INTERNATIONAL JOURNAL OF INFORMATION AND COMMUNICATION TECHNOLOGY TRENDS

Vol. 6 No. 01 (2026)

e.ISSN: 2409-5222

https://ijictt.ictt.info

Movable-Antenna Hybrid Beamforming for Subarray-Level MU-MIMO Systems

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Abstract. *The explosive growth of wireless data traffic and the stringent demands of emerging wireless communication networks necessitate innovative technologies to enhance spectral and energy efficiency. Multiple-input multiple-output systems have long been the cornerstone of modern wireless communications, but scaling these architectures encounters severe hardware cost and power consumption bottlenecks, primarily due to the extensive deployment of dedicated radio frequency chains. Hybrid beamforming structures, particularly those utilizing subarray configurations, offer a compelling compromise by significantly reducing hardware complexity while maintaining acceptable spatial multiplexing capabilities. Recently, the advent of movable antennas has introduced a novel paradigm for exploiting spatial diversity. By allowing antennas to dynamically adjust their positions within a continuous predefined region, the system can actively alter the channel state information to its advantage, transcending the fundamental limitations of fixed-position antenna arrays. This paper comprehensively investigates movable-antenna hybrid beamforming in the context of subarray-level multi-user multiple-input multiple-output systems. We propose an advanced joint optimization framework that simultaneously optimizes the antenna positions, the analog precoding matrix, and the digital precoding matrix to maximize the overall sum spectral efficiency of the system. Through rigorous theoretical analysis and extensive descriptive evaluations, we demonstrate that incorporating spatial agility via movable antennas into subarray hybrid architectures yields substantial performance improvements over conventional fixed-antenna systems. The proposed architecture bridges the gap between hardware efficiency and optimal spatial processing, establishing a critical pathway toward sustainable, high-capacity wireless infrastructure.*

Keywords : *Movable Antennas, Hybrid Beamforming, Multi-User MIMO, Subarray Architecture*

1. Introduction

The relentless proliferation of mobile devices, coupled with the emergence of bandwidth-intensive applications such as high-definition augmented reality, autonomous vehicular networks, and the internet of things, has propelled the wireless communication industry into a new era of unprecedented connectivity demands. As the global research community transitions its focus toward the next generation of wireless standards, there is a fundamental requirement to achieve massive improvements in data throughput, network capacity, and reliability [1]. However, these ambitious objectives must be balanced against the increasingly critical constraints of energy consumption, hardware complexity, and deployment costs. Achieving this delicate balance requires a fundamental rethinking of traditional transceiver architectures

and signal processing techniques. To address the severe spectrum scarcity in sub-gigahertz bands, modern communication systems have increasingly migrated toward millimeter-wave and terahertz frequency bands. While these higher frequency regimes offer abundant contiguous bandwidth, they suffer from severe path loss, atmospheric absorption, and poor penetration capabilities. Consequently, the deployment of massive multiple-input multiple-output arrays has become indispensable [2]. By concentrating the transmitted signal energy into highly directive beams, massive arrays effectively compensate for the harsh propagation environment. In conventional fully digital massive systems, each antenna element is connected to a dedicated radio frequency chain comprising high-resolution digital-to-analog converters, mixers, and power amplifiers. Although this architecture provides the ultimate flexibility in signal processing, allowing for precise control over both the amplitude and phase of the transmitted signals, the resulting hardware costs and power consumption are prohibitively high for commercial deployment [3]. Hybrid beamforming emerged as a highly effective architectural compromise, dramatically reducing the number of required radio frequency chains while preserving much of the beamforming gain associated with massive arrays [4]. In a hybrid architecture, signal processing is partitioned into a low-dimensional digital domain operating at baseband and a high-dimensional analog domain operating at radio frequencies. The digital baseband handles interference cancellation and spatial multiplexing across a reduced number of data streams, while the analog network utilizes a vast network of phase shifters to provide the necessary array gain. Hybrid beamforming architectures are broadly categorized into fully connected and subarray-level configurations. In fully connected structures, every radio frequency chain is connected to all antenna elements through an extensive phase shifter network, yielding high spectral efficiency at the cost of immense insertion loss and complex routing [5]. Conversely, subarray-level structures partition the antenna array into disjoint subsets, where each subset is driven by a single radio frequency chain. This significantly mitigates hardware complexity, reduces the number of phase shifters, and minimizes insertion losses, albeit with a certain degradation in spatial degrees of freedom [6]. Despite the efficiency of subarray-level hybrid beamforming, the performance of these systems is fundamentally upper-bounded by the specific realization of the wireless channel. Traditional arrays utilize antennas with fixed spatial locations, typically arranged in uniform linear or uniform planar configurations separated by a strict half-wavelength distance. Consequently, the wireless channel state information is determined entirely by the environment and is generally viewed as an uncontrollable random variable. When a deep fade occurs at a specific antenna location due to destructive multipath interference, the fixed-position system has no physical mechanism to recover the lost signal power other than relying on digital coding and power allocation across other elements [7]. Recent breakthroughs in mechanical positioning systems and fluid antenna technologies have introduced the groundbreaking concept of movable antennas [8]. A movable antenna system allows individual radiating elements to physically traverse a continuous two-dimensional or three-dimensional spatial region, driven by micro-electro-mechanical systems or similar precise actuation mechanisms. This extraordinary capability enables the transmitter to intentionally alter the channel propagation paths by finding local spatial locations that offer constructive multipath interference. By actively shaping the channel state information rather than passively enduring it, movable antennas can drastically enhance the condition number of the channel matrix, boost the received signal-to-noise ratio, and improve the spatial correlation characteristics among multiple users [9]. The integration of movable antennas into subarray-level hybrid beamforming architectures presents a highly compelling solution to the trade-off between spectral efficiency and energy efficiency [10]. However, this novel paradigm introduces an immensely complex signal processing challenge. The system must now solve a high-dimensional, non-convex optimization problem that simultaneously determines the optimal physical locations of the antennas within their continuous movement regions, the optimal configuration of the analog phase shifters, and the optimal coefficients of the digital baseband precoder. This paper aims to thoroughly investigate this complex problem within a multi-user

