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Design and Development Trends of Millimeter-Wave Multi-Beam Antennas

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Abstract: Millimeter-wave (mmWave) multi-beam antennas are integral to next-generation wireless communication systems, facilitating high-speed and high-capacity communication, and ensuring extensive coverage. Multi-beam antennas exploit fundamental principles such as beamforming, beam separation, frequency reuse, and interference mitigation, enabling a single aperture to generate multiple independently directed beams. And these antennas can be broadly classified into passive, active, and hybrid types based on their implementation, each providing distinct characteristics tailored to specific applications. Therefore, this paper reviews the research on multi-beam antennas over the past decade, summarizing their key features and applications, and predicting future development trends in mmWave multi-beam antennas. The results demonstrate that as mmWave technology continues to be increasingly adopted in communications, future multi-beam antennas will prioritize dynamic adaptability, system autonomy, and the reduction of structural complexity and cost, enhancing support for high-speed, low-latency, as well as high-capacity intelligent communication systems. This evolution will be critical for meeting the demands of emerging applications, including 5G/6G networks, IoT, and autonomous systems.

Keywords: Millimeter-Wave, Multi-Beam Antenna, Beamforming System, Antenna Design Optimization

1. Introduction

With the continuous saturation of traditional spectrum resources, the abundant spectrum availability in the millimeter-wave (30 GHz-300 GHz) and terahertz (300 GHz-3000 GHz) bands can meet the future communication system requirements for data transmission latency, speed, and capacity. Multi-beam antennas leverage beamforming principles to enhance the signal-to-noise ratio (SNR), thereby extending signal propagation distance. Additionally, by generating multiple independently directed beams, they improve signal coverage and expand communication capacity. As a result, millimeter-wave multi-beam antennas have become a core technology in modern communication systems, making their research highly significant. However, the development of millimeter-wave multi-beam antennas faces several challenges, including optimizing dynamic beam adjustment and tracking, improving environmental adaptability, reducing hardware complexity and cost, as well as meeting integration demands. This paper aims to review the fundamental principles, classifications, characteristics, and applications of millimeter-wave multi-beam antennas, evaluating the advantages and limitations of different types in practical applications. Moreover, key technical challenges and potential solutions are investigated. Particularly, it explores refining dynamic beam adjustment and

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tracking techniques, enhancing environmental adaptability, and reducing hardware complexity and cost, all of which are vital for ensuring the efficiency, low-latency, and high-capacity performance of millimeter-wave communication systems. By reviewing relevant literature, this study offers insights to drive innovation and application in millimeter-wave multi-beam antenna technology.

2. Fundamental principles and classification of millimeter-wave multi-beam antennas

2.1. Fundamental principles

A multi-beam antenna (MBA) is a type of antenna capable of simultaneously generating multiple independently directed beams within a single antenna aperture to cover a specific angular range [1]. As illustrated in Figure 1, the key principles involved in multi-beam antennas include beamforming, beam separation, frequency reuse, and interference suppression.

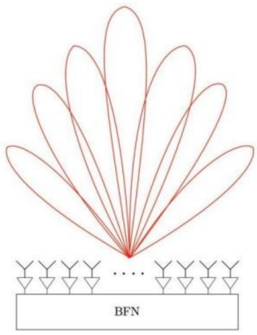

Figure 1: Schematic diagram of a multi-beam antenna

Beamforming depends on the principles of electromagnetic wave interference and superposition. By precisely controlling the amplitude and phase of signals emitted by individual antenna elements, it reinforces constructive interference in the target direction while inducing destructive interference in undesired directions. This process enhances radiation intensity toward the intended target while suppressing sidelobes and minimizing interference. To characterize array antenna radiation patterns, the array factor (AF) is introduced, defining the aspect of the radiation pattern influenced solely by the geometric arrangement of radiating elements in the antenna array and the amplitude and phase distribution of the excitation signals [2]. And the total radiation pattern of a multi-beam antenna can be expressed as shown as follows.

$$F(\theta, \Phi) = \sum_{m=1}^{M} \omega_m \cdot AF_m\,(\theta, \Phi) \cdot f_{element(\theta,\Phi)} \tag{1}$$

where M means the total number of beams, ω_m denotes the weighting factor of the m-th beam, $\mathrm{AF_m}(\theta, \Phi)$ represents the array factor of the m-th beam, and $f_{element}(\theta, \Phi)$ denotes the radiation pattern of a single element antenna. Building on this, beam separation is achieved by adjusting the physical structure of the antenna system and signal control strategies, ensuring that multiple beams maintain independent directivity and gain in space. This improves spectrum utilization efficiency and boosts communication capacity, with its effectiveness mainly reflected in the characteristics of the main lobe, sidelobes, and angular separation. Furthermore, spatial isolation and radiation pattern optimization enable frequency reuse while minimizing interference between beams and users. Since millimeter-wave multi-beam antennas operate at higher frequencies and typically require a large number of beams, they demand higher gain, miniaturization, integration, and precise beam steering. Moreover, their manufacturing necessitates significantly greater precision.

