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Review

A Review on Millimeter-Wave Hybrid Beamforming for Wireless Intelligent Transport Systems

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Abstract: As the world braces for an era of ubiquitous and seamless connectivity, hybrid beamforming stands out as a beacon guiding the evolutionary path of wireless communication technologies. Several hybrid beamforming technologies are explored for millimeter-wave multiple-input multi-output (MIMO) communication. The aim is to provide a roadmap for hybrid beamforming that enhances wireless fidelity. In this systematic review, a detailed literature review of algorithms/techniques used in hybrid beamforming along with performance metrics, characteristics, limitations, as well as performance evaluations are provided to enable communication compatible with modern Wireless Intelligent Transport Systems (WITSs). Further, an in-depth analysis of the mmWave hybrid beamforming landscape is provided based on user, link, band, scattering, structure, duplex, carrier, network, applications, codebook, and reflecting intelligent surfaces to optimize system design and performance across diversified user scenarios. Furthermore, the current research trends for hybrid beamforming are provided to enable the development of advanced wireless communication systems with optimized performance and efficiency. Finally, challenges, solutions, and future research directions are provided so that this systematic review can serve as a touchstone for academics and industry professionals alike. The systematic review aims to equip researchers with a deep understanding of the current state of the art and thereby enable the development of next-generation communication in WITSs that are not only adept at coping with contemporary demands but are also future-proofed to assimilate upcoming trends and innovations.

Keywords: MIMO; wireless intelligent transport systems; hybrid beamforming; millimeter-wave; next-generation communication system

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1. Introduction

The advent of fifth-generation (5G) wireless communication and beyond has been marked by an ever-growing demand for higher data rates and more reliable connections, particularly in the millimeter-wave (mmWave) frequency bands. These higher frequencies offer vast amounts of unused spectrum, which is essential for addressing the spectrum scarcity problem in current wireless systems. However, propagation challenges such as high free-space path loss and sensitivity to blockages must be overcome. A promising solution to these challenges lies in the adoption of multiple-input multi-output (MIMO) techniques which, when combined with advanced beamforming strategies, can significantly enhance signal directivity and array gain [1].

Hybrid beamforming has emerged as a pivotal technology that achieves a compromise between fully digital and fully analog beamforming techniques, offering both flexibility and power efficiency. This approach utilizes a reduced number of radio-frequency (RF) chains connected to a larger antenna array through phase shifters, switches, or attenuators. It is particularly well suited to mmWave MIMO systems where large antenna arrays can be packed into a compact form factor due to the small wavelength; yet, the cost and power consumption of fully digital beamforming with one RF chain per antenna element would be prohibitive [2]. The efficacy of hybrid beamforming is reliant on its design, crafted around multiple dimensions: link characteristics, user demands, band-specific propagation properties, scattering scenarios, structural constraints, duplexing modes, carrier frequencies, network topologies, as well as the applications envisioned ranging from cellular communication to satellite links. Each facet introduces distinct considerations, demanding a classification framework that systematically encapsulates the hybrid beamforming technologies [3].

Research in this sphere has produced a myriad of designs, algorithms, and methodologies that grapple with the intrinsic complexity of hybrid beamforming. A substantial volume of literature addresses algorithmic strategies for beamformer design, such as phase-only control, subspace methods, and sparse optimization. These techniques aim to tailor the beam patterns for enhanced throughput, reduce interference, and improve overall system capacity [4]. Moreover, recent advancements have expanded the application scope of hybrid beamforming, integrating it into diverse systems. These include but are not limited to Intelligent Transportation Systems (ITSs), unmanned aerial vehicles (UAVs) for robust control and communication, satellite communications for improved link reliability, (RADAR) for enhanced resolution and target detection, and a wireless local area network (WLAN) for higher throughput and coverage. Furthermore, reflective intelligent surfaces (RISs) have emerged as a new frontier, leveraging programmable metasurfaces to modify the propagation environment for improved communication performance [5].

In the context of Intelligent Transportation Systems (ITSs), the integration of satellite communication, mmWave roadside units, and connected vehicles present a multifaceted communication scenario, as illustrated by Figure 1. Satellites play a crucial role in providing wide-area coverage and connectivity for ITS applications, offering a reliable communication link that can support data exchange over vast geographical areas [6]. When combined with mmWave roadside units, which enable high-speed and low-latency communication at close proximity to the vehicles, the system enhances real-time data transmission, such as traffic updates, navigation information, and safety alerts [7]. Connected vehicles within this framework benefit from seamless connectivity and information exchange, enabling them to receive and transmit critical data for optimal navigation, collision avoidance, and overall traffic management in the intelligent transportation ecosystem. This integrated setup leveraging satellites, mmWave roadside units, and connected vehicles showcases a promising communication infrastructure for enhancing the efficiency, safety, and intelligence of modern transportation systems [8].

MmWave technology, with its wide bandwidth and precise beamforming capabilities, is increasingly being utilized to enhance communication in unmanned aerial vehicle (UAV) systems. This advancement offers a range of applications for UAVs, as illustrated in Figure 2, across various scenarios such as aerial photography, surveillance, and remote sensing. In these contexts, UAVs frequently generate substantial uplink data traffic by sending visual imagery, sensor readings, and other critical data to centralized control centers for analysis and decision-making. The high data transfer requirements inherent in aerial photography, surveillance, and remote sensing applications necessitate efficient and reliable communication links between the UAVs and the control centers. To address this challenge, mmWave access links are established to establish seamless connectivity between the UAVs and the core networks. These links can be established through ground-based base stations or satellite connections, depending on the specific operational requirements and coverage area [9].

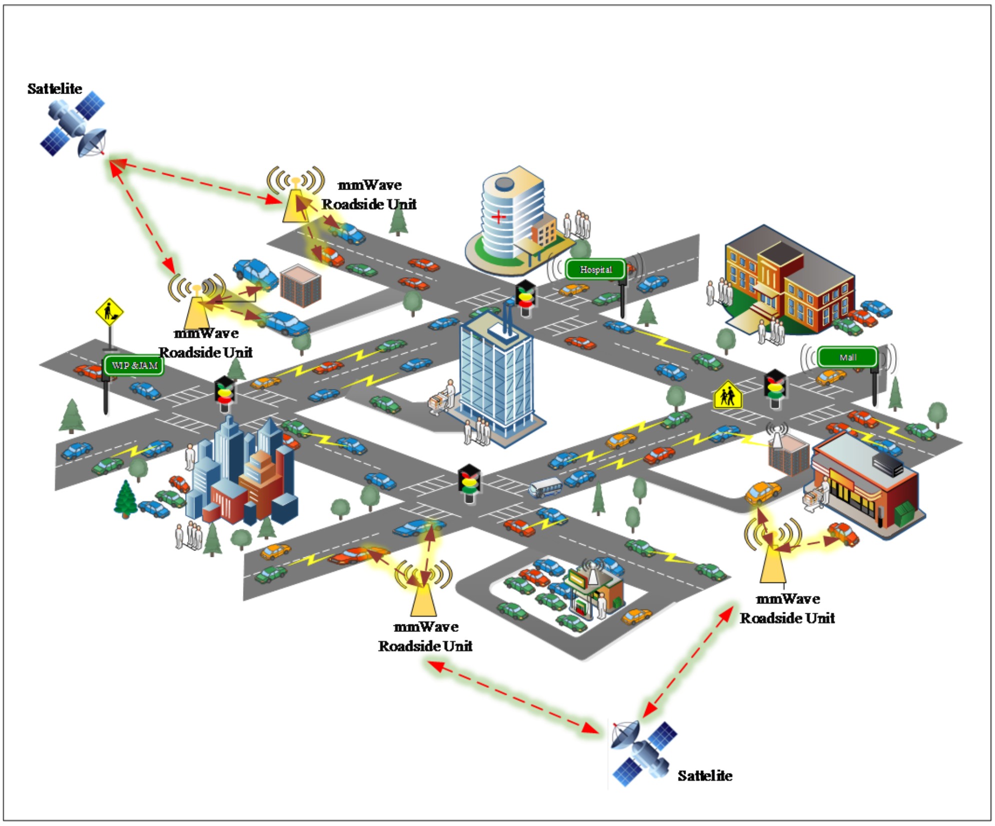

Figure 1. Intelligent Transportation Systems (ITSs): the integration of satellite communication, millimeter-wave (mmWave) roadside units, and connected vehicles.

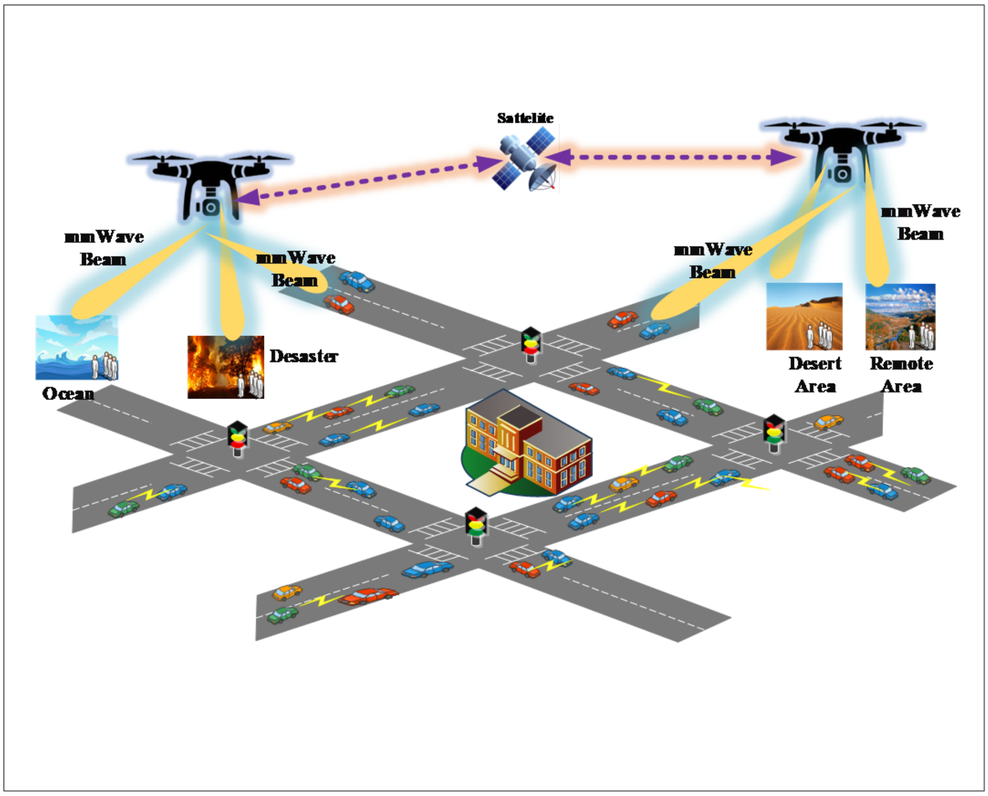

Figure 2. MmWave-unmanned aerial vehicle (UAV) communications with scenarios such as aerial photography, surveillance, and remote sensing.

For instance, in scenarios where UAVs are utilized for real-time surveillance or monitoring activities, the ability to transmit high-quality video streams and sensor data in a timely manner is paramount for effective decision-making and response. By leveraging mmWave access links, UAVs can establish robust connections with ground-based infrastructure or satellites, enabling the rapid and reliable transmission of data to control centers for analysis and situational awareness. Furthermore, in the realm of aerial photography, mmWave technology facilitates the efficient transfer of high-definition images and videos captured by UAVs, enabling photographers, filmmakers, and surveyors to obtain detailed and accurate visual data from aerial perspectives. This seamless connectivity enabled by mmWave access links ensures that visual and sensor data collected by UAVs can be transmitted in real time to control centers or storage facilities for processing, storage, and subsequent retrieval [10].

In the domain of remote sensing, mmWave-enabled UAV communications play a crucial role in collecting environmental data, conducting scientific research, and supporting precision agriculture applications. The reliable transmission of sensor data, including temperature readings, geographic information, and atmospheric data, contributes to improved spatial awareness, resource management, and decision-making in various sectors. The integration of millimeter-wave technology in UAV communications enables efficient, high-speed, and reliable data transfer, supporting a wide range of applications across aerial photography, surveillance, and remote sensing domains. By establishing mmWave access links through ground-based or satellite connections, UAVs can effectively communicate with core networks, facilitating the seamless transfer of visual, sensor, and other data for enhanced operational capabilities and situational awareness [11].

In this systematic review, we aim to provide a comprehensive roadmap for hybrid beamforming techniques applicable to mmWave MIMO communications, with an emphasis on wireless fidelity. We considered the following research questions while developing this unique systematic review.

- How can we use the techniques and metrics in hybrid beamforming to design better wireless systems that work well with modern technology?
- What factors affect the success of mmWave hybrid beamforming in wireless communication, and how can we optimize them to make systems work better?
- How can the latest research trends in hybrid beamforming help us create more efficient and effective wireless communication systems using new millimeter-wave technologies?
- How can we address the challenges, implement solutions, and focus on future research directions to improve the use of hybrid beamforming in wireless networks, considering the needs of today's technology and industry?

To provide answers to the above research questions, we developed a database consisting of 350 articles from various reputable sources and then we finally selected 132 articles to develop this unique systematic review. The salient contributions are highlighted as follows:

- A detailed literature review of algorithms/techniques used in hybrid beamforming along with performance metrics, characteristics, limitations, as well as performance evaluations are provided to enable communication compatible with modern trends.
- An in-depth analysis of the mmWave hybrid beamforming landscape is provided based on user, link, band, scattering, structure, duplex, carrier, network, applications, codebook, and reflecting intelligent surfaces to optimize system design and performance across diversified user scenarios.
- The current research trends for hybrid beamforming are provided to enable the development of advanced wireless communication systems with optimized performance and efficiency.
- Challenges, solutions, and future research directions are provided to equip researchers with a deep understanding of the current state of the art and thereby enable the development of next-generation communication systems.