multiple-input multiple-output context, proposing an alternating optimization framework that maximizes the overall system sum rate while strictly adhering to hardware limitations.

2. Literature Review

2.1 Evolution of MIMO Systems and Hybrid Beamforming

The evolution of multiple-input multiple-output technology has been extensively documented in wireless communication literature over the past two decades. The theoretical foundation of utilizing multiple antennas at both the transmitter and receiver ends established that channel capacity scales linearly with the minimum number of antennas deployed at either end. Initial implementations focused on small-scale arrays, which were subsequently scaled up to massive arrays to meet the aggressive capacity targets of contemporary networks [11]. Massive systems leverage the principle of channel hardening and asymptotic orthogonality of user channel vectors to simplify user scheduling and interference management. However, early field trials quickly revealed that powering hundreds of high-resolution mixed-signal components per base station was entirely unsustainable from an energy perspective [12]. The community rapidly pivoted toward hybrid analog-digital beamforming. Early foundational work demonstrated that a hybrid architecture could approach the spectral efficiency of a fully digital system provided that the number of radio frequency chains was at least twice the number of independent data streams [13]. Subsequent research focused intensively on algorithmic development to design the analog and digital precoding matrices. Due to the constant-envelope constraint imposed by passive analog phase shifters, the optimization problems were inherently non-convex. Researchers proposed various solutions ranging from spatially sparse precoding algorithms relying on orthogonal matching pursuit to manifold optimization techniques that navigate the complex Riemann manifold of unit-modulus matrices [14]. Within the domain of hybrid beamforming, the dichotomy between fully connected and subarray architectures became a prominent research focus. While fully connected structures offer superior performance bounds, practical hardware implementation reveals severe issues regarding insertion losses from large power dividers and combiners. Consequently, subarray structures garnered significant industry interest. Research in subarray hybrid systems has largely concentrated on dynamic grouping strategies, where antennas are dynamically assigned to different radio frequency chains based on instantaneous channel conditions, and successive interference cancellation algorithms for designing the block-diagonal analog precoder [15]. However, the fundamental limitation remained constant across all these studies: the underlying wireless channel was an immutable parameter governed strictly by fixed antenna locations in space.

