

# A Survey of Smart Antenna Technology: Architectural Evolution, Performance Comparison, and Future Challenges

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**Abstract:** Smart antenna technology, a critical innovation in wireless communications, significantly enhances system performance through dynamic beamforming and spatial filtering. It effectively addresses limitations of traditional antennas in anti-interference capability, spectrum utilization efficiency, and coverage flexibility, making it a fundamental component of fifth-generation (5G) and future mobile communication systems. This paper systematically reviews the primary technical approaches in smart antenna research, focusing on three mainstream implementations: switched-beam, adaptive beamforming, and hybrid architectures. A comprehensive analysis and comparison of their technical principles, performance characteristics, and application scenarios are provided. Based on the examination and synthesis of existing work, potential future research directions for smart antenna technology are also proposed.

**Keywords:** Smart Antennas; Switched-beam antenna; Adaptive beamforming antenna; Hybrid architecture antenna.

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## 1. Introduction

Smart antennas represent a groundbreaking technological innovation in the field of wireless communications. Evolving from conventional antenna systems through the integration of intelligent processing capabilities, this new type of antenna system marks a significant leap forward. While its origins can be traced back to early Adaptive Antenna Arrays, smart antennas have achieved a transformative shift from “fixed” to “smart” functionality by incorporating advanced digital signal processing algorithms and intelligent control technologies.

The core advantage of smart antenna systems lies in their unique triple-layer intelligence. Firstly, they possess precise spatial signal sensing capabilities, enabling real-time estimation of critical spatial information such as signal direction of arrival and angle of arrival. Secondly, these systems incorporate intelligent tracking algorithms that allow continuous localization and tracking of mobile signal sources. Finally, based on acquired environmental information, the system can autonomously perform spatial filtering and beam control. These characteristics collectively define the essential features that distinguish smart antennas from traditional ones.

Compared to traditional antennas, smart antennas not only enable algorithm-driven dynamic reconfiguration of parameters to improve spectral efficiency, extend coverage, and enhance anti-interference capabilities, but also offer greater flexibility through autonomous parameter optimization in response to environmental changes. This adaptability allows smart antennas to serve a wide range of application scenarios.

With the global deployment of 5G networks and the comprehensive advancement of 6G technology research and development, human society is rapidly moving toward an intelligent and interconnected digital era. In this process, various types of smart terminal devices are experiencing explosive growth—from smartphones with a penetration rate

exceeding 85% to rapidly expanding IoT devices, industrial drones, and wearable technology. Wireless connectivity has become critical infrastructure in modern society. According to the latest statistics from International Data Corporation (IDC), the number of active connected devices worldwide exceeded 30 billion in 2023 and is projected to reach 50 billion by 2030.

Faced with such a massive scale of devices and diverse application scenarios, traditional antenna technologies have revealed significant limitations. Firstly, the increasingly scarce spectrum resources demand antenna systems with higher spectral efficiency. Secondly, the significant increase in device density has resulted in increasingly prominent interference issues within wireless environments. Moreover, emerging applications—such as holographic communications, telemedicine, and digital twins—impose stringent requirements on communication quality. These challenges collectively drive the imperative for innovation in antenna technology.

In this context, smart antenna technology demonstrates significant potential for development, particularly in emerging fields such as Industry 4.0, intelligent transportation, and the low-altitude economy, where it is already creating substantial application value. For instance, Huawei's AirEngine series of commercial base stations, by adopting smart antenna technology, have achieved a 40% improvement in coverage range. Meanwhile, DJI's latest generation of industrial drones utilizes smart antennas to extend image transmission distances up to 15 kilometers, fully demonstrating the practical benefits of this technology.

## 2. Classification of Smart Antennas

The operational modes of smart antennas are primarily categorized into two types: switched-beam antennas and adaptive beamforming antennas. However, with technological advancements, modern smart antenna systems increasingly adopt a hybrid architecture that combines the simplicity of fixed beam systems with the flexibility of adaptive systems, thereby achieving an optimal balance

between performance and cost. This hybrid approach is emerging as a mainstream technical pathway in 5G-Advanced and 6G systems.

