit similar signals weighted by a scale factor, while the receiver adjusts received signals with another scaling factor before coherent combination. This process, enhancing the signal-to-noise ratio in the receiver setup, is known as beamforming gain, while the rate of change of error probability slope is termed diversity gain. The minimum number of RF chains corresponds to the quantity of antenna elements [12]. Beamforming employs a digital signal processor for flexibility in implementation and increased degrees of freedom for pure digital signal formation, albeit at the expense of architectural complexity and high power consumption due to each antenna requiring a unique RF chain. Analog beamforming can apply antenna weights either through phase shifting or time delay elements before or after RF signal up-conversion [13].

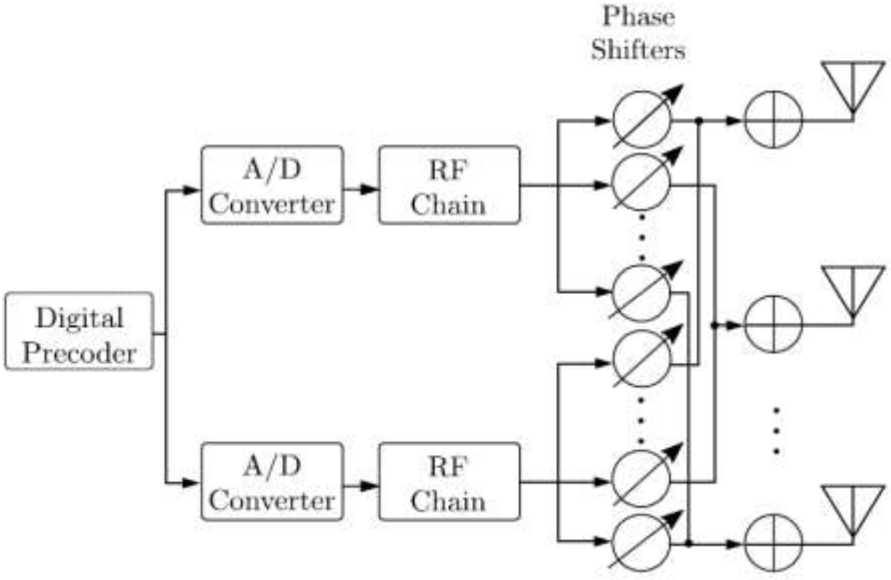

Figure 8: Architecture of Hybrid Beamforming

The Significance of Hybrid Beamforming

Hybrid beamforming techniques leverage both digital and analog methods, such as implementing HetNets and mmWave communication models with analog phase shifters, offering cost-effectiveness and low power consumption crucial for MIMO systems, where solely relying on mmWave MIMO can be both power-intensive and costly due to the combination of digital/analog signals for each antenna, hindering baseband signal processing [14]. This approach necessitates careful consideration of various impacted areas during design, including signal processing, channel estimation, precoding, and combining [15]. By employing fewer RF components, hybrid beamforming enables the processing of multiple baseband digital signal streams, contributing to antenna beamforming gain determination before analog processing takes place [16].

When implementing 5G networks with a mix of different types of base stations, known as HetNets, various technical issues can be addressed, such as increasing capacity and saving energy. This aids in creating a smoother network experience for users. HetNets combine low-power base stations like femtocells or picocells, which cover small areas, with high-power macro base stations (MBS). They are essential for boosting 5G networks by expanding coverage, improving capacity, and doing it all more affordably by reusing radio spectrum efficiently.

To make 5G networks energy-efficient and able to handle more users, a lot of different types of base stations are needed, including pico, macro, micro, and femtocells, set up on a large scale. Multihop communication, where signals hop between devices before reaching their destination, will be crucial for extending coverage in 5G wireless networks.