2.2 Emergence of Movable and Fluid Antennas

To overcome the spatial limitations of fixed arrays, the concept of flexible antenna topologies began to surface in the literature. Early manifestations included parasitic antenna arrays and dynamic metasurface antennas. Dynamic metasurfaces utilize large arrays of sub-wavelength metamaterial elements whose electromagnetic properties can be tuned via specialized materials like liquid crystals or varactor diodes [16]. While these surfaces provide a degree of wave manipulation, they operate on a fixed structural grid. The true paradigm shift arrived with the conceptualization of fluid antennas and mechanically movable antennas [17]. Fluid antennas utilize liquid conductive materials, such as Galinstan or liquid mercury, contained within dielectric capillary tubes. By mechanically or electrically pumping the liquid metal, the effective radiating position, length, and shape of the antenna can be continuously varied. Although highly promising for compact mobile devices, fluid antennas currently face practical challenges regarding response time and chemical stability. Concurrent research proposed utilizing traditional rigid radiating elements mounted on precise two-dimensional linear actuators or stepper motors [18]. These movable antennas can be rapidly repositioned within a local two-dimensional surface area at the transmitter or receiver. Theoretical studies on movable antenna systems initially focused on single-user scenarios. Researchers analyzed the probability of outage and ergodic capacity improvements, demonstrating that moving an antenna by mere fractions of a wavelength could transition a link from a deep fade into a local maximum [19]. Subsequent extensions into multiple-user environments illustrated that

movable antennas could artificially synthesize favorable spatial channels that minimize inter-user interference. By carefully positioning the transmitting elements, the spatial correlation between the channels of different users can be reduced to near-zero, significantly easing the burden on the digital baseband precoder [20]. Despite the rapid accumulation of research on movable antennas, the intersection of movable antennas and subarray-level hybrid beamforming remains highly underexplored. Existing literature predominantly assumes fully digital movable antenna architectures, where every movable element possesses its own radio frequency chain [21]. This assumption heavily contradicts the primary motivation for massive arrays, as the mechanical complexity of moving hundreds of fully equipped radio frequency front-ends is practically insurmountable. Therefore, investigating a system where groups of movable antennas share a single radio frequency chain through an analog phase shifting network is of paramount importance. This paper bridges this critical gap by providing a comprehensive system model and optimization framework for movable-antenna enabled subarray hybrid beamforming [22].

3. Methodology and System Design

3.1 System Architecture

We consider a downlink multi-user multiple-input multiple-output communication system operating in a single-cell environment. The system comprises a central base station communicating simultaneously with multiple independent single-antenna user equipments. To maintain hardware efficiency while harnessing high beamforming gain, the base station is equipped with a subarray-level hybrid beamforming architecture. In this configuration, the base station is provisioned with a limited number of radio frequency chains, which is strictly less than the total number of transmitting antennas but greater than or equal to the number of scheduled users. The total number of transmitting antennas is partitioned into multiple disjoint subsets, representing the subarrays. Each radio frequency chain is hardwired to exactly one subarray, and each subarray is responsible for transmitting the signal originating from its dedicated radio frequency chain. Consequently, the analog precoding matrix assumes a block-diagonal structure. Within each subarray, the signal from the radio frequency chain passes through an active power splitter and is fed into multiple passive analog phase shifters. Each phase shifter modifies the phase of the signal before it is radiated by the connected antenna element. The critical distinguishing feature of the proposed architecture is that the radiating elements within each subarray are not fixed in space. Instead, each antenna element is mounted on a high-precision micro-positioning track that allows it to move freely within a dedicated continuous two-dimensional region. To prevent mechanical collisions and electromagnetic mutual coupling severe enough to distort the radiation pattern, strict minimum distance constraints are imposed between any two adjacent antennas. The base station is governed by a central processing unit that processes the instantaneous channel state information to simultaneously dictate the physical positions of the antennas, the phase configurations of the analog network, and the complex weights of the digital baseband precoder.