Therefore, this paper categorizes smart antennas into three types based on their operational modes: switched-beam antennas, adaptive beamforming antennas, and hybrid architecture antennas.

## 2.1. Switched-Beam Antennas

Switched-beam antennas operate by covering spatial directions through a predefined set of fixed beam patterns. The system selects the optimal beam based on the received signal strength indicator (RSSI) to establish a communication link. This architecture offers advantages such as straightforward implementation and relatively low hardware cost, making it suitable for scenarios with relatively stable channel conditions and low user mobility. However, due to the inability to dynamically adjust beam shapes or directions, this system exhibits limited flexibility. It cannot achieve precise beam steering for fast-moving users, nor can it effectively suppress directional interference. As a result, such antennas are primarily used in early mobile communication systems (e.g., 2G networks) and large-scale IoT terminal devices where power consumption and cost are critical concerns. In modern high-capacity, high-reliability communication systems, they are increasingly being replaced by more advanced beamforming schemes.

The concept of switched-beam antennas can be traced back to 1961 when J. Butler proposed the Butler matrix[1]. This matrix utilizes a fixed set of phase shifters and power-division networks to generate multiple fixed orthogonal beams covering different directions, thereby laying the theoretical and practical foundation for most subsequent research on switched-beam antenna systems.

Switched-beam antennas were initially applied in satellite communications and electronic warfare (EW) systems for rapid signal scanning and direction finding[2].

With the continuous evolution of mobile communication technologies, enhancing network capacity and coverage has become a central focus. In this context, switched-beam technology was introduced as an initial solution for "smart antenna" systems. The book[3] provides a detailed exposition of the principles and architecture of switched-beam systems, clearly distinguishing them from fully adaptive arrays. It is regarded as a classic reference worthy of in-depth study.

With ongoing research and technological evolution, the theoretical framework and technical essence of smart antennas have become increasingly well-defined and refined. Numerous scholars have provided systematic explanations and definitions of the core concepts of smart antenna technology. In literature [4], the advantages and recent advancements in smart antenna transceiver architectures are summarized, along with proposed future development trends and challenges. Meanwhile, literature [5] reviews the historical development of smart antennas, clarifying the historical significance of fixed beam systems.

Subsequently, Brady et al. integrated the concept of beamspace MIMO communication with hybrid analog-digital transceiver architectures[6], proposing a physically precise computational modeling and analytical framework for CAP-MIMO (Continuous Aperture Phased MIMO). Experimental validation demonstrated that this system significantly enhances spectral efficiency.

Research on switched-beam antennas has reached a

relatively mature stage. In recent years, however, this technology has been revitalized in cutting-edge studies in the form of "new manifestations." For example, millimeter-wave beam management—such as SSB beam scanning in 5G NR[7]—and the codebook design for intelligent reflecting surfaces (IRS)[8] represent continuations and advancements of the foundational concepts underlying switched-beam antennas.

## 2.2. Adaptive Beamforming Antennas

Adaptive beamforming antennas represent a class of smart antenna systems grounded in advanced digital signal processing techniques. Their core operational principle lies in the real-time computation of complex weighting coefficients for signals received by individual antenna elements within the array, enabling the dynamic synthesis of an optimal beam that precisely directs radiation toward target users. By continuously updating the beamforming vectors, the system not only automatically tracks high-speed mobile user terminals but also adaptively forms nulls in the directions of interference sources, thereby effectively suppressing interference while optimizing spectral efficiency and significantly enhancing overall system capacity. This technology demands multi-channel RF chains and high-performance real-time processors for hardware implementation, along with computationally intensive operations including covariance matrix inversion and adaptive iterative algorithms at the processing level. These requirements result in significant implementation complexity and cost. Nevertheless, the technology demonstrates superior performance in beam flexibility, spatial resolution, and anti-jamming capability when compared to fixed-beam systems. Consequently, adaptive beamforming has become a mainstream technological solution in high-performance communication and sensing applications, including 4G/5G mobile communication base stations, military radar and electronic warfare systems, satellite communication terminals, and high-precision navigation and positioning devices.