Figure 3 illustrates the organization of this systematic review, which consists of five sections starting from Section 1, which constitutes a foundation stone; Section 2 contributes by providing critical knowledge; Section 3 contributes by providing comprehensive insights; Section 4 provides a thorough examination as well as an expert review; and finally Section 5 serves as an executive summary.

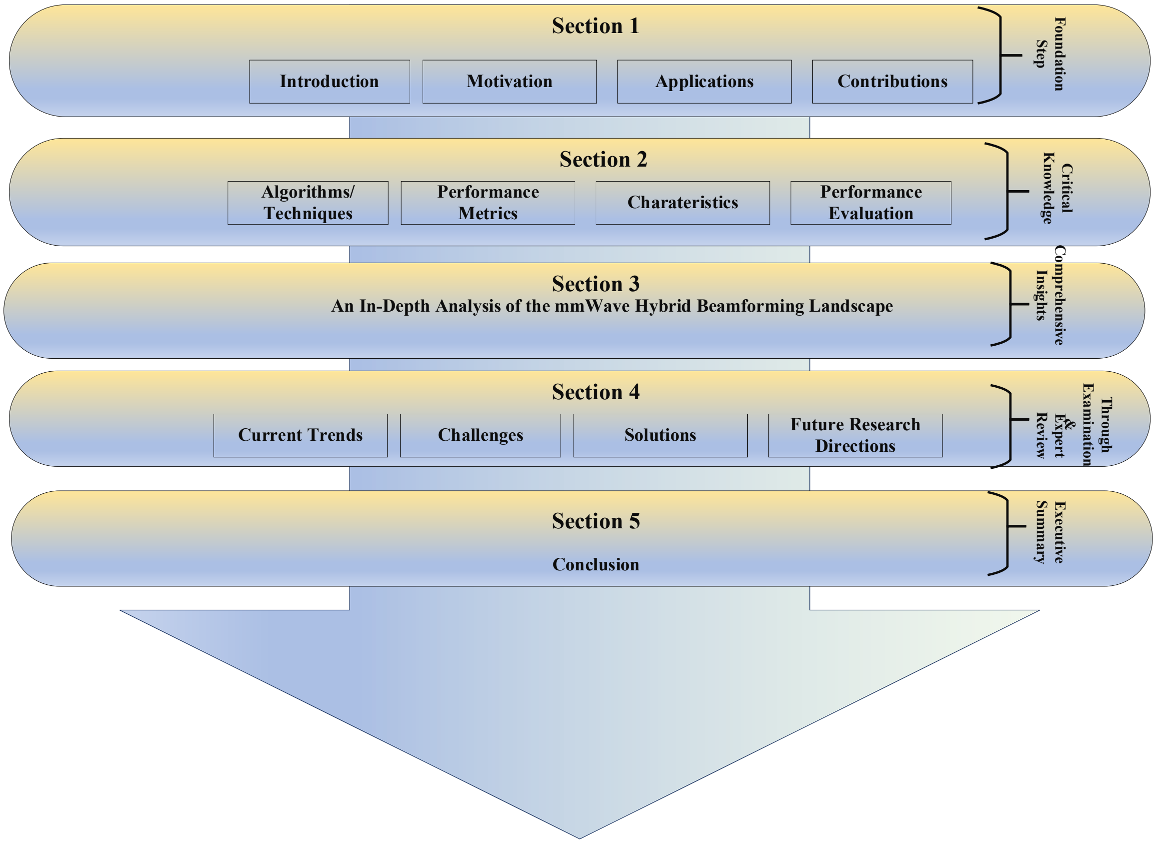

Figure 3. Organization of the systematic review.

2. Literature Review

Hybrid beamforming represents a hybridization of analog and digital beamforming techniques, offering a balance between the cost-effective analog approaches and the high-performance but complex digital solutions. In the realm of millimeter-wave wireless communications, where massive MIMO systems with large antenna arrays are prevalent, hybrid beamforming plays a pivotal role in optimizing beamforming efficiency while mitigating the inherent challenges of high-frequency propagation. Various algorithmic strategies and techniques have been proposed in the literature to address the complexities and limitations of hybrid beamforming in millimeter-wave systems [12]. Performance metrics in hybrid beamforming evaluation encompass a wide array of parameters, including spectral efficiency, signal-to-noise ratio, energy consumption, interference mitigation, system capacity, and overall communication quality. These metrics serve as benchmarks to assess the effectiveness and efficiency of different hybrid beamforming algorithms. Characterizing the characteristics of hybrid beamforming techniques involves understanding the interplay between analog and digital processing elements, the beamforming structure, the number of RF chains, the selection of beamforming vectors, and the optimization criteria utilized in the design process. Limitations of hybrid beamforming include hardware complexity, cost considerations, calibration challenges, and the trade-offs between analog and digital signal processing components [13].

Performance evaluations of hybrid beamforming algorithms provide insights into their practical applicability and effectiveness in real-world millimeter-wave communication scenarios. Evaluations often involve simulations, experimental validations, and comparative analyses against benchmark algorithms or conventional beamforming methods. By quantitatively assessing key performance indicators such as achievable data rates, system throughput, error rates, and computational complexity, researchers can gain valuable insights into the strengths and weaknesses of different hybrid beamforming approaches. Furthermore, performance evaluations help in benchmarking the proposed algorithms against state-of-the-art techniques, showcasing their advancements, optimizations, and potential for practical implementation in millimeter-wave communication systems [14].

The systematic review on millimeter-wave hybrid beamforming for wireless communications aims to provide a comprehensive overview of the algorithmic techniques, performance metrics, characteristics, limitations, and performance evaluations associated with hybrid beamforming approaches. By synthesizing and analyzing the findings from a diverse range of research studies, this review seeks to contribute to the understanding of the current landscape of hybrid beamforming in millimeter-wave systems, identifying emerging trends, challenges, and opportunities for future research and development in this critical area of wireless communication technology.

Table 1 provides a literature review of the algorithms/techniques used in hybrid beamforming along with performance metrics, characteristics, limitations, as well as performance evaluations.

Table 1. Literature review of algorithms/techniques used in hybrid beamforming along with performance metrics, characteristics, limitations, as well as performance evaluations.

S. No.	Algorithm/Method	Year	Reference	Performance Metrics	Characteristics	Limitations	Performance Evaluations
1	Environment-aware hybrid beamforming technique	2023	Di et al. [12]	Capacity vs. Antenna height Spectral efficiency (SE) vs. Transmit power SNR vs. Transmit power	The research introduces an environment-aware hybrid beamforming technique for mmWave massive MIMO systems, utilizing channel knowledge maps (CKM) to reduce real-time training overhead significantly.	Especially in scenarios with changing propagation conditions or dynamic user locations, there is a necessity for further research to optimize the CKM generation process and address potential inaccuracies or inconsistencies that could impact system performance.	The proposed environment-aware hybrid beamforming technique based on CKM demonstrates significant improvements in effective communication rates, even under moderate user location errors, compared to existing environment-unaware schemes.
2	Hybrid beamforming design to maximize the weighted sum rate (WSR)	2022	Chandan Kumar et al. [13]	Sum rate vs. SNR Sum rate vs. RF chains	The research presents a novel hybrid beamforming design for millimeter-wave full-duplex (FD) systems that maximizes the WSR.	The consideration of joint sum-power and practical per-antenna power constraints in the design require validation under different network configurations and channel conditions to assess the impact on system performance and efficiency.	The research demonstrates superior performance over half-duplex systems with limited RF chains, showcasing an optimized WSR considering practical hardware impairments, joint power constraints, and an optimal power allocation scheme.
3	Full-duplex integrated sensing and communication (FD-IAC) algorithm	2022	Md Atiqul et al. [14]	Velocity vs. Range Downlink rate vs. Downlink transmit power	The research presents an in-band FD-based ISAC system at millimeter-wave frequencies.	The joint optimization framework for designing the analog/digital (A/D) beamformers and self-interference (SI) cancelation to maximize Downlink (DL) communication rates and improve radar target sensing accuracy require validation under varying channel conditions, interference scenarios, and operational environments.	The research demonstrates accurate radar target estimation, high DL communication rates, and precise sensing of multiple targets using a joint optimization framework for A/D beamforming and SI cancelation, highlighting efficient performance and robustness in fifth-generation (5G) waveform environments.

Table 1. *Cont.*

S. No.	Algorithm/Method	Year	Reference	Performance Metrics	Characteristics	Limitations	Performance Evaluations
4	IRS-aided mmWave multiple-input multiple-output (MIMO) systems.	2022	Sung Hyuck et al. [15]	SE vs. Transmit power SE vs. Number of IRS elements SE vs. Number of paths SE vs. Estimation error	The research investigates the joint design of IRS reflection matrices and hybrid beamformers for mmWave MIMO systems.	The proposed joint design approach for IRS-aided hybrid beamforming architectures could face challenges related to hardware implementation, synchronization requirements, and scalability in dynamic communication environments.	The research demonstrates that the proposed joint design of IRS reflection matrices and hybrid beamformers for mmWave MIMO systems significantly enhances spectral efficiency and outperforms existing designs, leveraging sparse-scattering structures and angular sparsity in both narrowband and OFDM-modulated broadband scenarios.
5	Second-order cone program (SOCP) method, Penalty-based method, Semidefinite relaxation (SDR) algorithm	2022	Renwang et al. [16]	Transmit power vs. Total iteration number Transmit power vs. SINR Transmit power vs. Distance Transmit power vs. Number of elements of RIS	The research introduces a power minimization solution for a RIS-aided mmWave system with hybrid analog–digital beamforming.	The limitations of this research include the complexity and computational overhead associated with the proposed penalty-based algorithm and manifold optimization techniques.	The research showcases significant power reduction and improved system performance attributed to the optimized RIS response matrix and beamforming parameters, highlighting the crucial role of the RIS in enhancing communication efficiency and resource allocation.
6	Multi-layer RIS-assisted secure integrated terrestrial aerial network (ITAN) architecture	2022	Yifu et al. [17]	Energy efficiency (EE) vs. Number of received antennas Outage probability vs. Jamming power at each jammer EE vs. Channel uncertainty EE vs. jamming channel	The research introduces a multi-layer RIS-assisted ITAN.	The complexity and computational overhead associated with the proposed block coordinate descent (BCD) framework potentially limit the scalability and real-time applicability of the proposed architecture and optimization framework in dynamic network environments.	The research includes numerical results showcasing the architecture's capability in combating jamming and eavesdropping attacks, and outperforming various benchmark schemes, highlighting the potential of the proposed optimization framework in maximizing system EE performance and enhancing overall network security in ITAN scenarios.

Table 1. *Cont.*

S. No.	Algorithm/Method	Year	Reference	Performance Metrics	Characteristics	Limitations	Performance Evaluations
7	Gradient projection (GP)-based multiobjective evolutionary algorithm (GP-MEA)	2022	Zhen et al. [18]	SE vs. Number of iterations SE vs. Number of user equipments SE vs. Transmit power SE vs. Number of reflecting elements	The research investigates a robust beamforming design for RIS-assisted millimeter-wave systems with imperfect CSI, optimizing multiple parameters through a MEA approach.	The trade-off between beamforming gain, user priority, and error factor, while advantageous, requires careful tuning and optimization under diverse network conditions to achieve optimal system performance, which could impact the generalizability of the research findings across different deployment scenarios.	The research showcases enhanced wireless communication performance with a desirable trade-off among beamforming gain, user priority, and error factor.
8	K-bisection method	2023	Xin et al. [19]	Transmit power vs. Iteration number Relative frequency vs. Realized MSE Uncoded BER vs. Pilot SNR Transmit power vs. Iteration number Feasibility rate vs. MSE RIS Computational time vs. RIS element number	The research presents a novel hybrid beamforming approach utilizing reconfigurable intelligent surfaces (RISs) in a millimeter-wave system, with efficient inner majorization–minimization (iMM) and an alternating direction method of multipliers (ADMM) algorithms for analog and digital transmitter optimization.	The proposed iMM and ADMM methods, while faster than existing algorithms, still face scalability issues and practical constraints when applied to large-scale network deployments.	The proposed research outperforms existing methods by offering faster computational times through iMM and ADMM algorithms.
9	Gradient descent (GD) method	2023	Jiancheng et al. [20]	NMSE vs. Metasurface layers NMSE vs. Meta atoms Capacity vs. Metasurface layers Capacity vs. Meta atoms	Stacked Intelligent Metasurfaces (SIMs) are responsible for carrying out signal processing directly in the electromagnetic (EM) wave system.	The design involves low-precision analog-to-tigital converters and vice versa but needs multiple layers of metasurfaces for holographic beamforming.	By optimizing the number of phase shifters and having multiple layers of metasurfaces, using the GD method the capacity improvement is 150% as compared with a convential RIS.
10	Neural Network	2024	Hao Liu et al. [21]	Accuracy vs. Received SNR	The SIM-based optical–electronic neural network (HOENN) provides low latency for wireless sensing and coverage.	Despite the advantages of a novel framework it has physical implementation challenges and hardware imperfections.	The beamforming provides a reduction in hardware cost and coverage capability is improved.

3. An In-Depth Analysis of the mmWave Hybrid Beamforming Landscape

In a comprehensive analysis of the mmWave hybrid beamforming landscape, it is imperative to consider a myriad of factors that influence the deployment and optimization of hybrid beamforming techniques in wireless communication systems. The distinction between single-user and multi-user scenarios is critical in determining the design and effectiveness of hybrid beamforming algorithms, as the spatial multiplexing capabilities and interference management strategies vary significantly between these contexts. Moreover, the choice of link—whether downlink or uplink—introduces distinct challenges and opportunities in hybrid beamforming, necessitating tailored solutions for optimizing signal transmission and reception in each direction. The bandwidth considerations in mmWave hybrid beamforming are pivotal in determining the achievable data rates and spectral efficiency of communication systems. Narrowband mmWave applications may benefit from precise beamforming techniques that focus energy within limited frequency bands, while wideband mmWave systems require adaptive beamforming strategies to encompass broader frequency ranges and support high data throughput. The presence of rich scattering environments versus isotropic propagation characteristics further influences the design and performance of hybrid beamforming schemes, with rich scattering scenarios allowing for enhanced spatial diversity and more effective beamforming mechanisms.