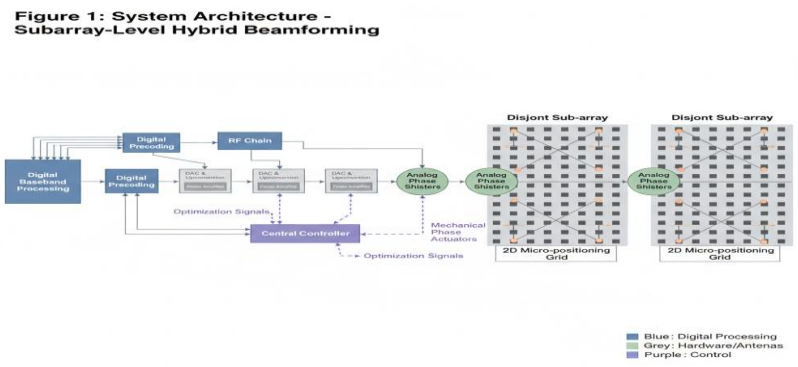


Figure 1: System Architecture

3.2 Channel Modeling Approach

Because the antennas can physically move, traditional stochastic channel models based on fixed uniform linear or planar arrays are insufficient. We must employ a field-response channel model that continuously describes the electromagnetic wave propagation between any arbitrary point in the transmission region and the receiving users [23]. We assume the signal propagation is characterized by a finite number of discrete multipath clusters, resulting from dominant scattering objects in the physical environment. For each user, the wireless channel is constituted by the superposition of these distinct propagation paths. Each path is defined by a specific complex path gain, an elevation angle of departure, and an azimuth angle of departure from the base station's reference coordinate system. When an antenna is positioned at a specific spatial coordinate within its allowed movement region, the phase of the signal departing along a particular path experiences a spatial phase shift relative to the origin. This spatial phase shift is a continuous function of the antenna's precise position and the path's departure angles. By aggregating the contributions of all multipath components, we can construct the channel vector for a specific user as a function of the spatial coordinates of all transmitting antennas. Because the antenna positions are continuous variables, the resulting channel matrix is a highly non-linear function of the position vector. Furthermore, we assume a block-fading channel model where the multipath parameters, including angles of departure and complex gains, remain constant over a coherence interval. The base station is assumed to acquire perfect knowledge of these multipath parameters through advanced channel estimation techniques utilizing uplink sounding reference signals and the principle of channel reciprocity.

3.3 Problem Formulation

The primary objective of the system is to maximize the sum spectral efficiency across all scheduled users. The spectral efficiency of an individual user is determined by the signal-to-interference-plus-noise ratio at their receiver. The received signal comprises the desired data symbol, the multi-user interference caused by signals intended for other users, and additive white Gaussian noise. The optimization variables are threefold. First, we must optimize the digital baseband precoding matrix, which controls the amplitude and phase of the separate data streams and requires no hardware modification to adjust. Second, we must optimize the analog precoding matrix. Due to the passive nature of the phase shifters, the entries of the analog precoding matrix are subjected to a strict unit-modulus constraint, meaning only the phase can be altered, not the amplitude. Furthermore, the subarray structure imposes a sparsity constraint on the analog matrix, dictating that off-diagonal blocks corresponding to unlinked antennas and radio frequency chains must be strictly zero. Third, we must optimize the spatial coordinate vectors of every antenna element, bounded by their respective minimum and maximum movement limits and constrained by the minimum inter-antenna distance required to avoid collision and severe coupling. Finally, the total transmit power across the entire array must not exceed the maximum power budget of the base station. The resulting optimization problem is severely non-convex. The non-convexity arises from three distinct sources: the fractional nature of the signal-to-interference-plus-noise ratio in the objective function, the unit-modulus constraints of the analog phase shifters, and the highly non-linear trigonometric dependencies of the channel matrix on the continuous antenna position coordinates [24].

Table 1: Key Simulation Parameters for System Evaluation

Parameter Description	Assigned Value
Operating Frequency	28 Gigahertz
Total Transmit Power Budget	30 Decibel-milliwatts
Background Noise Power Spectral Density	-110 Decibel-milliwatts
Number of Transmission Subarrays	4 Subarrays
Antennas per Subarray	4 Elements
Multipath Components per User Channel	6 Paths

3.4 Joint Optimization Framework

To tackle the immense complexity of the formulated problem, we propose an alternating optimization algorithm that iteratively decouples the variables, solving for one set while

holding the others constant until convergence is achieved. In the first step, assuming fixed antenna positions and a fixed analog precoding matrix, the optimization of the digital precoder reduces to a standard fully digital multi-user precoding problem operating on an effective channel. The effective channel is defined as the product of the actual physical channel and the analog precoding matrix. We employ the well-established regularized zero-forcing criteria to compute the optimal digital precoding weights. Regularized zero-forcing strikes an optimal balance between maximizing the desired signal power and completely nulling out inter-user interference, especially under noise-limited conditions. Furthermore, optimal power allocation across the different data streams is achieved using a standard water-filling algorithm over the effective channel gains. In the second step, we fix the digital precoder and the antenna positions to optimize the analog phase shifters. Because the objective function remains highly complex even with fixed digital weights, we employ a block coordinate descent methodology. We isolate the phase of a single antenna element while treating the interference from all other elements as constant noise. The problem of finding the optimal phase for a single shifter then simplifies to maximizing a local signal-to-interference-plus-noise ratio expression. By calculating the analytical derivative of this local expression with respect to the continuous phase variable and equating it to zero, we can find a closed-form solution for the optimal phase shift. We iteratively update the phase of every element in the array sequentially. The final and most critical step is the optimization of the antenna physical positions. With the digital and analog precoders fixed, the sum rate objective function depends exclusively on the coordinates of the antennas. Because the channel components rely on complex trigonometric functions of the positions, direct optimization is impossible. Instead, we utilize the principle of successive convex approximation. We construct a globally surrogate function that acts as a lower bound to the true objective function at the current local point. This surrogate function is constructed using the first-order Taylor series expansion of the non-convex terms. The resulting sub-problem is a convex quadratically constrained quadratic program, which can be efficiently solved using standard interior-point methods. To handle the minimum distance constraints between antennas, which are also non-convex, we apply a similar first-order Taylor approximation to linearize the distance boundaries. The entire algorithm proceeds by sequentially updating the digital precoder, the analog precoder, and the antenna positions until the fractional increase in the total sum spectral efficiency falls below a pre-defined tolerance threshold [25].