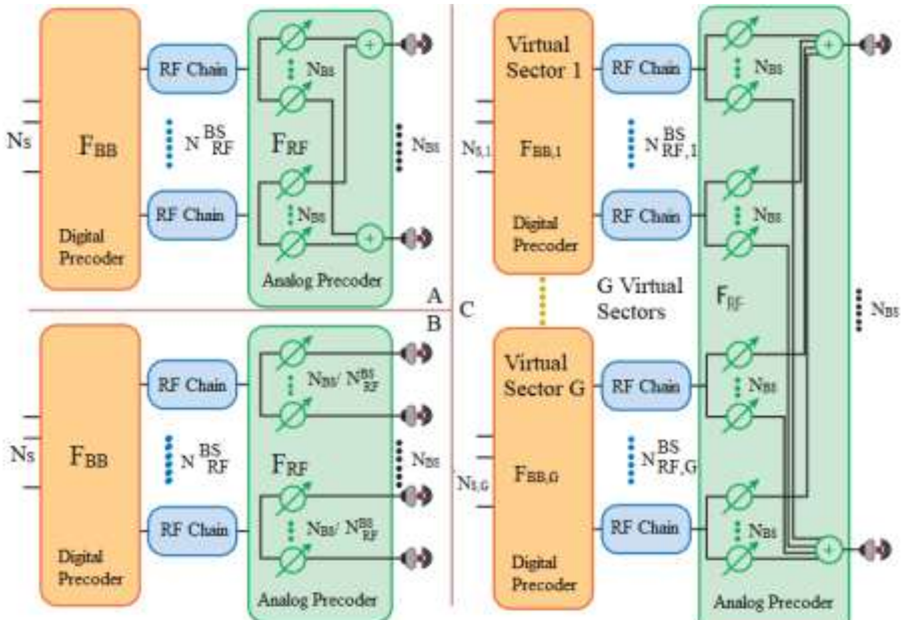

Figure 9: Block diagrams of hybrid beamforming structures at the BS for downlink transmission include full-complexity (A), reduced-complexity (B), and virtual sectorization (C) structures.

For specific applications like indoor multimedia and outdoor peer-to-peer connections, mmWave technology with hybrid beamforming, a method for focusing radio signals, can be used. Although mmWave technology is already used in some Wi-Fi standards, it hasn't been fully utilized in cellular networks because of issues like signal loss and interference. By using a mix of microwave and mmWave frequencies and techniques like software-defined radio (SDR) and hybrid beamforming, optimization of 5G networks for different applications, meeting regulations, and reducing path losses can be achieved [17]. Testing these techniques in real-world scenarios using SDR-based testbeds can help understand their effectiveness [18].

In areas with fewer users, techniques like zero-forcing (ZF) or max ratio transmission (MRT) can increase the capacity of massive MIMO networks, where multiple antennas are used for transmitting and receiving signals [17]. Finally, hybrid beamforming and mmWave signals for backhaul connections, which are the links that connect base stations to the core network, can be used for efficient communication in massive MIMO networks.

VI. ADVANTAGES OF HYBRID BEAMFORMING FOR 5G AND 6G

Hybrid beamforming offers a compelling solution for achieving high performance in 5G and future 6G networks. It combines the strengths of digital and analog beamforming techniques to address the challenges of millimeter-wave (mmWave) frequencies, which are crucial for enabling ultra-fast data rates in these next-generation networks. Here's a breakdown of the key advantages:

Facilitating mm-Wave Massive MIMO Communication: Hybrid beamforming plays a crucial role in enabling mm-Wave massive MIMO communication, which leads to a remarkable 1000x increase in the capacity of 5G and 6G wireless networks. This technology allows for more efficient use of the available spectrum and enables multiple antennas to transmit and receive signals simultaneously, significantly boosting network capacity. However, mm-Wave massive MIMO systems are susceptible to interference from users and can be quite complex to implement, especially in terms of digital beamforming. Digital beamforming involves adjusting the phase and amplitude of signals at each antenna to focus the transmission in a particular direction. The complexity of this process can lead to challenges in accurately steering signals and maintaining optimal performance. Additionally, the intricacies involved in implementing mm-Wave massive MIMO systems contribute to higher costs, both in terms of equipment and deployment. These systems require a large number of antennas and sophisticated signal processing algorithms, adding to the overall expense of building and operating the network [19].

Enhanced System Capacity: Dynamic Beam Steering: Hybrid beamforming allows for the creation of multiple, narrow beams that can be dynamically steered towards specific users. This spatial multiplexing enables serving multiple users simultaneously in the same frequency band, leading to increased network capacity and improved user experience [19].