The structuring of hybrid beamforming systems as fully connected or hybrid configurations has implications for system complexity, power consumption, and beamforming granularity. Fully connected architectures involve a one-to-one mapping between analog and digital components, while hybrid structures combine analog precoding and digital baseband processing to alleviate hardware constraints and enhance adaptability. Similarly, the choice between time-division duplexing (TDD) and frequency-division duplexing (FDD) in mmWave hybrid beamforming impacts the system's flexibility, interference management capabilities, and spectral efficiency, with implications for dynamic channel reciprocity and resource allocation.

Carriers in mmWave hybrid beamforming systems, such as orthogonal frequency-division multiplexing (OFDM) and non-orthogonal multiple access (NOMA), dictate the modulation and multiple access strategies employed in communication networks. The selection of carrier schemes influences system capacity, interference tolerance, and spectral efficiency, with implications for beamforming design and algorithm optimization. Furthermore, the network architecture, whether cellular or clustered, plays a key role in determining the deployment scenarios, coverage area, and interference coordination strategies in mmWave hybrid beamforming systems. Communication aspects such as channel state information (CSI) estimation, pilot signaling, and reconfigurable intelligent surfaces for power demand management and quality of service (QoS) optimization are integral to the performance and reliability of mmWave hybrid beamforming solutions. Leveraging reconfigurable intelligent surfaces allows for dynamic control of signal reflection and propagation paths, enabling efficient power allocation and QoS provisioning in mmWave communication environments. In addition, the application of mmWave hybrid beamforming extends beyond traditional wireless communication use cases, encompassing applications in radar systems for target detection and tracking, as well as in UAV communications for high-altitude and high-speed data transmission. The utilization of codebooks in mmWave hybrid beamforming systems, whether predefined or codebook-free, affects beam training overhead, adaptability to channel variations, and beam alignment accuracy, emphasizing the importance of codebook design and management in optimizing system performance and spectral efficiency. An in-depth analysis of these various facets of the mmWave hybrid beamforming landscape provides valuable insights into the design considerations, trade-offs, and opportunities in deploying efficient and scalable hybrid beamforming solutions for next-generation wireless communication networks. Figure 4 illustrates the summarized view of the in-depth analysis of the Mm-wave hybrid beamforming landscape.

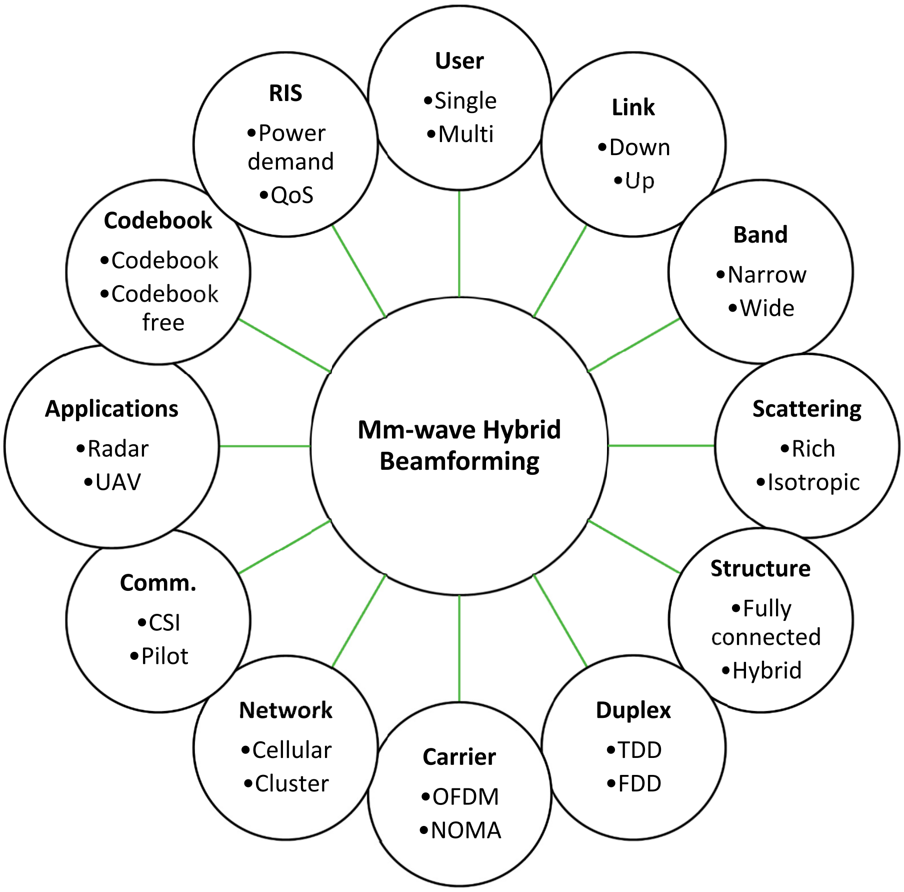

Figure 4. In-depth analysis of Mm-wave hybrid beamforming landscape.

3.1. User

On the basis of users, hybrid beamforming provides services to both single and multi-user systems.

3.1.1. Single-User

To provide hybrid beamforming implementation in a single-user system, high directivity is needed to minimize the impact of fading. The number of data streams is also an important prospective in beamforming to make it more reliable. The hybrid beamforming consists of two stages; if high performance is required, both stages need design flexibility.

- **Directional Beamforming**

The mm-wave spectrum is used by 5G beamformers to transmit and receive numerous beams. Using directed beamforming with multiple beams in MIMO and reusing the spatial spectrum is the greatest technique to decrease fading in the beamspace domain. Antenna components have zero bearing on beamspace, which is defined by the total number of beams on the transmit and receive sides. Reclaiming space while in single-access mode is possible using the space division single access (SDASA) protocol, a subset of space-division multiple access (SDMA). The multi-beam notion for single-user (SU) MIMO may provide data speeds in the gigabits per second range by using mm-wave and SDSA [22].

- **Data Streams Constraint Beamforming**

In particular scenarios where the number of RF chains exceeds the number of data streams, additional phase modifications are required. There is a need to either increase the number of RF chains with shorter phase shifts or decrease the number of RF chains with longer ones. The result is an improvement in spectrum efficiency [23].

- **Dual-Stage Beamforming**

Mm-wave MIMO uses beamforming to send energy in the way that the user wants. There is a middle ground between the inaccuracy of entirely analog methods and the expense and energy consumption of entirely digital methods; digital subband and analog broadband components are the result. Typically, a completely digital two-stage beamforming approach is generally used, which is based on a real-world-proven zero-forcing (ZF) and singular-value decomposition of the channel response [24].

3.1.2. Muti-User

In multi-user mm-wave networks, the analytical results show the trade-offs between power consumption, coverage, and rate. For millimeter-wave communications, multi-user MIMO is usually the best alternative to spatial multiplexing or single-user analog beamforming. This is because multiuser MIMO takes advantage of the transmitter's perfect channel state information [25].

One important step in improving connectivity and easing the spectrum bottleneck in the wireless communication network is to employ the underutilized mm-wave frequencies. To improve the spectrum efficiency of mm-wave relay networks, hybrid (analog/digital) beamforming of several data streams is often used when dealing with long-distance communication or very dynamic environments. We take a look at a hybrid beamforming method and the decode-and-forward approach for multi-user MIMO relay networks with mixed topologies and full-connected frameworks. Optimizing hybrid beamforming of relay communication is an optimization issue that aims to maximize the total rate of the entire network [26].

- **Users Constraint beamforming**

In scenarios where the number of users stays below the number of linked RF chains, the performance metric known as the maximum–minimum user rate performs at its best for completely digital beamforming. The channel capacity is relatively unaffected by the modest number of RF connections that are sufficient. When there are half as many RF lines as users, a time-fraction mm-wave approach may be used to determine a distinct maximum and minimum user rate. This approach may achieve a respectable user rate regardless of the amount of inter-cell interference, provided that the number of RF chains is half that of the users per cell at the base station or fewer [27].

- **Zero-Forcing Beamforming**

Consider the scenario where the channel state information is ideal; radio frequency beamforming, a mixed beamforming technique, is optimal for multi-user MIMO. The Robust regularized zero-forcing (RRZF) technique is used when the amount of channel information is restricted [28].

- **SINR Constraint Beamforming**

For a multi-user MIMO network to reduce interference and noise, an effective beamforming method is needed. This non-convex issue is solved using singular-value decomposition (SVD) with a modest level of complexity, where the number of RF chains is either larger than or equal to the quantity of users [29].

- **Power-Efficient Beamforming**

Hybrid digital–analog beamforming is famous due to low power demand as compared to the fully digital design in multi-user MIMO. Different types of connections have different impacts on power efficiency, cost-effectiveness, and service quality. One extreme case is the fully connected design, where all antenna components of the array are linked to each port of the radio frequency chain. The alternative is the one-stream-per-subarray (OSPS) layout, which uses links between individual subarrays and the antenna ports of radio frequency chains. In order to acquire the beam, the transmitter and receiver are thought of using codebook-based beamforming. The user's equipment's channel gain angle of arrival/departure pairs are the basis of this codebook. Data transmission makes use of three precoding options: analog maximum ratio transmission (MR-ZF), beamsteering (BMS), and analog maximum ratio baseband zero-forcing (BBM). Because it reduces complexity and delays problems, the MR-ZF is preferable for real-world applications [30].

- **DFT-based Beamforming**

In multi-user hybrid beamforming, the discrete Fourier transform (DFT) is used as an analog beam selection approach. The study of attainable rates in maximum ratio combining and zero-forcing receivers in the uplink system is carried out in the context of the Rician fading environment. In order to improve the possible downlink and uplink rates, the beam selection approach is based on mathematical equations and approximations [31].

- **Energy-Efficient Beamforming**

The signal processing of each link of the analog precoding matrix determines the overall power usage. This non-convex energy maximization issue is a challenging task. To solve this, there is a need to first reduce the issue to its most basic components: the ratio of the feasible rate to the power dissipation. Then, the digital and analog precoding matrices address the achievable rate issue and are updated in a cyclical fashion. This method facilitates the transformation of the issue into a convex one, for which a solution is readily solvable [32].

- **Non-iterative Processing Beamforming**

Low complexity in mm-wave channels is achieved by using a simple hybrid beamforming method based on non-iterative processing for multi-user downlink. In order to merge analog (RF component only) and digital (baseband) precoding, this design employs the hybrid regularized channel diagonalization (HRCD) technique [33].

- **Co-ordinated Beamforming**

The hybrid block-diagonalization (BD) precoder uses feedback for a multi-user MIMO architecture and is designed for both base stations and users. In order to achieve array gain using beamforming principles, it employs the Equal Gain Transmission (EGT) method. On mm-wave multi-user MIMO downlink systems, coordinated beamforming in hybrid schemes may send several transmission streams simultaneously. The design takes into account both the base station and the users. Also, the Modified Generalized Low-Rank Approximation of Matrices (MGLRAM) provides a viable and effective basis for this beamforming. The coordinated beamforming approach is competitive with or even surpasses the completely digital technique in terms of performance [34].

- **Efficient Array Gain Beamforming**

The greedy truncated power technique is used for downstream multi-user MIMO communication in order to achieve efficient array gain based on hybrid beamforming. This method may increase the effective array gain at mm-wave frequencies by sending several streams to each user. In terms of throughput, this method surpasses equal-gain-transmission (EGT) with different numbers of phase shifters [35].

- **Reduced-Interference Beamforming**

To minimize interference, multi-user MIMO employs a downlink method based on successive interference cancelation (SIC). Even with channel estimate inaccuracy and low-resolution (2-bit) phase shifters, this method outperforms zero-forcing in terms of complexity and spectral efficiency when dealing with interference and noise power [36].

- **Full-Stack Beamforming**

Using hybrid beamforming, the network capacity may be increased by sending numerous data streams concurrently to different users. If just analog beamforming is used, the SINR drops dramatically. When it comes to MMSE flat-frequency beamforming, less feedback means less capacity to minimize interference, while more feedback means more interference. The scheduler of multi-user MIMO, the beamforming architecture, and retransmissions work together to overcome this obstacle in full-stack hybrid beamforming [37].

3.2. Link

The hybrid beamforming techniques are attractive in downlink links as well as in uplink.

3.2.1. Downlink

In a single-user downlink scenario, increasing the number of base station antennas enhances system speed because of the larger diversity. In a scenario with multiple users, the number of cell users grows as the bit error rate (BER) decreases. This loss is more pronounced with conjugate beamforming precoding as compared to zero-forcing precoding [38].

- **Joint Two-stage Beamforming**

Hybrid beamforming can send out numerous streams to each user's device when there is perfect channel information. Unlike the conventional (functions independently) dual-stage design, this combined two-stage beamforming uses both stages to reduce data loss at the analog and digital stages. It employs the block-diagonalization method and water-filling approach to find the asymptotic solution in multi-user downlink MIMO [39].

- **Hardware Constraint Beamforming**

A blockage-dependent channel model is used for hybrid beamforming in multi-user MIMO in the presence of hardware constraints, showing a trade-off in power demand, achievable rate and coverage in a downlink cellular network. With more channel knowledge, the round-robin method of scheduling is better. This technique ignores computational complexity and channel overhead to provide better performance results [40].