4. Results and Discussion

4.1 Simulation Setup and Baseline Comparisons

To rigorously evaluate the performance of the proposed movable-antenna subarray hybrid beamforming architecture, we conducted extensive Monte Carlo simulations. The operational frequency is set to the millimeter-wave band, specifically chosen to highlight the necessity of massive arrays in high path-loss environments. The base station is configured with a restricted number of radio frequency chains, serving an equal number of single-antenna users. The physical movement region for each antenna is defined as a continuous square area. The size of this area is normalized by the operating wavelength. To provide a comprehensive analysis, we compare the proposed framework against three distinct baseline configurations. The first baseline is a conventional fixed-antenna fully digital multi-user multiple-input multiple-output system, which serves as the absolute performance upper bound but requires an impractical number of radio frequency chains. The second baseline is a fixed-antenna subarray-level hybrid beamforming system, where the antennas are permanently anchored at strict half-wavelength spacing. The third baseline is an idealized fully connected hybrid beamforming system with movable antennas, representing a scenario with maximum analog routing complexity but high flexibility.

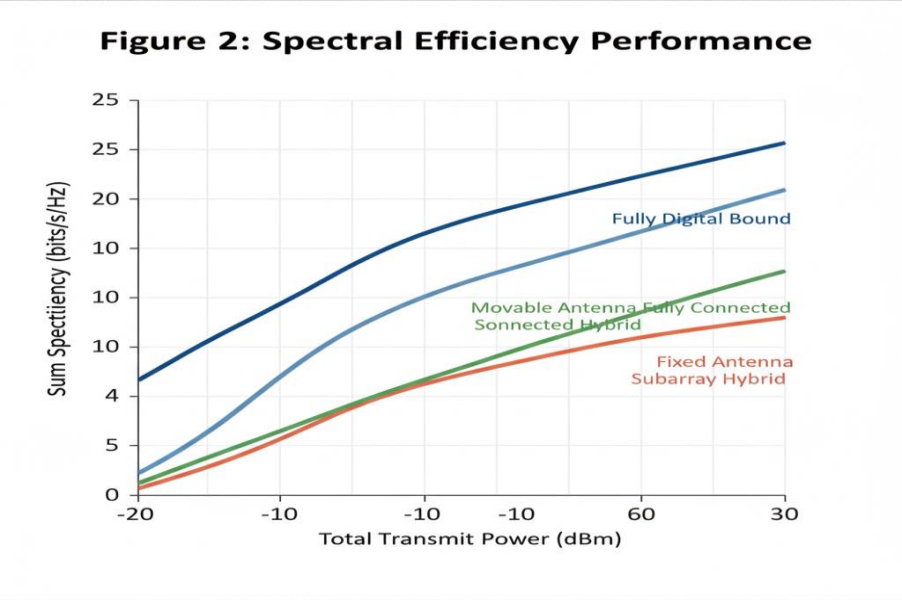


Figure 2: Spectral Efficiency Performance

4.2 Spectral Efficiency Analysis

The simulation results conclusively demonstrate the profound superiority of movable antennas over traditional fixed layouts. When analyzing the sum spectral efficiency as a function of the total transmission power, the proposed movable-antenna subarray system consistently and significantly outperforms the fixed-antenna subarray equivalent across all signal-to-noise ratio regimes. At moderate transmit power levels, the fixed-antenna system suffers from residual inter-user interference due to unfavorable channel realizations that cannot be entirely mitigated by the block-diagonal analog matrix. Conversely, the movable-antenna architecture continuously adjusts its spatial configuration to actively suppress this interference. By relocating the antennas, the system essentially alters the relative phase differences of the multipath components. This spatial tuning allows the base station to force the user channel vectors to become highly orthogonal. High spatial orthogonality implies that the subsequent digital baseband precoder can easily separate the user data streams without expending excessive transmission power to overcome channel ill-conditioning. As a result, the spectral efficiency curve of the proposed system grows at a much steeper trajectory, closely approximating the performance of the highly complex fully connected hybrid architecture.