Cost-Effectiveness and Power Efficiency: Reduced Hardware Complexity: Digital beamforming requires a dedicated radio frequency (RF) chain for each antenna element. This becomes expensive and power-hungry with the large antenna arrays used in 5G and 6G. Hybrid beamforming utilizes a combination of analog and digital processing. It employs a smaller number of RF chains for subarrays of antennas, significantly reducing cost and power consumption [20] [21] [22].

Improved Signal Quality and Coverage: Mitigating Path Loss: Millimeter waves suffer from high path loss, meaning the signal weakens significantly as it travels. Hybrid beamforming helps focus the signal energy towards the intended user, overcoming path loss and improving signal strength. This translates to better coverage and higher data rates at the user equipment [21].

Reduced Interference: Spatial Filtering: The ability to create focused beams allows hybrid beamforming to suppress unwanted signals from other users or interfering sources. This minimizes co-channel interference and improves the overall signal-to-interference ratio (SINR), leading to a more reliable and robust connection.

Scalability for Future Networks: Adaptable to Large Antenna Arrays: 6G is expected to utilize even larger antenna arrays for even higher capacity. Hybrid beamforming's ability to handle complex antenna configurations efficiently makes it well-suited for future network demands.

VII. CHALLENGES IN HYBRID BEAMFORMING FOR 5G AND 6G

While hybrid beamforming offers significant advantages, it also presents certain challenges that need to be addressed for optimal performance in 5G and 6G networks. Here's a breakdown of the key challenges:

Limited Degrees of Freedom: Balancing Analog and Digital Processing: The number of RF chains in a hybrid system limits the number of independent beams that can be formed. Finding the optimal balance between analog and digital processing to achieve the desired spatial resolution remains a challenge.

Channel Estimation and Feedback: Dynamic Channel Conditions - Millimeter wave channels are highly dynamic and prone to rapid changes due to blockage and user movement. Accurately estimating and feeding back channel state information (CSI) to the base station for beamforming adjustments is crucial yet challenging.

Complexity of Algorithms: Balancing Performance and Efficiency - Hybrid beamforming algorithms require complex computations to optimize beam patterns and resource allocation. Finding the right balance between achieving high performance and maintaining computational efficiency for real-time implementation is a challenge.

Hardware Calibration and Imperfections: Maintaining Accuracy - Imperfections in hardware components such as phase shifters and amplifiers can degrade the performance of hybrid beamforming. Developing robust calibration techniques and designing hardware with high accuracy remains an ongoing effort.

Scalability and Energy Efficiency: Trade-off between Performance and Power Consumption - As antenna arrays become larger in 6G, the number of RF chains and processing complexity might increase. Finding ways to scale hybrid beamforming while maintaining energy efficiency is a challenge.

Integration with Higher-Layer Protocols: Seamless Network Coordination - Hybrid beamforming needs to seamlessly integrate with higher-layer protocols like scheduling and resource allocation for optimal network performance. This requires efficient communication and coordination between different network layers.

VIII. RESEARCH DIRECTIONS

Centralized and Decentralized Learning: Cloud-RANs (C-RANs) enable centralized processing of data from distributed radios, offering significant advantages for AI-aided beamforming. Centralized learning leverages vast amounts of diverse data to train AI algorithms, improving latency, QoS, and spectral/energy efficiency [23, 24]. This approach overcomes limitations of storage and processing power faced by individual radios. Surprisingly, most research focuses on decentralized approaches, neglecting the potential of centralized training for tasks like codebook design and beam selection, which can be optimized for increased system capacity and power efficiency [25, 26]. Therefore, exploring centralized training and processing with C-RANs is a promising avenue for future research in AI-powered beamforming systems.

Reproducible Research: Lack of reproducibility hinders advancements in AI-aided beamforming research. While the field is rapidly growing, most studies rely on private, simulated datasets, making it difficult to compare and validate proposed solutions. A 2018 study found only around a third of research papers shared their data [27].

To address this, initiatives like the IEEE's MLC-ETI promote open-source code and datasets. This allows researchers to benchmark their models consistently and fosters collaboration within the scientific community. Openly available datasets and code are crucial not only for AI-based beamforming but for scientific progress as a whole. They accelerate innovation and ensure research builds upon a solid foundation.