- **Capacity Maximization and Interference Minimization Beamforming**

For downlink multi-user MIMO, a step hybrid beamforming method is used to enhance capacity in the first step and mitigate interference in the second step. The capacity is maximized by finding an equal response of the baseband channel by using radio frequency processing in analog. The interference is decreased by the block-diagonalization method. These two steps perform better than conventional block-diagonalization with a smaller quantity of RF chains in terms of capacity [41].

- **Inter-group Interference Minimization Beamforming**

Consider the scenario where the base station does not know the information of inter-group interference at any instant of time in downlink multi-user MIMO; this is a challenging issue to solve. Therefore, inter-group mitigation-based hybrid beamforming which consists of analog and digital beamforming is used. In the presence of a knocker channel model, an analog beamformer with a second-order statics problem, decoupling is required to optimize the analog precoder/combiner that mitigates that interference (inter-group) and noise, enhances the intra-group signal [42].

- **Efficient Transmission Beamforming**

Traditional mm-wave MIMO for multi-users with a large quantity of antenna are energy demanding when using high-resolution analog-to-digital converters and vice versa. To minimize the energy utilization, either the number of converters needs to be reduced or low resolution needs to be installed. A hybrid framework for multi-user downlink with a low-resolution converter is used at both the transmitter and receiver side. To minimize interference, a new data transmission technique utilizes a light-weight phased array to incorporate the beamforing matrix in the analog domain [43].

- **Joint Sensing Beamforming**

To reduce the components' complexity and hardware costs, a beamforming framework is utilized in systems which demand fewer radio frequency chains. Dual-functional radar communication (DFRC) uses radar and hybrid beamforming in the downlink [44].

3.2.2. Uplink

Various services are provided by hybrid beamforming in uplink.

- **Less Complexity with Interference Mitigation**

For multi-user MIMO communication in uplink, the hybrid beamforming method is used to reduce inter-user interference in which the analog and digital beamforming step are implemented. The Gram–Schmidt technique with low complexity can handle the analog step matrix, and the small dimensional effective channel MMSE can be used to obtain the digital beamforming matrix. Figure 5 depicts the unit cell architecture in which the base station is connected with N quantity of antennas and N_{RF} radio frequency chains such that the quantity of radio frequencies chains is less than number of transmitting antennas. When the number of radio frequency chains and phase shifters are equal, which is known as a fully connected architecture, the base station with a single antenna and user are served simultaneously and highly synchronized. Each phase shifter is connected with an adder and then connected with antenna through the amplifier which enhances the signal strength. This hybrid method has a large performance benefit over the existing ones and is robust enough to tolerate severe inter-user interference with low complexity, having a performance near to fully digital [45].

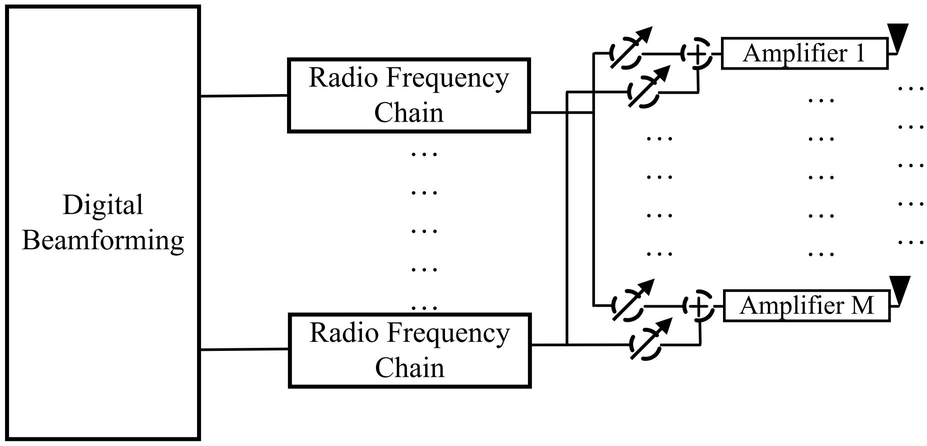

Figure 5. Hybrid architecture with amplifiers [45].

- **Scattering Mitigation**

The angle of arrival of different users varies in propagation pathways when they reach the base stations. The rough or diffuse scattering become significant when the wavelength is small or the frequency band is in mm-wave. Therefore, in multi-user MIMO, the scattering increases significantly. Different users with same angle of arrivals (AoAs) in the propagation pathways may cause user interference. Hybrid beamforming with the Gram–Schmidt method can be used to find the analog beamforming vectors, and in the digital domain the minimal mean square error (MMSE) method depending on the effective channel response is used to minimize the inter-user interference [45].

- **Detection**

A high-accuracy codebook is required for an exhaustive search technique, which is time consuming and requires more complexity. The opportunistic hybrid forming (OHBF) technique is used for detection in multi-user MIMO uplink communication. The base station randomly chooses some quantity of users for simultaneous transmission. This technique trains multiple slots and chooses the user group which has the best signal-to-interference-plus-noise ratio (SINR). To enhance the detection process more, a minimum mean square error (MMSE) filter is applied in the next step [46].

3.3. Band

The hybrid beamforming techniques are attractive in narrowband and wideband applications.

3.3.1. Narrowband

It offers a good compromise between the need for enough beamforming gains to compensate for propagation loss and the goal of lowering hardware costs and power usage. The performance metric used in [47] to describe the transmission's dependability is the mean square error (MSE). The hybrid transmit-and-receive beamformers are optimized alternatively using the alternating minimization approach in order to get around the challenge of solving the multi-variable design problem. In particular, an HBF algorithm based on manifold optimization is first put forth, directly addressing the analog component's constant modulus limitation.

3.3.2. Wideband

The discrepancy in the extra transmission distance of each subcarrier signal arriving at various antennas in the array, known as beam squint, is the cause of the frequency-dependent beam phase problem. Wide-spectrum MIMO-OFDM communication with hybrid beamforming with the beam squint technique begins by solving the frequency-dependent beam phase dilemma. The precoder design is the matrix factorization and the wide-spectrum hybrid precoding approach based on the manifold optimization, which seeks to identify the best precoder for the wide-spectrum communication [48].

The subarray structure used in Figure 6 addresses the issue of the hybrid beamforming design in MIMO-OFDM communication. It lowers the need for phase shifters because each RF chain should only be coupled to a single subarray. An adaptive hybrid analog–digital beamforming design based on a singular value thresholding technique is used [49]. The spectral efficiency of this design outperforms the semidefinite relaxation algorithm and offers a significant decrease in computational cost [50]. In Figure 6, it is illustrated that the system is equipped with N quantity of antennas and N_{RF} radio frequency chains.

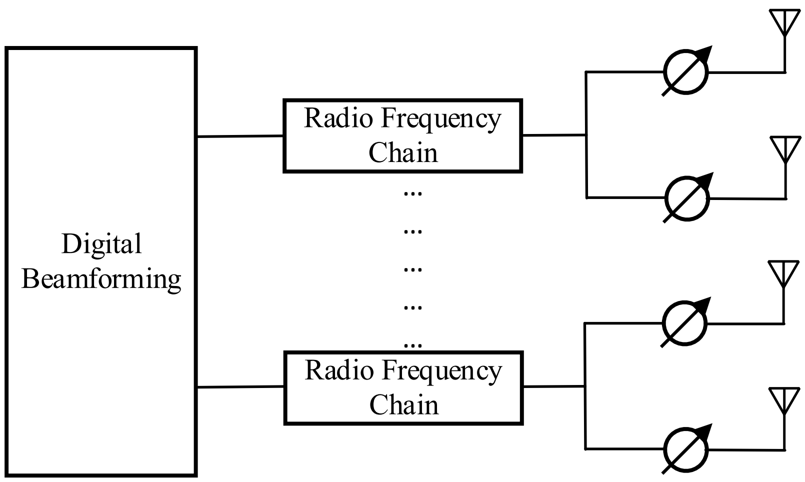

Figure 6. Subarray architecture [49,50].

- **Low-Resolution ADC Beamforming**

There are two primary ways to lower power consumption: digital beamforming using low-resolution analog-to-digital converters (ADCs) and hybrid beamforming. For a wideband multipath model, the impacts of transmitter impairments, numerous simultaneous users, and channel estimates have taken into account devices set at 60 GHz in the power consumption framework. The correlation of the quantization error is modeled to include various quantizers at each antenna and non-uniform quantizers. The outcome demonstrates that the ADC resolution reaches the ideal energy efficiency along with the signal-to-noise ratio (SNR). Furthermore, it is demonstrated that any desired trade-off between power usage and rate can be accomplished with mixed ADC resolutions, which are comparable to those obtained with a single ADC resolution [51].

- **Low-Resolution Phase Shifters**

In [52], a hardware-efficient, low-resolution phase shifter (PS) and adaptive antenna subarray hybrid beamforming design for a wideband mm-wave MIMO orthogonal frequency-division multiplexing (MIMO-OFDM) technology is discussed. Through the use of switch networks and PSs, each RF chain is dynamically connected to a non-overlapping antenna subarray, allowing numerous antenna diversity to be utilized to reduce the performance loss caused by the use of realistic low-resolution PSs. Next, an effective iterative hybrid beamformer algorithm is developed on the foundation of traditional block coordination descent (BCD) techniques. Additionally, a convergence and complexity evaluation for the algorithm is given. The superiority of this hybrid beamforming technique with dynamic subarrays and low-resolution phase shifters (PSs) is illustrated by extensive simulation data.

- **Wideband**

Alternating direction method of multipliers (ADMM)-technique-based hybrid beamforming is used for channel estimation in the uplink MIMO system for wideband. This channel estimation depends on precise pilot estimation in the channel with small complexity. The prediction of the channel depends on the received channel matrix. Its performance is impressive, with a smaller quantity of radio frequency chains in the presence of high-noise environment [53].

3.4. Scattering

Hybrid beamforming is able to handle rich scattering as well as isotropic scattering.

- **Rich Scattering**

In the analog beamformer, the precoder and combiner are acquired using singular-value decomposition (SVD). The objective is to reduce the overall strength of inter-stream interference (ISI), a phenomenon caused by the eigenmode, while maximizing the power of the desired data stream. The original analog beamformers in the channel's transmitter and receiver served as the basis for the digital beamformers. The findings demonstrated superior performance in difficult scattering settings [53].

- **Isotropic Scattering**

A generic hybrid beamforming architecture with selection is proposed for low-complexity multi-user MIMO transceivers. One possible shape for the beamforming matrix is a rectangular matrix with columns that are not orthogonal. It is possible to solve a connected Grassmannian subspace packing issue for a channel with isotropic scattering inside the subspace covered by a Dirty-paper coding beamformer [54].

3.5. Structure

There exist three types of structures, namely fully connected, hybrid connected, and partially connected.

3.5.1. Fully Connected

The beamforming system makes use of digital and analog precoders that are structured in a certain way. We might say that completely and partly linked structures are just specific examples of connected beamformers. Results showed that compared to completely linked structures, partly connected ones are less efficient in the spectrum [55]. The spectral efficiency approaches that of a completely linked structure as the quantity of the RF chains grows. In comparison to the completely linked structure, the partly connected structure displayed superior performance in terms of energy efficiency [56].

3.5.2. Hybrid Connected

In mmWave massive multiple-input multiple-output (MIMO) systems, the performance of the hybrid beamforming system based on the full-connected structure is comparable to that of the full-digital one. But it is severely limited because of the complicated circuit wiring in real-world applications [57].

Subconnected

The subconnected structures in hybrid beamforming are used to mitigate interference and enhance the capacity of a system. In multi-user MIMO, a subconnected architecture is necessary when many streams are needed; this is to ensure quality of service. This design calls for a base station with extra antenna arrays for downlink communication. For analog–digital beamforming, a piece-wise approach is ideal, supposing complete channel information. In order to maximize capacity while minimizing data loss, hybrid beamforming is used [57]. The capability of analog/digital approaches fully digital in stages, according to the rationale of information theory. The effect transmitter and receiver are integrated into the analog beamformer using a piece-wise dual joint iterative approximation (PDJIA) technique. During internal iteration, the optimal phase selected during external iteration of the analog combiner is used as the initial value. In order to obtain the optimal analog matrix for beamforming, this method reduces the number of iterations needed. The performance of single-user and multi-user MIMO can be improved by using successive interference cancelation (SIC) techniques. This approach converges rapidly [58].

Partially Connected

There are partially connected hybrid beamforming structures, which are discussed one by one in this section.

The cellular communication spectrum is inadequate for mobile traffic. Consequently, hybrid beamforming using an antenna selection approach makes use of massive antenna structures. Given an overall number of antennas, the primary goal of this approach is to choose the optimal number of transceivers, and secondarily, the optimal number of antennas per transceiver. The second goal is to look at the optimal combination of N (transceivers) and M (active antennas per transceiver). When it comes to channel estimate, it performs better [59]. For a multicasting network to provide effective power transmission, a combination of beamforming and antenna selection methods is used. When the number of phase shifters is smaller than the number of radio frequency chains, the antenna selection method works better. In Figure 7, the hybrid multi-group architecture is connected with N quantity of antennas and N_{RF} radio frequency chains. In this design, each radio frequency chain is attached to a power splitter and then connected with group of phase shifters. Each phase shifter is connected with an adder and finally aligned with a transmitting antenna. The multi-grouping of the phase shifters provides better analog beamforming and decreases the burden of beamforming operation on the digital beamformer [60].

For point-to-point and multi-user situations in high and scattering channels, a hybrid beamforming architecture with closed-form spectral efficiency approaches is proposed. Second, when high scattering channels are considered, a novel approach of phase shifter selection is required that simultaneously reduces power consumption in the phase shifter system and improves spectral efficiency. Also, the phase shifters of the RF beamformer need to be adjusted in order for the singular vectors, which are formed by the channel matrix components, to coincide with one another when there are several antennas. As a result, the performance is improved. In addition to facilitating asymptotically optimum behavior, the method also reduces computation latency and is easy to implement. Incorporating digital phase shifters into a hybrid beamforming approach results in a reduced performance limit, and the system is otherwise straightforward and successful [61].