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2.2. Classification and characteristics

Based on the implementation method, millimeter-wave multi-beam antennas can be broadly divided into passive, active, and hybrid types based on their implementation method [3].

2.2.1. Millimeter-wave passive multi-beam antennas

Millimeter-wave passive multi-beam antennas can be classified into several types based on different beamforming network implementations, including passive circuit topology matrix-based designs, reflector-based designs, and lens-based designs. A millimeter-wave multi-beam antenna with a passive circuit topology achieves beamforming via a feed network incorporating components such as directional couplers, cross couplers, phase shifters, and power dividers. These antennas are ideal for miniaturization and integration, hence providing benefits such as low power consumption, wide bandwidth, and structural simplicity at millimeter-wave frequencies while remaining cost-effective. However, their fixed beam directions limit flexibility and adjustability.

Millimeter-wave multi-beam antennas based on passive circuit topology matrices are commonly used in 5G communication systems, millimeter-wave wireless backhaul, satellite communications, meteorological radar, military radar, millimeter-wave imaging, the Internet of Things (IoT), and intelligent systems. Representative beamforming matrices include the lossless Butler and Nolen matrices, both utilizing fast Fourier transform (FFT), as well as the lossy Blass matrix. Compared to the other matrices, the Butler matrix excels in port isolation and beam orthogonality.

For example, in 2017, Zhong et al. proposed an 8×8 Butler matrix-based multi-beam antenna using substrate-integrated waveguide (SIW) technology, as illustrated in Figure 2 [4]. This antenna operates in the 28-31 GHz frequency range and generates eight beams directed at $\pm 7°$, $\pm 21°$, $\pm 37°$, and $\pm 55°$, with gains ranging from 11 to 16 dBi. The design refines the matrix structure, effectively minimizing the overall antenna size.

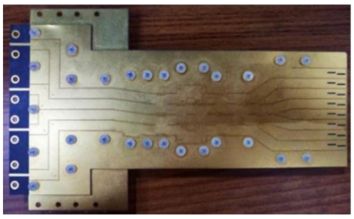

Figure 2: Dual-layer multi-beam antenna based on an 8×8 butler matrix

Moreover, in 2017, Cao et al. proposed a 38 GHz millimeter-wave multi-beam antenna design for 5G communications, as shown in Figure 3 [5]. This design employs a 4×8 Butler matrix based on substrate-integrated waveguide (SIW) along with a microstrip antenna array. The central beams achieve a gain of 19.8 dBi, while the side beams reach 21 dBi. Due to its multi-layer structure, this multi-beam antenna significantly reduces the overall size.