Semi-Supervised, Active and Reinforcement Learning: While supervised learning offers high performance, it often relies on labeled data that can be scarce, expensive, or unrealistic in wireless communication scenarios. This presents a challenge for training beamforming models.

Here, alternative learning techniques emerge as promising solutions:

Unsupervised learning: When labeled data is unavailable, unsupervised learning can be effective, and research suggests it can even outperform supervised methods in some cases [28].

Semi-supervised learning: If a limited amount of labeled data exists, semi-supervised learning leverages both labeled and unlabelled data, offering advantages over purely supervised or unsupervised approaches.

Active learning: This technique focuses on efficiently labelling data by manually labelling a small portion and using a model to automatically label the rest. This iterative process progressively improves the model's accuracy with minimal human effort [29].

Reinforcement learning: This approach eliminates the need for labeled data altogether. The model learns through trial and error, receiving rewards for successful actions (selecting optimal beams) and refining its strategy over time [30].

Future research should prioritize exploring and advancing these alternative learning techniques to address data limitations and achieve robust beamforming models for real-world wireless communication systems.

Prototypes and Practical Demonstrations: While simulations offer valuable insights, real-world prototyping is crucial for developing commercially viable AI-aided beamforming for 5G and 6G. Simulations often fail to capture the complexities that can hinder real-world performance, such as hardware limitations. Understanding these complexities is essential for effective beamforming. For example, researchers need to account for impairments caused by hardware imperfections and synchronization issues [31]. Unfortunately, most research focuses on simulations, neglecting the prototyping stage. This gap presents a significant opportunity for future research. By building prototypes that address real-world channel and hardware limitations, researchers can validate the effectiveness of proposed solutions and pave the way for practical AI-powered beamforming systems.

Secrecy and Safety: User privacy is paramount for telecom providers, yet ML offers immense potential for network optimization using vast user data sets. The challenge lies in training these models without compromising user data. Federated learning offers a solution by training models on user devices using gradient information instead of raw data, mitigating privacy risks. Additionally, ML models, especially neural networks, are vulnerable to adversarial attacks where malicious data corrupts the training process. Autoencoders, a type of neural network, have shown promise in anomaly detection for network security. However, the impact of adversarial attacks on ML-assisted beamforming systems is a nascent research area with significant risks [32]. Consequently, there's a growing interest in developing privacy-preserving systems and ML models robust against such attacks.

Computer Vision: Millimeter wave (mmWave) and terahertz (THz) communication rely on line-of-sight (LoS) links due to their high directivity and susceptibility to blockages. Beamforming is crucial in these bands, but traditional methods require extensive beam training overhead, reducing efficiency. Here's where optical sensor-aided beamforming emerges.

By leveraging computer vision techniques and sensors like LiDAR cameras, this approach gathers information on device location and surrounding environment. This eliminates the need for complex CSI measurements and allows simultaneous beam selection for both transmitter and receiver. Additionally, incorporating GPS data or fusing it with optical and CSI data can further enhance accuracy [33].

As a new and exciting research area, optical sensor-aided beamforming presents numerous opportunities. From handover prediction to beam and base station selection, this technology holds immense potential. Machine learning algorithms can analyse optical data and address challenges like blockage mitigation and handover prediction. Studies like those using LiDAR data for pre-emptive handovers demonstrate the promising future of this field. The marriage of computer vision, machine learning, and optical data can revolutionize beamforming for mmWave and THz communication [34].

Beamforming at Low-SNR Conditions and Joint Optimization: Beamforming faces significant challenges in low-SNR environments, particularly in beam selection, tracking, and blockage prediction. Traditional methods like eigen-decomposition and MUSIC struggle at low signal strength, highlighting the need for new approaches. Initial research suggests that Machine Learning (ML) offers promise in low-SNR scenarios with limited data samples [35].

Additionally, computer vision and sensor-driven ML algorithms show potential for tackling these challenges.

However, two key areas remain largely unexplored:

Joint Parameter Optimization: Optimizing beams, power allocation, and interference management simultaneously to maximize spectral and energy efficiency.

Joint Beam Selection and Blockage Prediction: Combining beam selection with blockage prediction for proactive handover management.

While some studies explore these areas, like online learning for beam training and handover they often lack consideration for high-mobility scenarios. Existing models struggle with joint optimization problems, leaving significant room for advancement in these critical areas.