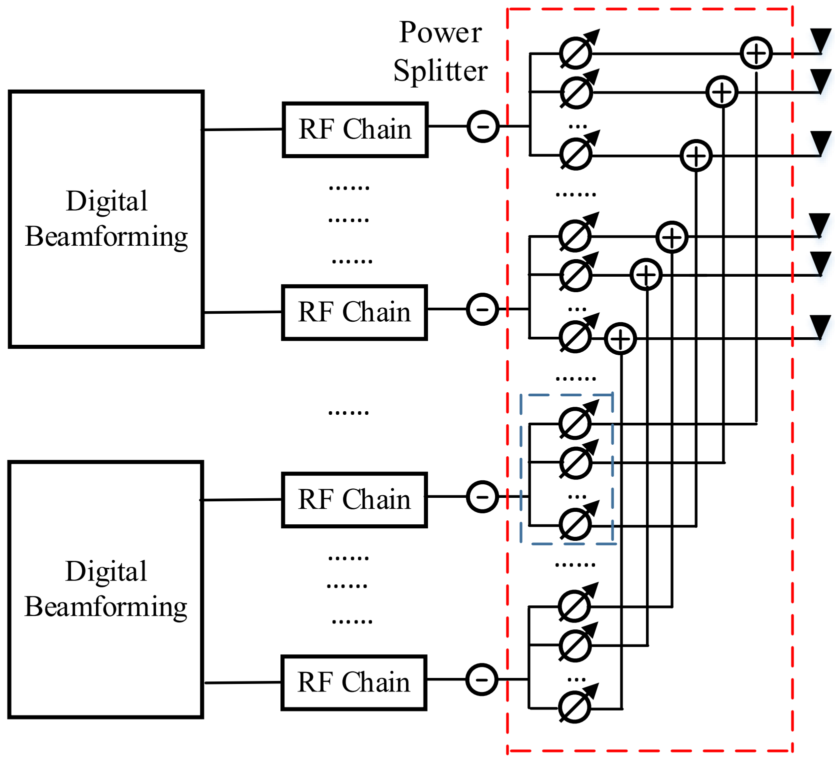

Figure 7. Muti-group hybrid beamforming design [60].

A typical hybrid MIMO system may obtain a large MI gain with little complexity and expense by simply adding passive phase shifters, since the DFT matrix is channel-independent. The ergodic rate of the MRC combiner reaches the same ideal scaling law as that of the two-stage analog combiner. A decrease in quantization error with increasing RF chain density accomplishes this. Figure 8 decpits the unit cell architecture in which the base station is connected with N quantity of antennas and N_{RF} radio frequency chains such that the quantity of radio frequencies chains is less than number of receiving antennas. There are two steps for an analog beamforming combiner; the disadvantage of this design is that it needs more phase shifters. Each radio frequency chain is connected with two low-resolution analog-to-digital converters (ADCs); therefore, less digital processing is required [62].

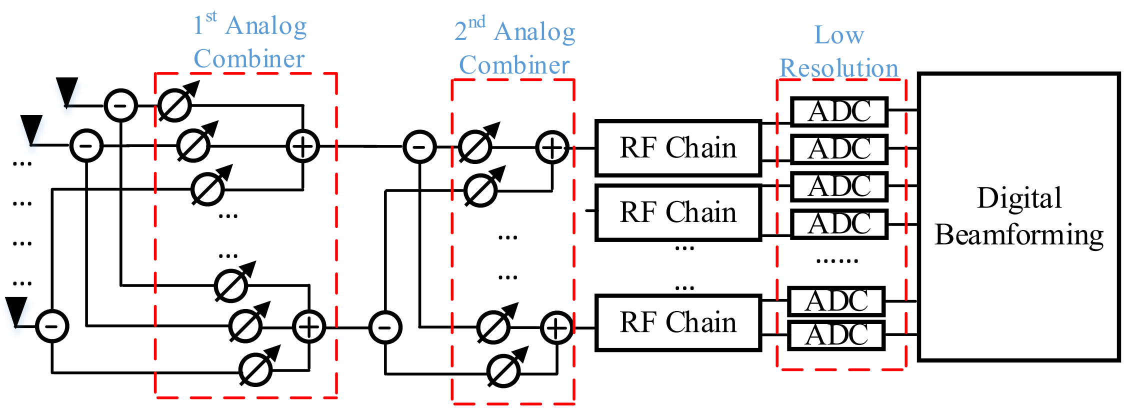

Figure 8. Double analog combiner with low-resolution ADCs [62].

For a mixed-structure stepped antenna array, the optimal beam pattern is obtained using a hybrid beamforming design. The first step is to determine the beamforming vector bases that will maximize power distribution throughout the specified angle range by referring to the radiation power ratio. The next step is to use the bases to solve a max–min optimization problem using the semidefinite relaxation (SDR) technique. This will flatten the response of the passband, which is the required angle range. The desired beam pattern may be found in the reference beamforming vector that this produces. Finally, given a phased array antenna with a hybrid structure, the beamforming vector can be determined using hybrid decomposition. In Figure 9, the hybrid antenna array architecture is connected with N quantity of antennas and N_{RF} radio frequency chains such that the quantity of radio frequencies chains is less than number of transmitting antennas. Each power splitter is connected with a single radio frequency chain; the splitter divides the power in order to provide more phase shifting in the analog portion. Then, power is added again by using the adder connected to the antenna. This architecture provides improved beam concentration [63].

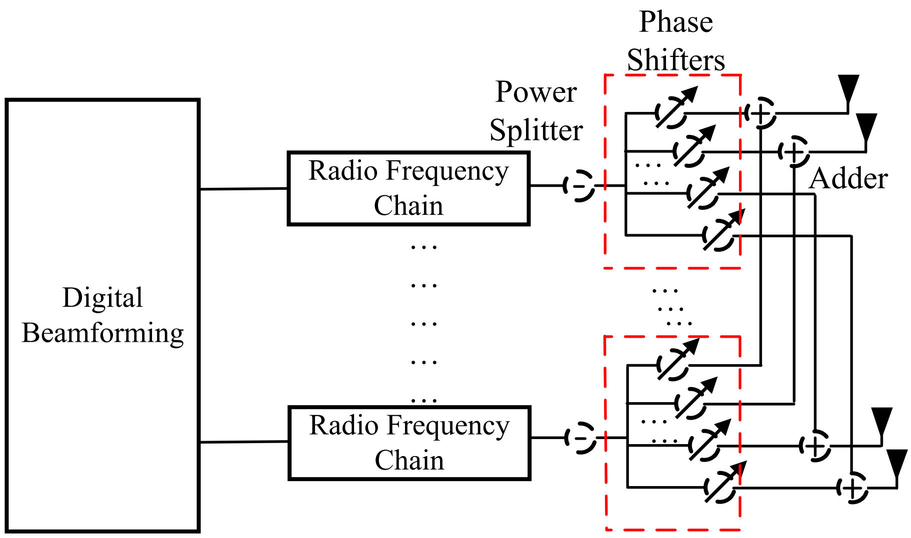

Figure 9. Hybrid architecture [63].

Massive MIMO hybrid beamforming with PS selection may significantly enhance energy efficiency while preserving almost all of the spectral efficiency. The benefits of energy savings are more apparent for fully connected hybrid beamformers.

In Figure 10, it is shown that the system is equipped with N quantity of antennas and N_{RF} radio frequency chains. The beamforming operation is carried out through analog and digital beamforming. The analog beamformer is composed of $N \times N_{RF}$ analog radio frequency beamformers. The digital part consists of $N_s \times N_{RF}$ digital baseband beamformers. In this subconnected architecture, each radio frequency is attached with N_p quantity of phase shifters attached through the switches. The total number of switches open is represented by N_{so}. The number of working antennas N_w or the antenna which dissipates power is equal to N-N_{so}. This N_p is equal to the ratio of N_w to N_{RF}. The advantage of this design is that the energy efficiency is further improved due to switches, although the beamforming gain is reduced.

In Figure 11, it is shown that the system is equipped with N quantity of antennas, N_{RF} radio frequency chains, and a quantity of data streams N_s. The beamforming operation is carried out through analog and digital beamforming. The analog beamformer is composed of $N \times N_{RF}$ analog radio frequency beamformers. The digital part consists of $N_s \times N_{RF}$ digital baseband beamformers. In this architecture, each radio frequency is attached to N_p quantity of phase shifters equal to N. The advantage of this design is beamforming gain with huge hardware complexity [64].

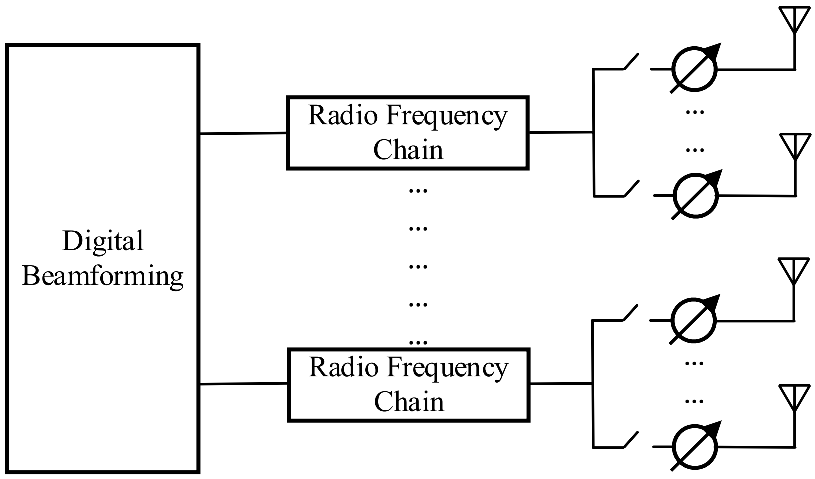

Figure 10. Subconnected architecture with switches [64].

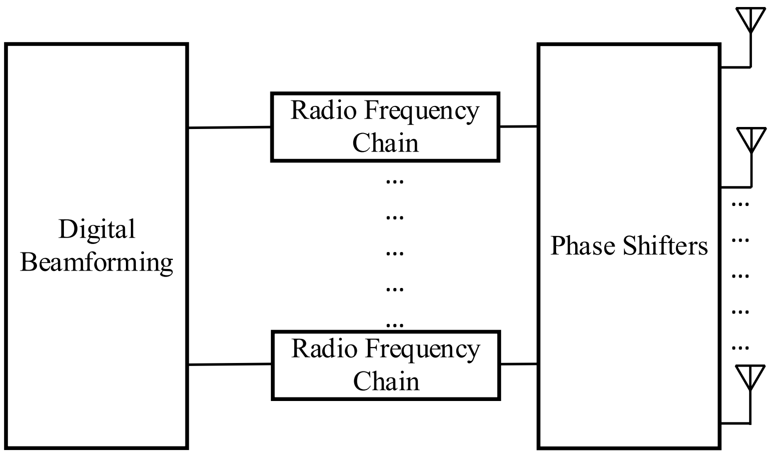

Figure 11. Fully connected architecture [64].

3.6. Duplex

Full-duplex communication is beneficial for hybrid beamforming, as it significantly boosts system performance.

- **Full-Duplex with CSI**

Full-digital precoders are used to obtain the baseband precoder and RF beamformer in HBF systems. The mm-wave frequency band is suitable for this hybrid beamforming full-duplex. In order to reduce the amount of self-interference, the RF beamformer weight, precoder, and combiner matrices for both the transmitter and the receiver are developed simultaneously. After the whole digital solution is acquired, the beamformer, precoder, and combiner matrices are generated using an iterative procedure that is based on the ideal simplified condition of perfect channel state information (CSI). Then, the HBF solution is derived from the digital response using the least-squares approach [65].

- **Full-Duplex with RF Chain having Dynamic Range**

A mixed beamforming architecture enables a mm-wave receiver to operate in full-duplex mode, establishing simultaneous in-band connections and communications with two devices. This design offers beam alignment schemes and codebook-based analog beamforming. For full-duplex system studies, such as those including beamforming-based approaches and analog and/or digital self-interference cancelation, it is helpful to determine the amount of self-interference reduction required at various locations in the receiver. The goal of this effort should not be to provide a fully operational mm-wave system; rather, it is meant to demonstrate a design technique that takes into account certain practical aspects. This approach has the potential to be a gold standard for systems limited to a certain dynamic range and those that function in the real world [66].

- **Full-Duplex with Limited Dynamic Range**

With the advent of full-duplex (FD) radio, which allows for simultaneous transmission and reception on the same frequency band, data speeds are increased by a factor of up to two. An improved weighted sum rate (WSR) in a single-cell mm-wave multiple-input multiple-output (MIMO) FD system is the goal of a novel hybrid beamforming (HYBF) design. The HYBF technique is unique in that it considers not only the overall sum-power restrictions but also the actual per-antenna power limits. Users of the uplink (UL) and FD BS have their demands satisfied by a novel optimum power distribution approach that takes into account interference, self-interference (SI), and LDR noise. A completely digital half-duplex (HD) system with varying amounts of LDR noise and RF chain numbers may reach the maximum gain for a multi-user (MU) mm-wave FD system. This layout outperforms the HD method using a small number of RF chains across the board when it comes to LDR noise. An advantage of this design is that it allows for amplitude control at the analog stage [67].

- **Sensing and Full-Duplex Communication**

The capacity of Integrated Sensing and Communication (ISAC) to enhance spectrum efficiency via the sharing of hardware and spectrum to facilitate simultaneous sensing and communication activities has garnered significant attention in recent years. One important technique that might aid ISAC usage is in-band full-duplex (FD), which can transmit and receive data simultaneously. A large-scale MIMO base station (BS) node communicates with a downlink (DL) multi-antenna user using a hybrid analogue and digital (A/D) beamforming process. When using the BS receiver, the DL user may pick up radar objects inside its coverage area by using the same waveform [68].