The theoretical foundation of adaptive beamforming antennas originated in the radar field during the 1960s. Key milestones included the adaptive sidelobe cancellation technique proposed by Howells[9] and the Least Mean Squares (LMS) algorithm introduced by Widrow, which together laid the groundwork for subsequent development of this technology.

Subsequent efforts by researchers led to a flourishing period of algorithmic development in the 1970s and 1980s. A key advancement was made by Capon in 1969 with the design of the Capon beamformer[10]. This method minimizes output power while maintaining a distortionless response to the desired signal, thereby effectively suppressing interference and noise and significantly enhancing the resolution of spatial spectrum estimation. In 1986, Schmidt developed the Multiple Signal Classification (MUSIC) algorithm[11]. By leveraging the covariance matrix of received data, this method achieves significantly higher resolution than conventional approaches. Roy introduced the ESPRIT algorithm by exploiting the translational invariance property of sensor arrays[12]. This approach eliminates the need for computationally intensive spectral peak searches and instead directly estimates the direction of arrival (DOA) by exploiting the rotational invariance of the signal subspace. As a result, ESPRIT requires less computational effort, has lower complexity, and operates at a higher speed. Both the MUSIC

and ESPRIT algorithms are considered classical and have been widely applied across numerous fields including radar, sonar, and wireless communications.

With advancements in digital signal processor (DSP) technology, digital beamforming (DBF)—which reduces antenna size and improves resolution—transitioned from theory to practical implementation. It was successfully integrated into smart antenna systems for 3G/4G mobile communications[13], marking a leap from conceptual research to commercial deployment.

Subsequent research on adaptive beamforming antennas has focused on enhancing the robustness and intelligence of algorithms. These efforts aim to overcome various practical channel impairments while actively exploring deep integration with machine learning technologies. This direction promotes the evolution of beam optimization and management toward advanced stages of autonomous and intelligent decision-making.

Yang Kunde et al. utilized generalized diagonal loading techniques to identify the optimal trade-off between array gain and robustness in adaptive beamforming methods under varying conditions[14]. Shi Yingchun et al. employed p-norm constraints instead of the conventional 2-norm to comprehensively correct error uncertainties[15], thereby addressing performance degradation issues in beamformers. Feng Qing et al. developed robust Capon beamforming methods based on steering vector uncertainty[16], including a doubly constrained robust Capon beamforming approach. These robust adaptive beamforming techniques have been primarily applied in fields such as sonar, GPS anti-jamming, and mobile communications.

Wang Ji et al. applied deep reinforcement learning to their research[17], proposing an intelligent multi-user near-field broadband communication system assisted by an omnidirectional reconfigurable intelligent surface (RIS). This system optimizes beamforming and enhances the achievable rate for users. Wang Ying et al. addressed the near-field communication scenario in ultra-massive MIMO systems by designing a beam training scheme based on Convolutional Neural Networks (CNN) and a beam tracking scheme utilizing Long Short-Term Memory (LSTM) networks[18]. These approaches effectively reduce training overhead while simultaneously achieving superior performance in terms of achievable rate and normalized beam gain. Such intelligent beam optimization and management techniques are primarily applied in ultra-massive MIMO near-field communication systems.

### 2.3. hybrid architectures Antennas

The hybrid architecture antenna effectively integrates the flexibility of digital beamforming with the low-complexity advantages of analog beamforming by combining digital precoding and analog beamforming technologies. It has emerged as a mainstream solution to address the challenges of high-frequency communication scenarios such as millimeter-wave and terahertz bands. This architecture achieves an optimal balance among multiple dimensions, including system spectral efficiency, link reliability, hardware complexity, and power consumption, making it particularly suitable for large-scale MIMO systems and extremely high-frequency communications. However, its design process is relatively complex, requiring co-design and joint optimization of both digital and analog domains. This involves multiple aspects such as radio frequency chain

design, beam codebook generation, channel state information acquisition, and cross-domain resource scheduling, in order to fully exploit its technical potential in future mobile communications, satellite networks, and integrated sensing and communication systems.