Channel Estimation: Accurate channel estimation in mmWave and THz beamforming systems is difficult due to complex channels, limited coherence time, high susceptibility to impairments, sparse multipath components, hardware constraints, and beam misalignment. New techniques are needed to address these challenges and achieve accurate, efficient, and scalable channel estimation [36, 37].

Identifying the Best Machine Learning Algorithm for a Specific Beamforming Use Case: Selecting the best Machine Learning (ML) algorithm for beamforming in 5G/6G is complex due to several factors. A major hurdle is the lack of standardized datasets for benchmarking and comparing algorithm performance. This makes it difficult to identify the clear winner for a specific application [38].

Beyond datasets, several factors influence algorithm choice:

Limited Labelled Data: Supervised learning often requires labelled data, which can be scarce for beamforming tasks. This restricts the pool of usable algorithms.

Data Quality and Generalization: Poor quality or unrepresentative training data can lead to models that underperform in real-world scenarios. Research on robust algorithms requiring less data is crucial.

Scenario-Specific Performance: Algorithm performance varies depending on factors like user mobility and antenna count. There's no one-size-fits-all solution.

Computational Efficiency: Resource-constrained devices might not be able to handle computationally expensive algorithms. Lightweight and efficient algorithms are necessary.

Real-Time Decisions: Beamforming often requires real-time decisions based on channel conditions. This eliminates some ML techniques that are too slow.

Balancing Performance Metrics: Different algorithms optimize different metrics. Finding the right balance for a specific application requires careful consideration.

Ultimately, there's no single best ML algorithm for all beamforming applications. Future research should focus on standardized datasets, improved training data quality, and developing efficient algorithms suitable for resource-constrained devices. Exploring novel ML techniques that can handle the complexities of 5G/6G beamforming is also crucial for future advancements [39].

IX. CONCLUSION

This paper provides a thorough examination of various classes of massive MIMO beamforming techniques. It offers valuable insights into how different hardware, software, and advanced methodologies can be effectively combined to create an efficient, cost-effective, and energy-efficient wireless communication system. Compared to conventional narrowband beamforming, the mm-Wave broadband beamforming technique demonstrates significant advantages for massive MIMO wireless communication systems. This is primarily due to the utilization of antenna arrays comprising low-power circuitry and the implementation of bandwidth-reducing techniques, which help lower costs.

Furthermore, the hybrid beamforming technique, which integrates analog and digital beamforming methods, greatly enhances the efficiency of massive MIMO wireless communication systems. The performance of this system is currently constrained by the level of cellular technology, such as 5G, or any subsequent generations of wireless communication systems. In essence, as cellular technology advances and becomes integrated into this system, its performance can be further elevated.

REFERENCES

[1] Allanki Sanyasi Rao et al. “Terahertz Communications: Applications, Challenges and Open Research Issues for Next Generation 6G Wireless Networks” in an International Journal for Innovative Engineering and Management Research, ISSN: 2456-5083, doi.org/ 10.48047/IJIEMR/V12/ISSUE 08/44,Vol.: 12, Issue: 08, Aug 2023, Pages: 295-315

[2] Chataut, R., & Akl, R. (2020). Massive MIMO systems for 5G and beyond networks - overview, recent trends, challenges, and future research direction. *Sensors*, *20*(10), 2753.

[3] F. Sohrabi and W. Yu, “Hybrid digital and analog beamforming design for large-scale antenna arrays,” IEEE J. Sel. Topics Signal Process., vol. 10, no. 3, pp. 501–513, Apr. 2016.

[4] Ahmed, I., Khammari, H., Shahid, A., Musa, A., Kim, K. S., De Poorter, E., & Moerman, I. (2018). A survey on hybrid beamforming techniques in 5G: Architecture and system model perspectives. IEEE Communications Surveys & Tutorials, 20(4), 3060-3097.

[5] https://www.forbes.com/sites/bijankhosravi/2018/04/30/todays-black-clouds-over-facebook-will-part-look-at-their-golden-ideas-in-5g/?sh=75d94a97313b

[6] Mietzner, J., Schober, R., Lampe, L., Gerstacker, W. H., & Hoeher, P. A. (2009). Multiple-antenna techniques for wireless communications-a comprehensive literature survey. *IEEE communications surveys & tutorials*, *11*(2), 87-105.