- **Full-Duplex with Power Management**

Due to the elimination of the necessity for two distinct channels for data transmission and reception, hybrid beamforming and combining for mm-wave full-duplex MIMO interference channel full-duplex (FD) communication has the potential to revolutionize wireless communications. Using cooperative K-pairs of massive MIMO FD nodes, this study broadens the use of point-to-point FD transmission in the millimeter-wave spectrum. In order to efficiently and affordably handle large MIMO FD networks, a combined technique for weighted sum rate (WSR) maximization and joint hybrid beamforming is used [69].

- **Time-Division Duplex**

In a mixed anlog–digital beamforming system, none of the numerous available calibration techniques can be directly used. This is the main reason why large-scale MIMO systems have not caught up to approaches that rely on TDD reciprocity. Methods for evaluating entirely digital devices have been available for almost a decade, but no one has ever managed to crack this code. Full utilization of the beamforming potential is achieved by the TDD hybrid beamforming systems by reciprocity adjustment, which allows them to achieve full CSIT. This paves the way for novel applications of mixed beamforming systems, which provide an alternative to teaching beams using a predetermined set of beams [70].

- **Frequency-Division Duplex**

A training scheme for FDD large MIMO systems accurately identifies the training signals and, with this training setup, the aim is to minimize the steady-state channel MSE within the context of Kalman filtering. With the goal of reducing application cost and power use, a transmit precoding technique is employed that reduces the dimensionality training sequence. Then, a hybrid analog–digital beamforming technique that uses a small number of RF chains for digital baseband precoding is subjected to the low-dimensional restriction. To achieve this, a uniform linear array (ULA) is applied at the base station in accordance with the Toeplitz distribution theorem. When dealing with large antenna arrays, a deterministic equivalent technique for performance analysis provides a helpful approach to training parameter setting [71].

3.7. Carrier

Hybrid beamforming techniques are compatible with OFDM as well as NOMA waveforms.

3.7.1. OFDM

The carrier waveform OFDM is very helpful in hybrid beamforming.

- **OFDM Radar Communication**

Orthogonal frequency-division multiplexing (OFDM) maximizes band utilization in dual-function radar communication (DFRC) systems while simultaneously ensuring communication stability against multipath fading and improved radar estimate accuracy. A completely digital beamforming solution would be costly due to the fact that each receiver has its own RF link. For the OFDM-DFRC technique to work, mixed beamforming is required [72].

- **Shared Array Antenna with OFDM**

The capacity of millimeter-wave frequency bands to accommodate very high data rates for the upcoming 5G mobile communications system is attracting a lot of interest. On the other hand, hybrid beamforming systems that include both digital precoding and analog beamforming have been considered as potential answers that might provide an optimal trade-off between functionality and complexity. Examining the overall average transmission power limit for multi-beam broadcasts and the peak-to-mean envelope power ratio across the antenna components, the hybrid beamforming design with a "shared array antenna" is chosen. The hybrid beamforming architecture under consideration should use the non-trivial normalization factors in order to achieve the optimal average transmission power while staying within the total power restriction. The hybrid beamforming system that makes use of a shared array antenna accounts for total power normalization. In order to evaluate the efficacy of multi-beam transmission diversity in comparison to single-beam analog beamforming, several modeling outcomes are presented [73].

- **Hybrid Sub-system Beamforming using OFDM**

Meeting the practical requirements of hybrid beamforming for multi-carrier systems, orthogonal frequency-division multiplexing systems with numerous inputs and outputs for indoor mm-wave channels use the sub-system SVD (SS) hybrid beamforming architecture. The channel estimate becomes less difficult in a realistic setting with less channel state information (CSI) based on the statistical properties of indoor mm-wave channels. Using the SS hybrid beamforming algorithm as a foundation, the limited feedback SS (LSS) system constructs broadcast beamformers using the receiver's limited information. Also developed is a quick codeword selection mechanism to facilitate the LSS algorithm's search. Despite its simplicity, the SS algorithm achieves results comparable to those of conventional full-digital beamforming. However, although having less CSI, the LSS method outperforms the prior one and is simpler to implement [74].

- **Weighted Optimization using OFDM**

An alternate maximization scheme based on Riemannian manifold optimization is employed to enhance the analog precoding in the hybrid beamforming solutions, which are designed for huge multiple-input multiple-output (MIMO) and orthogonal frequency-division multiplexing (OFDM) systems, in order to obtain the best weighted spectral efficiency. Using a locally optimal technique to enhance digital precoding yields an optimum alternating maximization algorithm. Another maximization process that is both less effective and simpler to develop each time is an iterative approach for digital precoding that is based on weighted minimal mean square error (MMSE). It is shown that when the user-specified weights are not significantly different, the two alternating maximization approaches perform similarly. The upper limit of the weighted geometric and arithmetic means of mean square errors (MSEs) is used to do this. Digital beamforming makes use of matrix decomposition, whereas analog beamforming makes use of weighted MMSE. Unlike the two iterative alternating maximization techniques, it achieves the goal of maximizing weighted spectral efficiency with little performance penalty. Because of this, it is an excellent jumping off point for time-saving iterative algorithms [75].

3.7.2. NOMA

To minimize interference across user groups, a NOMA-based hybrid beamforming approach is used, which takes advantage of the k-means algorithm. A user's channel correlation value determines whether they are assigned to a group with high correlation or a group with low correlation. As far as energy efficiency is concerned, this method outperforms the status quo of a completely digital architecture [76].

The alternating optimization method based on reconfigurable intelligent surface NOMA achieves higher results in terms of attainable rate in [77]. A combination of digital and analog beamforming techniques, including optimization of power consumption and phase shifts, allows this to happen. According to [78], NOMA outperforms OMA in terms of sum rate because it minimizes intercluster interference. By changing the users and applying singular-value decomposition (SVD) on each user's channel response, the NOMA-based system outperforms both LOS and NLOS in terms of sum rate [79].

3.8. Network

To provide quality of service, hybrid beamforming is used in cellular and heterogeneous networks.

- **Cellular Network**

There has been a lot of focus on physical layer and signal processing issues in mm-wave hybrid beamforming. An easily implementable mathematical model is created to depict the core concepts of hybrid beamforming in mm-wave cellular networks. As far as hybrid beamforming techniques go, Turbo-Hybrid Beamforming is the first to achieve the 1 ms real-time benchmark [80]. Many Resource Blocks compatible with multi-MIMO will be required by next-gen cellular phone networks, which will use solely commercial GPU devices [81]. Also, adopting mm-wave and massive multiple-input multiple-output (MIMO) technology into wireless networks is a crucial step towards enhancing network capacity, range, and quality-of-service (QoS) for future communications. A large number of symmetric antennas are used to increase the data flow and system speed. Power consumption and computational complexity are both increased when the number of antennas and radio frequency (RF) connections increases. Alternating minimal mean square error (Alt-MMSE) is a hybrid beamforming method that is used to address these concerns [82]. Further, directed broadcast across unlicensed mm-wave bands is required for sharing mm-wave bandwidth with an eye on frequency and space allocation. The total rate for all cellular users is improved with the least amount of disturbance to WiGig and cellular networks using an iterative channel distribution and hybrid beamforming algorithm [83].

- **Clustering Network**

A matrix factorization approach is used to decompose the challenge of hybrid precoding/combining design. Both completely linked and partially linked structures are compatible with it. The user clustering approach is straightforward and simple to implement. Making a massive MIMO system that can support several users at mm-wave frequencies requires certain techniques. It furthermore offers services at frequencies lower than 6 GHz. In order to construct the analog RF precoders, clusters are formed using the AoDs of the users' beams or tracks. The algorithm's performance is enhanced by incorporating the properties of the unconstrained fully digital solution into the design of the digital baseband precoders for the fully connected structure, therefore adding an additional orthogonality criterion. The partially connected structure uses a distinct set of angle bins for each set of RF chains, which are in turn allocated to various user clusters. The digital baseband precoders are constructed using semi-definite programming (SDP) relaxation [84].

- **Multiple Cells Network**

Within and between cells, multi-cell wireless systems experience interference. One way to lessen this interference is to use coordinated multipoint (CoMP) techniques [85]. Four mixed beamforming schemes—analog and digital—are proposed for mmWave communication with many cells, users, and streams using CoMP. Spectrum efficiency can be improved compared to the no-coordination situation using CoMP-based maximizing of the signal-to-leakage-plus-noise ratio. The amount of interference, which is impacted by cell size and user count, determines the variations in spectral efficiency among beamforming methods [86].

- **Heterogeneous Network**

Every mobile user has their own antenna, which is built on a heterogeneous network for beamforming. Big hybrid antenna arrays that are completely coupled are used by both macro-cell base stations (MBSs) and small-cell base stations (SBSs). A simple variant of hybrid beamforming relies only on Eigenbeamforming. Both MBSs and SBSs use the Eigendecomposition of backhaul channels to locate fixed multi-beams [87]. Heterogeneous networks employ a distributed hybrid analog–digital architecture in tiny cells. The central unit handles the digital processing, while the tiny-cell base stations handle the analog processing. The access points may reduce the amount of data sent to the central unit by using fewer RF chains instead of antennas. This is the primary justification for considering small-cell distributed mixed analog–digital processing [88].

- **Cloud radio access Network**

It is well recognized that hybrid beamforming provides a simple solution to issues encountered in systems with several antennas. In a downstream cloud radio access network (C-RAN) architecture, the analog and digital components of the hybrid beamforming method for remote radio heads (RRHs) function well. "Cloud" computing uses a baseband processing unit (BBU) to carry out digital operations. Before being sent to the RRHs across the restricted capacity fronthaul connections, the precoded baseband signals are quantized. This approach takes into account two distinct channel state information (CSI) scenarios: (1) the optimal CSI at the BBU and (2) the fact that CSI does not necessarily work [89]. Finding the optimal fronthaul quantization techniques and digital beamforming at the BBU, as well as the optimal analog radio frequency (RF) beamforming at the RRHs, requires considering the impact of quantization noise on the precoding matrices at the receiver. Hybrid beamforming designs use two approaches, namely fixed subarray and dynamic subarray layouts, to further simplify the hardware and consume less power. In order to enhance the EE's performance in a CRAN, it is recommended to use a K-means-based antenna design approach for the dynamic subarray architecture [90].

3.9. Communication

Handling large volumes of signals in the air is challenging due to pilot contamination and the critical role of channel state information in hybrid beamforming. Additionally, beamforming enhances connectivity in indoor communications.

- **Air Compass Communication**

To lower the processing mean square error (MSE) in the hybrid beamforming system of the air compass, it is essential to simultaneously enhance both the analog and digital beamforming at the access point, as well as the digital beamforming of the transmitting devices, especially given the large volume of signals from numerous devices [91]. A kind of digital predistortion called BO-DPD is used to make the large-scale hybrid beamforming array more linear by using over-the-air diversity feedbacks, or OTA DFBs. By estimating and linearizing the main beam signal without using complex feedback settings, the DPD interacts with hardware in the HBF array [92].

- **Pilot Contamination**

In order to locate several user data streams, the hybrid beamforming design makes use of numerous RF chains. The hybrid beamforming system incorporates both low-dimensional digital beamformers and high-dimensional analog beamformers. Improving data signals and making the Kronecker decomposition technique more generic for a single-user system are the goals of the analog beamforming matrix. In order to aid with spatial multiplexing, the digital version employs the widely used digital minimum mean square error (MMSE) beamforming algorithm for signal separation. A closed-form analysis of the AoA spectrum reveals that as the array size, the square root of the pilot sequence length, or the minimum distance between data and interference increases, the inter-cell interference (pilot contamination level) decreases. Consequently, various approaches can be employed to address pilot contamination. The next step is to determine the gain of the associated path. This can be achieved by directing an analog beam along the data's intended route, known as coherent-combining (CC), or by minimizing interference between paths, known as zero-forcing (ZF) [93].

- **Channel State Information**

For 5G mm-wave MIMO hybrid beamforming to work, downlink channel state information (CSI) is required. This approach is based on frequency-division duplexing (FDD). Because of the high-level input data required for massive MIMO communication and the short wavelength of the mm-wave band, channel response may vary very quickly. To reduce the feedback overhead, a phase beamforming method is used to take advantage of the improved phase stability of the channels. Simply being aware of which beam combinations provide the most robust link between the sender and receiver is sufficient; this is known as implicit channel knowledge. The suggested methodology is both simpler and easier to implement than hybrid beamforming algorithms that rely on explicit CSI [94]. The fundamental idea behind this approach is to efficiently resolve critical parameters such as the channel response's Frobenius norm, beamforming gain, or absolute value. One limitation of all compressed sensing systems is that they cannot tolerate deviations from certain ideal beam patterns [95]. To solve the sum rate maximization issue with limited feedback, a joint scheduling and hybrid beamforming method with a two-stage channel state information (CSI) feedback system is used. Using channel quality feedback, the base station (BS) first narrows down the potential RF beamforming vectors [96].

This hybrid beamforming approach, when combined with multi-user scheduling, makes the achievable rate performance more attractive by considering the benefits of random hybrid beamforming and zero-forcing. This method outperforms the RF beamforming scheme and the ZF-based beamforming system, respectively [97].

- **Indoor Channels**

Indoor 60 GHz spatial-division multiple access (SDMA) communication makes use of a hybrid architecture that employs phased antenna arrays (PAAs) for downlink beamforming (BF). With minimal feedbacks, multiple access and inter-symbol interferences (MAI/ISI) may be handled using a low-cost time-domain hybrid BF (HBF) approach in simultaneous multiple access (SDMA). This technique makes use of the spatial variety offered by several baseband processing units and the directivity offered by a PAA in RF beam patterns. A powerful beamformer is necessary to minimize the signal-to-interference-plus-noise ratio (SINR) for each user while utilizing the least amount of overall transmit power in order to provide stable signal quality in wireless multimedia streaming over indoor 60 GHz radio [98].