The development of hybrid architecture antennas clearly demonstrates an evolutionary path from demand-driven inception to technological maturity. In the early 2010s, with the emergence of 5G research, millimeter-wave communication[19] imposed urgent requirements for large-scale antenna arrays. However, the prohibitively high hardware complexity and power consumption of fully digital beamforming solutions hindered their practical deployment, thereby catalyzing the exploration of new architectural paradigms.

According to Ehab Ali et al., the integration of massive Multiple-Input Multiple-Output (MIMO) systems with beamforming antenna array technology is expected to play a critical role in fifth-generation (5G) mobile communication systems[20]. The authors systematically reviewed and classified various optimal beamforming techniques in existing wireless communication systems, and further proposed a novel optimized beamforming method. This approach achieves optimal performance within massive MIMO architectures, addressing the core requirements of next-generation wireless communication systems for high throughput and low interference.

Since the early 2020s, research on hybrid architecture antennas has focused on defining the fundamental configurations of such systems. Two predominant structures—the fully-connected and the sub-connected architectures—have been extensively proposed and investigated. The central objective has been to establish a feasible balance between system performance and implementation complexity.

To address the demands of 5G and future networks for high data rates, high reliability, and massive traffic capacity, Zhang et al. investigated three emerging multi-antenna technologies expected to play crucial roles in beyond-5G (B5G) networks: cell-free massive MIMO, beam-domain massive MIMO, and intelligent reflecting surfaces. The study systematically elaborates on the fundamental principles, core characteristics, and recent advancements of these technologies, while also providing perspectives on future research directions[21].

Following the fulfillment of fundamental requirements, the field has entered a phase of deepening and expansion, with research extending to key issues such as channel estimation, beam training, precoding design, and energy efficiency optimization under hybrid architectures. Hong et al. investigated the joint design of the IRS reflection matrix and hybrid beamformer in narrowband MIMO systems and further extended the approach to orthogonal frequency division multiplexing (OFDM)-based broadband MIMO systems[22]. Liu et al. addressed the issue of mitigating the double-fading effect in cascaded links by proposing an active intelligent reflecting surface (IRS)-assisted rate-splitting multiple access (RSMA) scheme for millimeter-wave hybrid antenna arrays. Although the active IRS consumes additional power, this scheme enables more efficient utilization of the active IRS and ultimately enhances the energy efficiency of the system[23].

Zhang et al. addressed the trade-off between direction-of-arrival (DOA) estimation accuracy and power consumption in hybrid analog-digital (HAD) based large-scale antenna

arrays[24]. They derived a dynamic maximum likelihood estimator applicable to both HAD architectures and conventional all-digital structures, while also introducing a novel metric termed "DOA efficiency" to quantify the balance between DOA estimation performance and power consumption across different architectures.

The research group led by You Changsheng highlighted the critical role of extremely large-scale antenna arrays in future wireless communication systems, while also noting that the massive number of antenna elements required for deployment poses severe challenges in terms of hardware cost and system power consumption. To address this issue, the group investigated the problem of near-field beam focusing under the constraint of low-resolution phase shifters[25], with their

work focusing on the hardware implementation architecture of hybrid beamforming. They proposed an innovative method based on Fourier series expansion, which effectively overcomes the difficulty of characterizing beam pattern properties under phase quantization conditions.

## 2.4. Comparative Analysis

Through a systematic analysis and comparison of the operational principles, performance characteristics, and application scenarios of the three aforementioned types of smart antennas, including switched-beam, adaptive beamforming, and hybrid architecture antennas, the key findings are summarized in Table 1.

**Table 1.** Performance Evaluation of Smart Antennas

Antennas	Switched-Beam Antennas	Adaptive Beamforming Antennas	Hybrid Architecture Antennas
Working Principle	Selects the optimal beam from a predefined set of fixed beams	beams Dynamically synthesizes optimal beam by real-time weight calculation	Combines digital precoding and analog beamforming
Advantages	Simple implementation, low cost	High flexibility, strong anti-interference, excellent performance	Balanced performance and cost
Disadvantages	Limited flexibility, weak anti-interference	High complexity, high cost	Complex design, requires cross-domain joint optimization
Typical Applications	Early cellular networks, low-cost IoT terminals	High-end radar, military communications	5G/6G base stations, modern satellite communications

They do not represent mutually substitutable solutions but are respectively suited to different application scenarios. In contexts where peak performance is prioritized and cost is not a primary constraint, adaptive beamforming (fully digital architecture) remains the preferred solution. For cost-sensitive applications with requirements for low system complexity, switched-beam approaches or their derivative concepts (such as codebook-based mechanisms) continue to offer practical value. Meanwhile, in systems employing large-scale antenna arrays—particularly those operating in high-frequency bands—the hybrid architecture achieves a more favorable trade-off among performance, complexity, and power consumption, making it a major focus of current and future research.