[7] Nam, W., Bai, D., Lee, J., & Kang, I. (2014). Advanced interference management for 5G cellular networks. *IEEE Communications Magazine*, *52*(5), 52-60.

[8] Jänis, P., Koivunen, V., & Ribeiro, C. B. (2011). Interference-aware radio resource management for local area wireless networks. *EURASIP Journal on Wireless Communications and Networking*, *2011*, 1-15.

[9] Kumar, S., Kovacs, I. Z., Monghal, G., Pedersen, K. I., & Mogensen, P. E. (2008, September). Performance evaluation of 6-sector-site deployment for downlink UTRAN long term evolution. In *2008 IEEE 68th Vehicular Technology Conference* (pp. 1-5).

[10] Franci, D., Coltellacci, S., Grillo, E., Pavoncello, S., Aureli, T., Cintoli, R., & Migliore, M. D. (2020). Experimental procedure for fifth generation (5G) electromagnetic field (EMF) measurement and maximum power extrapolation for human exposure assessment. Environments, 7(3),

[11] Tombaz, S., Frenger, P., Athley, F., Semaan, E., Tidestav, C., & Furuskar, A. (2015, December). Energy performance of 5G-NX wireless access utilizing massive beamforming and an ultra-lean system design. In 2015 IEEE Global Communications Conference (GLOBECOM) (pp. 1-7).

[12] Patcharamaneepakorn, P., Armour, S., & Doufexi, A. (2012). On the equivalence between SLNR and MMSE precoding schemes with single-antenna receivers. *IEEE Communications Letters*, *16*(7), 1034-1037.

[13] Stockar, S., Marano, V., Canova, M., Rizzoni, G., & Guzzella, L. (2011). Energy-optimal control of plug-in hybrid electric vehicles for real-world driving cycles. *IEEE Transactions on Vehicular Technology*, *60*(7), 2949-2962.

[14] Saquib, N., Hossain, E., Le, L. B., & Kim, D. I. (2012). Interference management in OFDMA femtocell networks: Issues and approaches. *IEEE Wireless Communications*, *19*(3), 86-95.

[15] Ahmed, I., Khammari, H., Shahid, A., Musa, A., Kim, K. S., De Poorter, E., & Moerman, I. (2018). A survey on hybrid beamforming techniques in 5G: Architecture and system model perspectives. IEEE Communications Surveys & Tutorials, 20(4), 3060-3097.

[16] Passoja, M. (2018). 5G NR: Massive MIMO and Beamforming–What does it mean and how can I measure it in the field. *URL: https://www. rcrwireless. com/20180912/5g/5g-nr-massive-mimo-and-beamformingwhat-does-it-mean-and-how-can-i-measure-it-in-the-field*.

[17] Shekhar Ravi Yarrabothu, Pitchaiah Telagathoti, (2019) Massive MIMO and Beamforming Techniques of 5G Networks, International Journal of Engineering and Advanced Technology,

[18] Z Lodro, N Shah, E Mahar, (2015) Design of 5G Antenna', IEEE Global Communications Conference (GLOBECOM), Pages 1-7, 2015.

[19] Cameron, T. (2019). Bits to beams–RF technology evolution for 5G mmWave radios. *Analog Devices, Norwood, MA, USA, Tech. Rep*.

[20] Kammoun, A., & Alouini, M. S. (2019). Elevation beamforming with full dimension MIMO architectures in 5G systems: A tutorial. *IEEE Communications Surveys & Tutorials*, *21*(4), 3238-3273.

[21] Pirinen, P., Pennanen, H., Pouttu, A., Tuovinen, T., Tervo, N., Luoto, P., ... & Latva-aho, M. (2018). RF driven 5G system design for centimeter waves. *Wireless Communications and Mobile Computing*, *2018*.

[22] Chen, S., Sun, S., Xu, G., Su, X., & Cai, Y. (2020). Beam-space multiplexing: practice, theory, and trends, from 4G TD-LTE, 5G, to 6G and beyond. *IEEE Wireless Communications*, *27*(2), 162-172.