3.10. Reconfigurable Intelligent Surface

Due to the substantial signal loss associated with mm-wave frequency bands, hybrid beamforming has been considered an integral component of mmWave communications. A novel technique called an intelligent reflecting surface (IRS) has recently been proposed as a way to improve the performance of mm-wave communication systems. This technology makes use of inexpensive passive reflecting components.

- **Fewer RF Chains**

Signals are sent from the base station (BS) to the users in a downlink hybrid beamforming RIS-based multi-user system with few discrete phase shifts. The digital beamforming is handled by the BS, while the analog beamforming is handled by the RIS. Two side issues arise from a RIS-based HBF mixed-integer sum rate maximization problem; for the RIS-based analog beamforming problem, outer approximation is the method of choice. The digital beamforming subproblem is addressed by using zero-force beamforming (ZF) in conjunction with power allocation [99].

- **Less Power Demand**

Each RF chain is only linked to a distinct set of antenna components in a subconnected hybrid architecture that takes into account RIS-assisted multi-user downlink hybrid beamforming at the base station and reflection coefficients at the receiver–injector station. Using a subconnected architecture is preferable due to its reduced power consumption and hardware expenses. It is also necessary to fix the quality of service (QoS) issue, i.e., identify the base station (BS) that uses the least amount of power during transmission while still meeting the SINR constraints of all users. The issue is not convex at all due to the deeply coupled variables and unit-modulus phase shifts; so, a two-layer penalty-based technique is used to resolve it. In the inner layer, the penalized issue is solved using the BCD approach; in the outer layer, the penalty factor is varied until convergence [100].

- **More Safety**

Transmission solutions that are both safer and more energy efficient are crucial components of an ITAN. This is for the simple reason that RIS technology may significantly enhance data security while also reducing system power consumption. For reduced power consumption and attack protection, a multi-layer RIS-assisted secure hybrid beamforming ITAN architecture is used. The block coordinate descent (BCD) architecture uses incomplete angular channel state information (CSI) to improve the user's received decoder, the digital precoder for terrestrial and aerial usage, and the multi-layer RIS analog precoder, all with the goal of maximizing the system's energy efficiency (EE). For the purpose of the received decoder, a heuristic beamforming method is created. A technique known as iterative sequential convex approximation, which makes use of the auxiliary variables and first-order Taylor series expansion, provides the basis for the digital precode [100].

- **Limited-Resolution Phase Shifters**

Multi-user communications based on a RIS that have reasonable propagation models and restricted phase shifts face significant hurdles. First, the RIS components are very close together, which means that data rates may be affected by signal correlation. This is particularly true when the RIS is the only channel by which the BS and users may transmit LoS data. Additionally, the RIS necessitates discrete phase changes, which leads to a sum rate maximization or mixed-integer programming issue that is particularly challenging to resolve in complicated domains. One solution to these issues is the HBF method, which combines digital beamforming at the base station with analog beamforming at the receiver input sub-system (RIS) using limited-resolution phase shifters. Digital beamforming and RIS-based analog beamforming are two subproblems that are assessed in the mixed-integer sum rate maximization problem. To resolve these issues, an iterative technique is used. When compared to conventional HBF systems, this one based on a RIS can cut down on radio frequency (RF) chains by half. Sum rate is affected numerically and conceptually by RIS size and the number of discrete phase changes. This contributes to the theoretical investigation of the pure LoS scenario [100].

- **Narrowband and Broadband**

An analog beamformer and an IRS reflection matrix are used in narrowband IRS-aided hybrid beamforming via the use of effective channel response. By capitalizing on angular domain frequency-selective mm-wave channels, this approach is also applicable to broadband MIMO-OFDM systems [101].

- **High Array Gain**

To transmit several data streams operating concurrently in the spatial domain with the same channel gain, RIS-assisted mm-wave hybrid MIMO systems use a geometric mean decomposition-based beamforming technique. Thus, it is possible to obtain a greater BER without allocating more power or adding more bits. The best multiple beams are obtained from an oversampling 2D-DFT codebook using a simultaneous orthogonal matching pursuit technique [101].

- **Quality of Service**

In order to enhance the quality of service (QoS) for customers, mm-wave RIS systems use a hybrid analog and digital beamforming method bounded by symbol detection mean squared error (MSE). An analog transmitter, RIS, and analog receiver are developed using the inner majorization–minimization (iMM) approach, while a digital transmitter is built using an alternating direction method of multipliers (ADMM). When compared to SDR and interior point, the iMM and ADMM approaches are noticeably quicker. The iMM approach employs channel normalizatio to streamline calculations in response to changes in large-scale route loss. To counteract variations in path loss on a wide scale, the ADMM technique employs adaptive parameterizations [102].

3.11. Applications

The following section will explore various applications considering radar, a WLAN, Railway, security perspectives, satellite, and also UAVs.

- **Radar**

A subarray architectural technique for developing a multi-carrier dual-function radar communication (DFRC) system is able to accommodate a large number of users. The challenge of hybrid beamforming design for DFRC systems is to provide an optimal transmit beam pattern while reducing power consumption and maximizing the sum rate [103]. Using the transmit beam of a dual-functional radar communication (DFRC) base station (BS), hybrid beamforming aims to approach the objective radar beam pattern as closely as possible, considering the signal-to-interference-plus-noise ratio (SINR) of communication users and the total transmission power of the DFRC BS. By adding a phase vector to the objective beam pattern and applying the alternating minimization method, more freedom is given to the beam design problem. The intended transmit beam is used to locate the analog and digital beamformers. The alternating minimization approach is used, and they are subject to the constant envelop restriction of the phase shifter network in mm-wave MIMO. When the SINR of the communication users stays the same, a larger antenna array increases the radar beam even more [104].

In multiple-input multiple-output (MIMO) systems, optimal utilization of the congested spectrum requires simultaneous sensing and communication [105]. One way to achieve this is by facilitating simultaneous sensing and providing communication users with high-capacity connectivity [106].

- **WLAN**

A two-tiered beamforming design is known as hybrid beamforming. Analogue beamforming, the first level, uses inexpensive phase shifters to regulate the signal phases sent by each antenna. Digital beamforming using RF chains constitutes the second tier. In order to achieve spatial multiplexing gain, digital beamforming prevents interference between users, whereas analog beamforming increases the beamforming gain of each RF chain. The beam-user selection hybrid (BUSH) algorithm has few positive aspects. By using several antenna components, the access point may achieve a high digital beamforming gain with phased array antennas. The RF chains may also minimize inter-receiver interference by using the receivers' fine-grained CSI feedbacks. Implementing BUSH in WLANs has its own set of challenges. It is not simple to discover the AoAs of several users simultaneously in 802.11 WLANs. Users do not necessarily dispatch pilots to the access point (AP) in WiFi networks, in contrast to LTE systems where centralized control is present. Additionally, WiFi systems have much longer sounding times. In multi-user multiple-input multiple-output (MU-MIMO) systems that use hybrid beamforming, analog beamforming selects a fixed number of predefined beam patterns, while digital beamforming selects a fixed number of RF chains. When there are an excess of antennas and insufficient RF links, BUSH digital–analog hybrid beamforming can be a useful solution. One way to reduce system latency is to collect AoA data from several users simultaneously using separate subcarriers for each user [107].

- **Railway**

For High-Speed Railway Communications (HSRC), pilot workload and hardware complexity are critical factors in the development. Utilizing the high spatial resolution of the array and beam alignment, a new approach for compensating for Doppler frequency offset (DFO) is proposed. To recover the CSI and monitor the beam gain, an angle-domain (AD) tracking approach is suggested using spatial angular information. In order to reduce computational complexity and hardware overhead, hybrid beamforming is used. The AD technique seeks to follow linearly variable beam gain by using the temporal coherence of the channel, as opposed to tracking the nonlinearly varying angle of arrival (AOA). This simplifies the calculation. There is no need for extra signals, such as synchronization signals, since the angular information is approximated from regular pilot signals that are then used for tracking channels [108].

- **Security**

Prior studies focused on various performance metrics, such as power minimization. Conversely, methods exist for optimizing the secret rate. To ensure secure downlink transmission, the base station (BS) employs a uniform planar array (UPA) configuration to regulate the beams' azimuth and elevation angles, as well as to provide sufficient bandwidth and gain across the coverage region. Improved system performance is possible with the UPA configuration by use of three-dimensional beamforming techniques. Beamforming makes use of three distinct hybrid subarray designs: interlaced, fully connected, and partially connected. In the absence of perfect information about the wiretap channel's angle of departure (AoD), a limited optimization problem is utilized to determine the optimal spectrum efficiency and energy efficiency that satisfy the demands of cellular users for a specific SNR value [109].

An inactive reflector system based on a RIS improves performance against jamming and eavesdropping. The reconfigurable intelligent surface (RIS) may greatly reduce power consumption and improve data security. A multi-user cellular network's spectrum efficiency and security may be enhanced with the use of RIS-assisted wireless transmitters. The design of the user-side receive decoder, the digital precoder and artificial noise (AN) at the base station (BS), and the analog precoder at the RIS are all taken into account concurrently in order to solve the worst-case sum rate maximization issue. Finding a good response that meets the least attainable rate restriction, the maximum wiretap rate need, and the maximum power limitation is conducted using an alternative optimization (AO) approach. To facilitate the generation of a closed-form solution for the receiver encoder, a heuristic approach is used to strengthen weak angular CSI. After this, the majorization–minimization (MM) approach may be used to reframe the initial issue into a more manageable form [110].

- **Satellite**

Optimizing resource allocation in an integrated terrestrial satellite network (ITSN) based on frequency forward transmission and hybrid beamforming user scheduling are necessary to improve the system sum rate and energy economy. Using a combination of beamforming and user scheduling, we can reduce the sum rate maximization issue to a power allocation problem. To enhance power sharing for each user terminal (UT), logarithmic linearization and the minimal mean square error (MMSE) criteria are used [111].

- **UAV**

The need of the present age is NOMA-enabled mobile edge computing networks helped by UAVs. An unmanned aerial vehicle (UAV) carrying a wirelessly powered mobile edge computing (MEC) system may improve transmission efficiency in a few ways: NOMA hybrid beamforming and non-orthogonal multiple access (NOMA). The UAV offers mobility, while the MEC platform supplies computing services and electricity to IoT devices. There has to be massive coverage, little power usage, and lightning-fast computations from the IoT devices [112]. For unmanned aerial vehicle (UAV) deployment and optimal hybrid beamformer design, the polyhedral annexation method and the deep deterministic policy gradient (DDPG) algorithm are useful tools. For line-of-sight (LoS) channels, a hybrid beamforming design is used to obtain a power allocation plan and a near-closed-form depiction of the rate. Antenna density has an inverse relationship with total transmitted power for UAVs [113].

3.12. Codebook

Hybrid beamforming can be broadly categorized into two main types: codebook-based and codebook-free.

- **Codebook-Based**

Mm-wave bands have huge bandwidths, enabling high data rates and thereby mm-wave communications in small-cell networks boost system speed [114]. Due to the poor quality of the mm-wave channel, mm-wave communication systems rely on beamforming, which requires a multitude of sensors to generate powerful and focused beams. In this setup, the codes known by the transmitter and the receiver are identical. For the selected beamforming vector, the receiver then transmits this codebook back [115]. A large codebook size allows for the fabrication of thin beams with a sharp rolloff. A smaller codebook is preferable for practical reasons, such as the time and effort required to search for codewords and provide responses. When creating the codebook, it is important to consider how mm-wave connections function as channels in order to obtain the greatest possible total speed [116]. The transmitter employs hybrid beamforming for the channel-link-based codebook. The first step is to identify the optimal beam configuration for every codeword [117]. With the right beam pattern, you can make a codebook design guideline that everyone can follow. Next, the codebook is designed to minimize the mean square error (MSE) between the ideal beam pattern of each code vector and its actual beam pattern. Orthogonal matching pursuit (OMP) allows for this MSE decrease. Beamforming in the mm-wave system is enhanced by the proposed codebook, as shown [118].

The codebook-based MIMO system employs a hybrid beamforming technique with partly interfering beam feedback, and it serves many users [119]. The analog portion of the precoding makes use of a non-uniform amplitude beamforming vector Taylor codebook and a typical discrete Fourier transform (DFT) codebook with uniform amplitude beamforming vectors [120]. In order to obtain a general notion of the effective channel matrix, the digital precoding phase employs zero-forcing (ZF) [121]. In multiple-user multiple-input multiple-output (MU-MIMO), a beam pairing technique facilitates beam selection and mitigates inter-beam interference [122,123].

Codebook-based beamforming [124] has six major advantages. (1) It is compatible with RIS technology, providing backwards compatibility. (2) The pilot overhead is adaptable and scalable according to the situation. (3) The reduced complexity makes it a more attractive technology. (4) This technology mitigates the propagation error. (5) The control link requires less capacity, making it more durable. (6) The channel imperfections are considered in the codebook, which becomes more robust.

- **Codebook-Free**

Hybrid beamforming that automatically turns on the right amount of radio frequency (RF) chains uses fractional programming to enhance energy efficiency and find the optimum number of active RF chains and data streams. The solution changes rapidly based on the current channel conditions. The combined analog/digital (A/D) precoder and combiner matrices at the transmission and receiver are developed using gradient pursuit (GP). These codebook-free methods consisting of the alternating direction method of multipliers (ADMMs) and the singular-value decomposition (SVD) build the precoders and combiners [125].