## 3. Future Works

The future of smart antenna technology will see its evolution from a standalone "technology" into an "intelligent infrastructure" that underpins the intelligent connectivity of all things. Its core evolutionary logic progresses from "point intelligence" (individual antenna arrays) to "surface intelligence" (environments constructed with smart metasurfaces), and ultimately to "system intelligence" (end-to-end systems deeply integrated with AI). Future smart antennas will become more efficient, more intelligent, and more invisible, seamlessly blending into our surroundings to provide robust connectivity and sensing capabilities for the digital world—silently and effortlessly. We summarize the future development directions of smart antennas into the following aspects:

(1) Revolutionary Innovations in Architecture and Materials

At the hardware level, smart antennas are undergoing a fundamental transformation from discrete arrays to

continuous electromagnetic surfaces. Metasurface-based antennas can dynamically control the wavefront of electromagnetic waves, enabling lighter, thinner, and more conformal designs. Furthermore, dynamically reconfigurable hybrid architectures are gradually maturing, allowing autonomous switching among modes such as energy harvesting, sensing, and communication based on service requirements, thereby achieving optimal adaptation of functionality and resources.

(2) Deep Integration with Emerging Enabling Technologies

The future development of smart antennas will heavily rely on deep integration with emerging technologies such as artificial intelligence (AI), machine learning (ML), and reconfigurable intelligent surfaces (RIS). By leveraging various AI algorithms, the system can achieve intelligent prediction and management of beams, significantly reducing measurement overhead and accomplishing near-zero-latency beam switching and resource allocation. Meanwhile, RIS will collaborate with active antenna systems to jointly construct intelligent propagation paths that integrate reflection, refraction, and transmission through programmable control of the electromagnetic environment. This synergy will fundamentally transform the characteristics of traditional wireless channels and provide critical support for new frequency band applications, such as terahertz communications in 6G.

(3) Significant Expansion of Application Scenarios

Smart antennas will play an even more critical role beyond traditional mobile communications. Integrated Sensing and Communication (ISAC) represents a major evolutionary direction, enabling high-precision positioning, gesture recognition, and even 3D imaging by analyzing state changes in electromagnetic wave propagation. This provides fundamental sensing capabilities for fields such as autonomous driving, human-computer interaction, and smart

healthcare. Furthermore, in integrated space-air-ground-sea networks, smart antennas serve as core components for achieving high-speed satellite-terrestrial links, stable communication with anti-sway aerial platforms, and deep-sea data transmission.

In summary, smart antenna technology is progressively evolving from "array elements" toward "system empowerment." Its advancement relies not only on innovations in antenna design itself, but also on deep interdisciplinary integration with artificial intelligence, materials science, open network architectures, and other fields, in order to support the revolutionary demands of future wireless systems in terms of capacity, coverage, intelligence, and multi-functional convergence.

## 4. Conclusion

This paper presents an analysis of smart antenna technology, which plays a crucial role in modern communication systems by effectively addressing the limitations of conventional antennas in anti-interference capability, spectrum efficiency, and coverage flexibility. First, the basic concept and significance of smart antennas are elaborated. Furthermore, the current research landscape is systematically reviewed, focusing on three mainstream implementations: switched-beam antennas, adaptive beamforming antennas, and hybrid architecture antennas. Based on this review, a comprehensive comparative analysis of the performance and applicable scenarios of each antenna type is conducted. Finally, building upon existing research, potential future research directions for smart antennas are explored. As an inevitable product of evolving communication demands, smart antenna technology still faces numerous challenges, with many critical issues requiring further in-depth investigation.

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