[23] Yu, D.; Lee, H.; Park, S.H.; Hong, S.E. Deep Learning Methods for Joint Optimization of Beamforming and Fronthaul Quantization in Cloud Radio Access Networks. IEEE Wirel. Commun. Lett. 2021, 10, 2180–2184.

[24] Zhong, C.H.; Guo, K.; Zhao, M. Online Sparse Beamforming in C-RAN: A Deep Reinforcement Learning Approach. In Proceedings of the 2021 IEEE Wireless Communications and Networking Conference (WCNC), Nanjing, China, 29 March–1 April 2021; pp. 1–6.

[25] Costa, L.R.; Silva, Y.C.; Lima, F.R.M.; Klein, A. Beam allocation based on spatial compatibility for hybrid beamforming C-RAN networks. In Proceedings of the WSA 2019—23rd International ITGWorkshop on Smart Antennas VDE, Vienna, Austria, 24–26 April 2019; pp. 1–6.

[26] Pan, C.; Ren, H.; Elkashlan, M.; Nallanathan, A.; Hanzo, L. Robust beamforming design for ultra-dense user-centric C-RAN in the face of realistic pilot contamination and limited feedback. IEEE Trans. Wirel. Commun. 2018, 18, 780–795.

[27] Gundersen, O.E.; Gil, Y.; Aha, D.W. On reproducible AI: Towards reproducible research, open science, and digital scholarship in AI publications. AI Mag. 2018, 39, 56–68

[28] Huang, H.; Xia, W.; Xiong, J.; Yang, J.; Zheng, G.; Zhu, X. Unsupervised Learning-Based Fast Beamforming Design for DownlinkMIMO. IEEE Access 2019, 7, 7599–7605.

[29] Chiu, S.E.; Ronquillo, N.; Javidi, T. Active Learning and CSI Acquisition for mmWave Initial Alignment. IEEE J. Sel. Areas Commun. 2019, 37, 2474–2489.

[30] Zhang, Y.; Alrabeiah, M.; Alkhateeb, A. Reinforcement Learning of Beam Codebooks in MillimeterWave and Terahertz MIMO Systems. arXiv 2021.

[31] Andrews, J.G.; Buzzi, S.; Choi, W.; Hanly, S.V.; Lozano, A.; Soong, A.C.; Zhang, J.C. What will 5G be? IEEE J. Sel. Areas Commun. 2014, 32, 1065–1082.

[32] Ren, K.; Zheng, T.; Qin, Z.; Liu, X. Adversarial Attacks and Defenses in Deep Learning. Engineering 2020, 6, 346–360.

[33] Roy, D.; Salehi, B.; Banou, S.; Mohanti, S.; Reus-Muns, G.; Belgiovine, M.; Ganesh, P.; Bocanegra, C.; Dick, C.; Chowdhury, K. Going Beyond RF: How AI-enabled Multimodal Beamforming will Shape the NextG Standard. arXiv 2022, arXiv:2203.16706.

[34] Alrabeiah, M.; Hredzak, A.; Alkhateeb, A. Millimeter Wave Base Stations with Cameras: Vision Aided Beam and Blockage Prediction. arXiv 2019, arXiv:1911.06255.

[35] Xie, H.; Feng, D.; Yu, H. Fast and robust adaptive beamforming method based on l1-norm constraint for large array. Electron. Lett. 2015, 51, 98–99

[36] Lin, C.; Li, G.Y.L. Terahertz communications: An array-of-subarrays solution. IEEE Commun. Mag. 2016, 54, 124–131

[37] Noh, S.; Lee, J.; Lee, G.; Seo, K.; Sung, Y.; Yu, H. Channel estimation techniques for RIS-assisted communication: Millimeter-wave and sub-THz systems. IEEE Veh. Technol. Mag. 2022, 17, 64–73

[38] Jiang, C.; Zhang, H.; Ren, Y.; Han, Z.; Chen, K.C.; Hanzo, L. Machine Learning Paradigms for Next-GenerationWireless Networks. IEEE Wirel. Commun. 2017, 24, 98–105.

[39] Huang, H.; Guo, S.; Gui, G.; Yang, Z.; Zhang, J.; Sari, H.; Adachi, F. Deep Learning for Physical-Layer 5GWireless Techniques: Opportunities, Challenges and Solutions. IEEE Wirel. Commun. 2020, 27, 214–222.