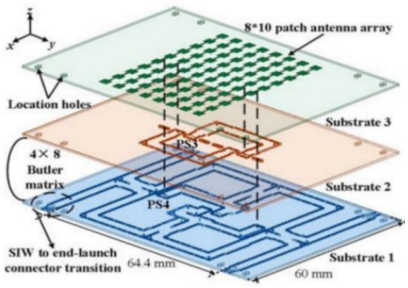

Figure 3: 38 GHz multi-beam antenna with A multi-layer structure

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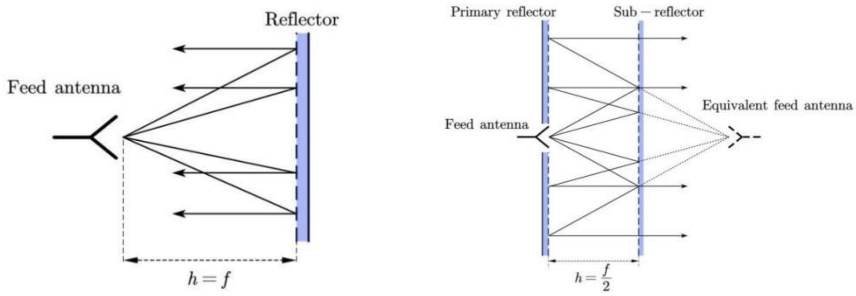
Millimeter-wave multi-beam antennas based on reflectors typically uses quasi-optical principles for beamforming. By switching different feed sources to offset-feed the reflector antenna, high-gain beams with different directions are achieved, as shown in Figure 4(a) [6]. Traditional multi-beam reflector antennas are constructed using metallic processes, thereby leading to high costs, large size, and significant weight. Since the 1960s, advances in microstrip reflector antennas have streamlined manufacturing, minimizing size and weight. In the 1990s, the emergence of reflectarray antennas attracted widespread research interest worldwide. In 2000, W. Menzel from Germany first proposed the folded reflectarray antenna, which offers a more compact size and superior performance. Its working principle is illustrated in Figure 4(b). However, this type of antenna has a limited number of beams, a relatively small coverage area, and significant gain loss for edge beams.



(a) (b)

Figure 4: (a) Reflectarray antenna diagram; (b) folded reflectarray antenna diagram

In addition, Figure 5 illustrates a millimeter-wave high-gain filtering antenna based on a folded planar reflectarray, where a polarization-sensitive bandpass frequency selective surface replaces the traditional polarization grid as the sub-reflector of the folded planar reflectarray antenna [7]. This antenna features high gain, low loss, as wll as compact size. Despite its single-directional wave, the design offers insights for future folded reflectarray multi-beam antenna research.

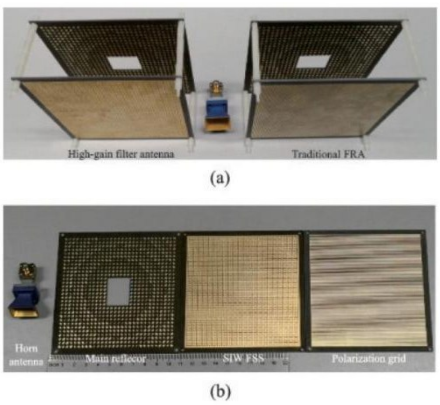


Figure 5: Millimeter-wave high-gain filtering antenna based on a folded reflectarray (a: comparison with a traditional design; b: key components)

Millimeter-wave multi-beam antennas based on reflectors are widely utilized in Ka-band satellite communications, millimeter-wave radar (such as automotive collision-avoidance radar and imaging radar), and radio astronomy telescopes. Similarly, these antennas based on lenses use quasi-optical principles, where electromagnetic lenses modify the phase of electromagnetic waves to achieve focusing and enhance gain. Multi-beam operation is realized by off-axis feeding with different feed sources. Unlike reflector-based designs, lens-based multi-beam antennas avoid aperture blockage by

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placing the feed source opposite the beam radiation. Common electromagnetic lenses include the Luneberg lens and the Rotman lens. These lens structures efficiently transform plane and spherical waves, providing high gain, low insertion loss, and excellent port isolation. Furthermore, due to their quasi-optical nature, they support operation across a broader frequency range. The Rotman lens is smaller, more cost-effective, and suited for mass production via PCB technology than the Luneberg lens. However, its beam directions are relatively fixed, resulting in lower flexibility. Due to their distinct features, these two lens types serve different application scenarios. The Luneberg lens, with its larger size and higher flexibility, is primarily used in satellite communications, radar, and radio astronomy. In contrast, the Rotman lens is better suited for cost-sensitive, compact, and highly integrated applications, such as 5G communications and millimeter-wave sensors.

Figure 6 shows a wideband millimeter-wave multi-beam array antenna based on SICL, operating at 20.5-31.5 GHz with a $\pm 30°$ scanning range. Its simple structure, low profile, and high integration help overcome narrow beamwidth and limited scanning range issues, thus making it valuable for wideband millimeter-wave antenna research [8].