4. Current Research Trends, Challenges, Solutions, and Future Research Directions

4.1. Current Research Trends

Millimeter-wave (mmWave) hybrid beamforming is a critical technology for enabling high-data-rate communication systems such as 5G and beyond. Hybrid beamforming is an attractive approach because it balances the trade-off between the hardware complexity of digital beamforming and the performance of analog beamforming. Here are some of the current trends [126–130] in this area, as highlighted in Figure 12 below:

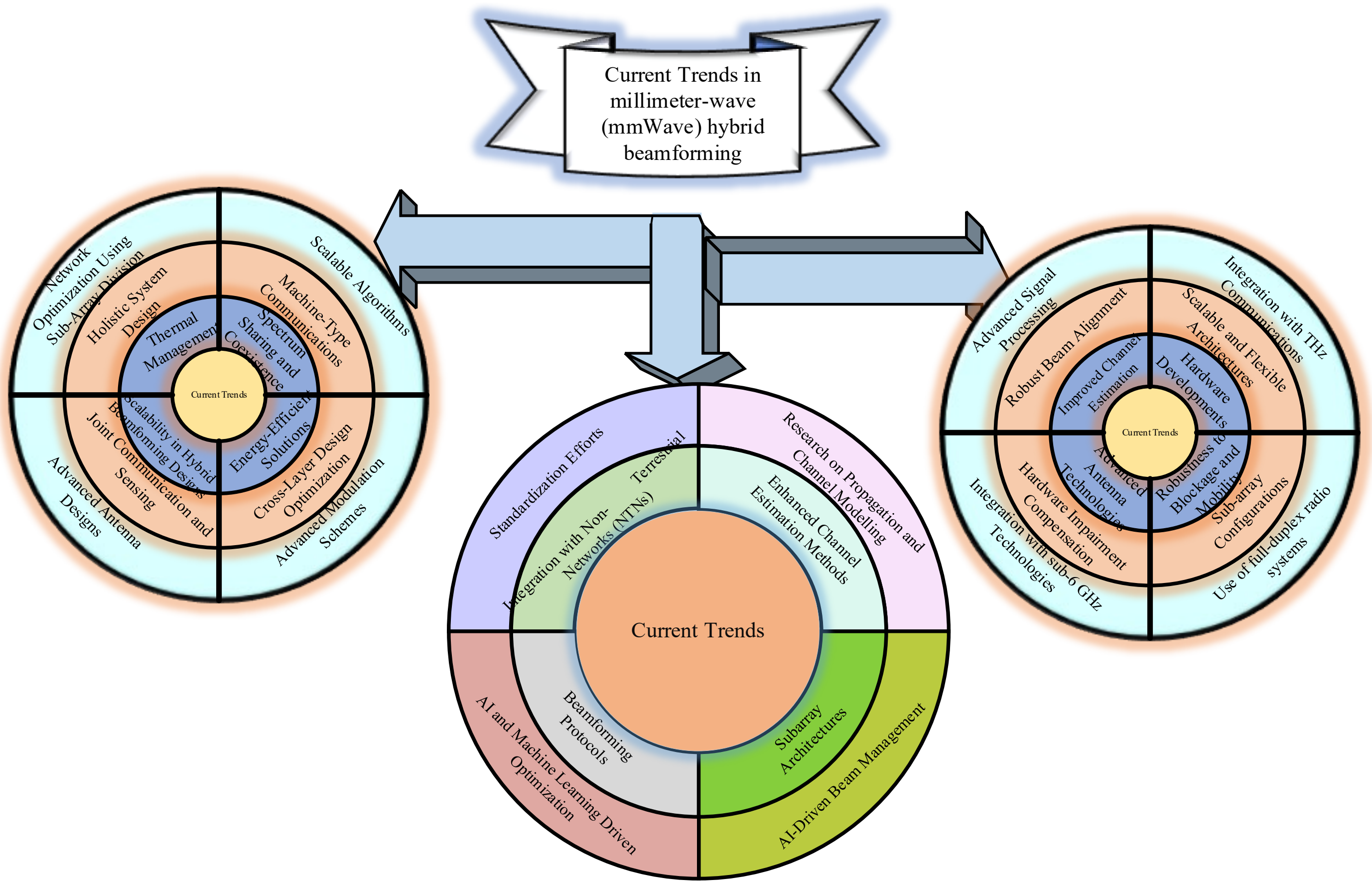

Figure 12. Current trends in Mw-wave hybrid beamforming field.

- Energy-Efficient Solutions: With the increased power consumption associated with high-frequency operations and large antenna arrays, there is a trend toward developing power-efficient beamforming solutions. This includes both circuit-level innovations and algorithmic optimizations to minimize power usage without sacrificing performance. It also includes focusing on designs that minimize power consumption without significantly compromising on performance, which is crucial for the widespread deployment of mmWave technologies in mobile devices and base stations.

- AI- and Machine Learning-Driven Optimization: There is a growing interest in utilizing artificial intelligence (AI) and machine learning (ML) algorithms to optimize hybrid beamforming, especially in dynamic environments. These techniques can help with channel estimation, beam selection, and adaptive beamforming strategies that react to changing conditions and user demands.
- AI-Driven Beam Management: AI and machine learning algorithms are being explored to dynamically manage beamforming in real time, taking into account user mobility and varying channel conditions. AI can optimize beam direction and power allocation efficiently, potentially outperforming traditional algorithms.
- Beamforming Protocols: Research into new protocols and signal processing techniques aimed at faster and more accurate beam alignment is ongoing. This is crucial for ensuring robust mmWave communication in mobile environments.
- Subarray Architectures: There is a shift toward more sophisticated subarray configurations that allow for more flexible and powerful beamforming options, including the ability to form multiple beams simultaneously and serve several users.
- Research on Propagation and Channel Modeling: Continuous research on the better understanding of mmWave propagation characteristics and channel modeling is ongoing. Accurate models are vital for the design and simulation of hybrid beamforming strategies.
- Standardization Efforts: Efforts are being made to create and refine industry standards that support the widespread adoption of mmWave technologies, including hybrid beamforming approaches.
- Integration with sub-6 GHz Technologies: To ensure wide coverage and reliable connectivity, there is a trend towards integrating mmWave beamforming technologies with sub-6 GHz systems, allowing for seamless transition and better overall performance in various use cases.
- Integration with Non-Terrestrial Networks (NTNs): As 5G evolves, there is an increased interest in the integration of mmWave hybrid beamforming with NTNs such as satellites and high-altitude platform stations (HAPS), expanding coverage and capacity.
- Advanced Antenna Designs: There has been a push for more innovative antenna designs that allow for better control of the beamwidth and direction, providing enhanced performance in mmWave systems.

4.2. Challenges, Solutions, and Future Research Directions

Challenges, solutions, and future research [131–135] are illustrated in the following Figure 13.

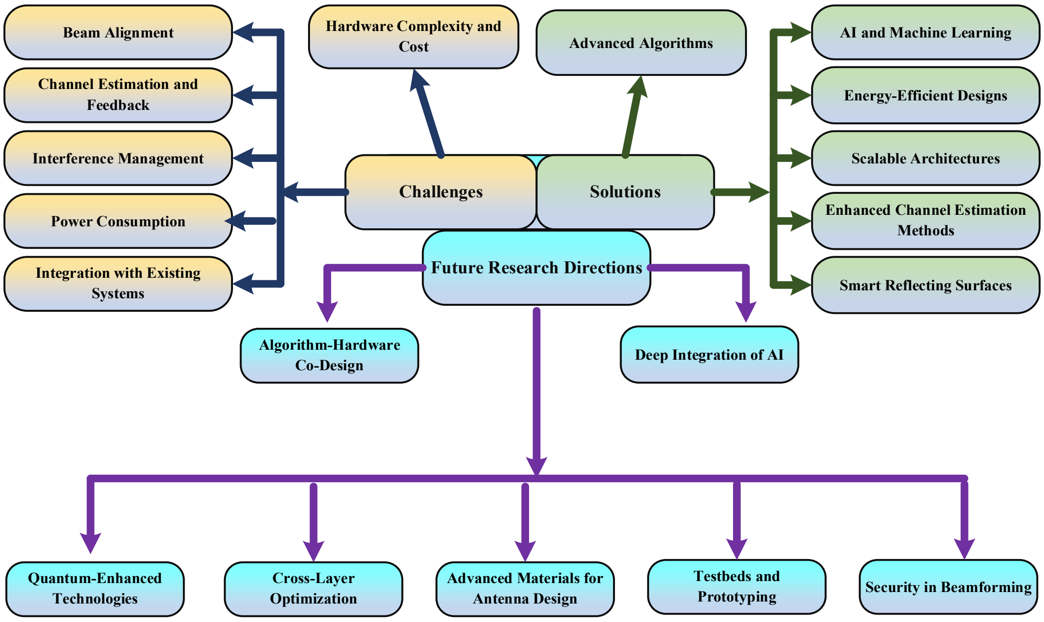

Figure 13. Challenges, solutions, and future research directions in Mw-wave hybrid beamforming field.

4.2.1. Challenges in Hybrid Beamforming for Millimeter-Wave MIMO Communications

- **Hardware Complexity and Cost:** Implementing hybrid beamforming requires a balance between digital and analog components which can increase the hardware complexity and associated costs. This could be a significant obstacle for widespread adoption.
- **Beam Alignment:** At millimeter-wave frequencies, the beam widths are very narrow, making accurate beam alignment critical and challenging, particularly in mobile scenarios.
- **Channel Estimation and Feedback:** Accurate channel information is crucial for effective beamforming. The high dimensionality of MIMO systems at millimeter-wave frequencies makes channel estimation and feedback more complex.
- **Interference Management:** In dense networks, managing interference between multiple beams and users without significant degradation of the signal quality is challenging.
- **Power Consumption:** Higher-frequency operations could lead to increased power consumption, posing challenges for battery-powered devices like UAVs and mobile handsets.
- **Integration with Existing Systems:** Ensuring compatibility and coexistence with legacy systems is important for a smooth transition and requires careful design and standardization.
- **Regulatory and Standardization Issues:** As millimeter-wave technologies are still developing, regulatory frameworks and standardization efforts have to keep pace to ensure interoperability and efficient spectrum use.

4.2.2. Possible Solutions

- **Advanced Algorithms:** Developing sophisticated algorithms for beam selection, tracking, and adaptation can mitigate alignment problems and optimize system performance [20].
- **AI and Machine Learning:** Machine learning techniques can be employed to predict channel conditions, optimize beamforming in real time, and manage interference effectively [21].

- **Energy-Efficient Designs:** Hardware and circuit-level innovations that focus on energy efficiency can help reduce power consumption.
- **Scalable Architectures:** Modular beamforming designs that can scale up or down, depending on system requirements, may reduce complexity and cost [124].
- **Enhanced Channel Estimation Methods:** Low-complexity channel estimation methods and protocols for efficient feedback can improve overall system performance [136].
- **Smart Reflecting Surfaces:** Intelligent surfaces with reflective elements can be used to dynamically modify the propagation environment to improve signal coverage and reduce interference.

4.2.3. Future Research Directions

- **Algorithm–Hardware Co-Design:** Research that brings algorithmic design in sync with hardware capabilities will be key to optimizing performance and cost.
- **Deep Integration of AI:** AI could be deeply integrated into the communication systems for proactive interference management, predictive maintenance, and self-optimizing networks.
- **Quantum-Enhanced Technologies:** Incorporating quantum computing principles may help solve complex optimization problems related to beamforming and provide significant improvements in computational speed and efficiency.
- **Cross-Layer Optimization:** Efforts to optimize the interaction between various layers of the communication protocol stack can yield efficiency gains in hybrid beamforming systems.
- **Advanced Materials for Antenna Design:** Research into new materials that allow for more flexible and efficient antenna designs could revolutionize the way beamforming is implemented.
- **Testbeds and Prototyping:** Large-scale testbeds for real-world prototyping can help in understanding the practical challenges and performance boundaries of hybrid beamforming technologies.
- **Security in Beamforming:** As the directionality of communication increases, so does the need for secure beamforming to prevent eavesdropping and jamming. Advanced security protocols must be researched.
- **Vehicle-to-Vehicle Communication:** When both the transmitting and receiving sides are mobile, the RIS locations, number of phase shifters required, derivation of time-changing approximate/exact angles and distances, efficient capacity of the channel, and significant outage probability are things of concern. Optimizing all these parameters are still open areas of research.

By addressing these challenges, refining solutions, and continuously pushing the boundaries of research, millimeter-wave MIMO communication can achieve its full potential, providing the necessary foundations for next-generation wireless networks.

5. Conclusions

Hybrid beamforming in mm-wave MIMO designs provides an attempt to utilize the available bandwidth in spectral and energy-efficient ways, thereby reducing the power requirement and enabling cost-effectiveness in a wide range of applications. This systematic review has meticulously analyzed the landscape of millimeter-wave hybrid beamforming for wireless communications, shedding light on its potential to revolutionize next-generation wireless systems. By examining various algorithms, performance metrics, and techniques, we have unveiled the strengths and limitations inherent in current hybrid beamforming solutions. Our review underscores the critical role of hybrid beamforming in optimizing system design and performance across diverse user scenarios, incorporating factors such as user density, link quality, band usage, scattering effects, and network applications. The analysis reveals that hybrid beamforming not only improves spectral efficiency but also enhances system robustness, making it a cornerstone technology in the evolving milieu of wireless communications. As we stride toward an era defined by ubiquitous and seamless connectivity, hybrid beamforming emerges as a pivotal enabler of advanced wireless communication systems, equipped to meet contemporary demands and pre-emptively address future challenges. By highlighting current research trends and outlining key challenges along with potential solutions, this review serves as a comprehensive guide for both academia and industry professionals. It also provides strategic insights for the continuous advancement of hybrid beamforming technologies. Also, the insights garnered from this review are intended to equip researchers and engineers with the knowledge necessary to drive innovation in wireless communications forward. Through continued exploration and development, hybrid beamforming is poised to significantly influence the trajectory of wireless technology, paving the way for more efficient, reliable, and adaptive communication systems that can seamlessly accommodate the growing demands of a hyper-connected world.

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