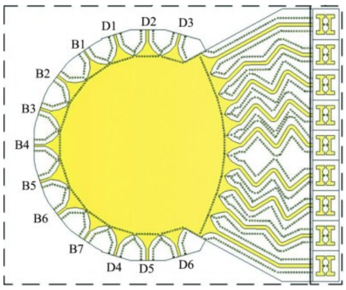

Figure 6: Wideband millimeter-wave multi-beam array antenna design based on SICL

2.2.2. Millimeter-wave active multi-beam antennas

Millimeter-wave active multi-beam antennas dynamically adjust the phase and amplitude of each antenna element through an active beamforming network (BFN) to generate multiple independent beams. Their key advantage lies in highly flexible real-time beam control, allowing adjustments in beam quantity, width, direction, and gain while supporting beam splitting and multi-target tracking, thereby enhancing spatial multiplexing. Furthermore, independent gain control for each antenna element improves overall antenna gain. However, these benefits come at the cost of higher power consumption, increased complexity, and higher costs. Active multi-beam antennas have evolved from phased array antennas, with common active phase-shifting implementations including RF phase shifting, IF phase shifting, baseband phase shifting, and LO (local oscillator) phase shifting. The baseband phase shifting, also known as digital beamforming, processes signal amplitude and phase in the digital domain, offer superior performance. This processes signal amplitude and phase in the digital domain, allowing for the integration of various RF algorithms (e.g., beamforming and anti-jamming algorithms), resulting in more flexible and precise beam control. Since beamforming is implemented through software algorithms, hardware complexity is reduced. Consequently, digital multi-beam technology is gaining increasing attention.

On the hardware front, numerous studies are exploring ways to further enhance the performance of digital multi-beam antennas. To fully exploit the beam control flexibility of digital multi-beam technology and address the limited spatial coverage of conventional planar array antennas, Zhai et al., proposed a spherical conformal array antenna design that adopts a fullerene-based structure, also known as C60, forming a spherical array composed of 12 pentagonal and 20 hexagonal subarrays, as shown in Figure 7 [9]. This effectively expands the coverage area of the array antenna, thereby facilitating multi-target tracking, measurement, and communication.

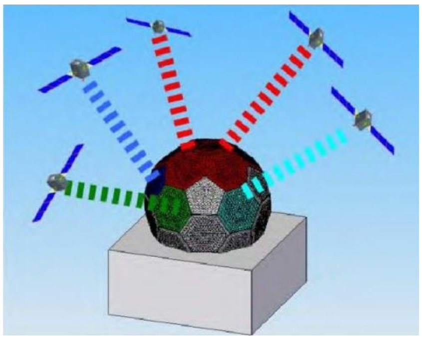

Figure 7: Spherical shaped array antenna

At the algorithm level, there is significant room for improving digital multi-beam antennas. To address the technical challenge of fast synthesis of broadband multi-beams, prior studies utilized digital signal processing and field-programmable gate arrays (FPGAs) to generate high-code-rate broadband modulated signals and perform wide and narrowband multi-beam electronic scanning solely through software programming [10]. For broadband multi-satellite multi-beam scenarios, a digital multi-beam anti-jamming system was designed based on an adaptive acquisition algorithm, stabilizing carrier phase, enhancing spatial gain, and further boosting spatial resolution [11]. Active multi-beam antennas, with their superior performance, are widely used in 5G/6G, radar, satellite communications, and imaging, showing great potential for future development.

2.2.3. Millimeter-wave hybrid multi-beam antennas

Despite the numerous performance advantages of digital multi-beam antennas, their requirement for independent signal processing at each antenna element in a large-scale array leads to exponentially increasing hardware costs and power consumption due to the high demands on ADC/DAC bit width, sampling rates, and the computational power of FPGA and DSP hardware. In contrast, traditional analog multi-beam antennas use fixed beamforming networks for static beams, reducing cost and power but limiting flexibility. For example, to achieve a balance between cost, power efficiency, and beamforming flexibility, Molisch et al. proposed hybrid multi-beam array antennas, employing a two-stage digital-analog beamforming scheme, where low-dimensional digital precoding at the baseband is complemented by phase-controlled signal adjustment for precise beam shaping [12,13].

For hybrid beamforming in millimeter-wave large-scale MIMO systems, Xu et al. systematically reviewed and categorized the research into two primary approaches: hybrid beamforming based on ideal channel conditions and hybrid beamforming based on the beam pairing [14]. The former has higher algorithmic complexity, requiring either classical digital beamforming methods or complete channel state information (CSI) at the receiver. The latter reduces the dimensionality of the original channel matrix, eliminating the need for full CSI, and instead achieves hybrid beamforming through codebook design and beam search algorithms. As a key technology for 5G/6G, hybrid beamforming holds significant potential for further development in areas such as wideband channel modeling, beam search and fast switching, and system complexity reduction.

3. Future prospects

3.1. Advances in millimeter-wave beamforming optimization

One of the key research areas in millimeter-wave multi-beam antennas remains the optimization of beamforming techniques. The primary objective is to enhance beamforming accuracy, efficiency, and flexibility while minimizing hardware complexity and power consumption. On the hardware side,

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research is likely to focus on high-performance RF link design, the development of low-loss materials, and highly integrated beamforming chips. On the software side, hybrid beamforming remains a crucial direction, thus requiring further optimization of algorithms that integrate baseband precoding with analog beamforming. Besides, dynamic beam management and tracking are critical research areas. For example, deep reinforcement learning-based adaptive beam tracking algorithms enable rapid beam adjustments in dynamic multi-user environments, enhancing beam switching efficiency, interference resilience, and overall adaptability.

3.2. Integrated optimization of Intelligent Reflecting Surfaces and millimeter-wave communication

Intelligent Reflecting Surface (IRS) enhances wireless communication link quality by dynamically adjusting the phase and amplitude of reflected signals via programmable metasurfaces. And it can greatly boost signal coverage and link reliability in millimeter-wave communication systems while reducing propagation loss and enhancing energy efficiency without increasing transmission power. The integration of IRS with millimeter-wave multi-beam antennas has become a research hotspot, particularly in combining IRS with beamforming to optimize both beam directionality and signal quality. Future research will focus on reinforcement learning-driven IRS phase control algorithms to automate phase tuning. These algorithms dynamically adjust the phase of IRS elements in real time based on CSI to achieve optimal signal reflection. Another critical challenge lies in developing low-power, cost-efficient tunable materials with enhanced tunability and reflection efficiency. In addition, advances in material science, such as novel two-dimensional materials like graphene and transition metal dichalcogenides, offer enhanced tunability and efficiency for IRS components. Also, integrated metasurface control chips are key to large-scale IRS deployment.

3.3. Spectrum expansion and optimization of spectrum utilization

Spectrum expansion is a key research direction to meet growing data transmission demands. While millimeter-wave expansion has made progress, transitioning to the terahertz (THz) band (0.3-3 THz) poses significant challenges. The high-frequency nature of THz waves necessitates breakthroughs in waveguide materials and manufacturing techniques. Transmission at these frequencies is limited by antenna size, radiation loss, and atmospheric absorption, requiring low-loss waveguide materials and high-precision antenna design. In particular, novel metals, metamaterials, and 2D materials like graphene are attracting growing research attention. Also, optimizing spectrum utilization is crucial for future communication systems, with intelligent spectrum scheduling enabling dynamic resource allocation and management. Advancing spectrum-sharing technologies, especially in mmWave and THz bands, will ease resource constraints. Integrating cognitive radio technology enables intelligent systems to identify idle spectrum, adaptively allocate channels, and reduce inter-band interference.

3.4. Miniaturization, integration, and energy efficiency

The miniaturization and integration of mm-wave multi-beam antennas are key to addressing spatial and cost constraints in communication systems. As IC technology advances, Antenna-on-Chip and System-in-Package solutions enable compact, integrated designs by embedding multiple antenna elements and hardware into a single chip, minimizing size and enhancing reliability. Innovative design strategies, such as 3D folded arrays and multifunctional integrated packaging, are gaining attention. 3D folded arrays boost spatial efficiency, boosting antenna performance while reducing physical footprint. Also, intelligent optimization algorithms applied to beamforming networks help reduce dependency on large-scale array elements, thereby lowering hardware complexity, cutting power consumption, and enhancing energy efficiency. Future research in energy efficiency will focus

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on adaptive power control strategies and intelligent sleep modes. AI-driven optimization algorithms dynamically regulate power distribution and operations in real time, reducing overall power consumption. In large-scale high-frequency systems, energy efficiency is vital for sustainable communications, driving performance and eco-friendly solutions.

4. Conclusion

As a fundamental element of modern communication technology, mm-wave multi-beam antennas play a significant role in maximizing spectrum efficiency, extending signal coverage, and boosting communication capacity. Passive, active, and hybrid multi-beam antennas each have great potential in different application scenarios. This paper summarizes the fundamental principles of multi-beam antennas, discussing their working mechanisms, development history, characteristics, and research progress across the three main categories: passive, active, and hybrid multi-beam antennas. In the future, as mm-wave and terahertz technologies become widely adopted in 5G/6G communications, satellite communications, IoT, as well as communication-sensing applications, these antennas will place greater emphasis on advanced dynamic adaptability, greater system autonomy, and optimized structural efficiency to minimize complexity and cost. These advancements will provide essential support for the realization of high-speed, low-latency, and high-capacity intelligent communication systems.

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