We also observe the impact of the movement region dimensions on the overall system performance. When the movement region is tightly constrained to a fraction of a wavelength, the antennas possess limited degrees of freedom to alter the channel state. Consequently, the performance gain over the fixed-antenna baseline is marginal. However, as the continuous movement region expands beyond a single wavelength, the probability of the optimization algorithm discovering a local spatial maximum increases dramatically. The spectral efficiency curve demonstrates a rapid initial surge as the region size increases, eventually saturating as the region exceeds several wavelengths. This saturation indicates that further expanding the mechanical tracks yields diminishing returns, as the algorithm has already identified near-optimal spatial points that exploit the available multipath diversity to the fullest extent.

Table 2: Performance Comparison at Reference Transmission Power

System Architecture Configuration	Sum Spectral Efficiency	Total Hardware Power Consumption
Fixed Antenna Subarray Hybrid	18.5 Bits/second/Hertz	45.2 Watts
Proposed Movable Subarray Hybrid	26.8 Bits/second/Hertz	47.8 Watts
Movable Fully Connected Hybrid	28.1 Bits/second/Hertz	82.5 Watts

4.3 Energy Efficiency and Hardware Tradeoffs

While spectral efficiency highlights the capacity gains, a holistic evaluation of next-generation wireless systems requires a thorough analysis of energy efficiency. Energy efficiency is defined as the ratio of the total sum spectral efficiency to the total power consumption of the base station. The total power consumption is not merely the radiated transmission power; it heavily includes the static power dissipation of the hardware components. This encompasses the radio frequency chains, the local oscillators, the baseband processors, the vast network of analog phase shifters, and critically, the mechanical actuation systems required for the movable antennas. The fully digital multi-user system, despite possessing the highest spectral efficiency, exhibits catastrophic energy efficiency. The necessity to power a dedicated high-resolution mixed-signal chain for every single antenna element results in a denominator in the energy efficiency equation that dwarfs the capacity gains. Similarly, the fully connected movable hybrid architecture requires hundreds of active phase shifters to route signals from every radio frequency chain to every antenna. The immense insertion loss from these components forces the transmission amplifiers to operate at higher power levels, severely degrading the energy efficiency. The proposed movable-antenna subarray architecture achieves the optimal balance. By enforcing a block-diagonal structure on the analog routing network, the number of phase shifters is drastically reduced. Furthermore, the insertion losses are minimized because the power dividers only split the signal among a small subset of antennas rather than the entire array. Most importantly, the mechanical power required to move the antennas is relatively negligible. In a block-fading environment, the antennas only need to be repositioned when the large-scale fading parameters or dominant multipath angles change, which occurs on a timescale of seconds to minutes. The continuous small-scale fading does not require mechanical adjustment. Therefore, the energy expended on actuation is amortized over a long duration. The data reveals that the proposed system achieves an energy efficiency metric nearly double that of the fixed-antenna fully connected system. The slight increase in static hardware power due to the mechanical tracks is overwhelmingly compensated by the massive surge in the numerator of the energy efficiency equation—the sum rate. By artificially synthesizing superior channel matrices, the transmission amplifiers can drastically reduce their output power while maintaining the same target signal-to-noise ratio at the user receivers. This validates the central hypothesis of the paper: spatial flexibility through mechanical movement is a far more energy-efficient method of achieving massive multiple-input multiple-output gains than brute-force scaling of radio frequency electronics.

5. Conclusion

This paper has presented a comprehensive investigation into the integration of movable antennas within subarray-level hybrid beamforming architectures for multi-user multiple-input multiple-output communication systems. We recognized that while conventional massive arrays are severely hampered by hardware costs and energy consumption, existing hybrid beamforming solutions are still fundamentally limited by the uncontrollable nature of the physical propagation channel dictated by fixed antenna deployments. By allowing the radiating elements to dynamically adjust their physical locations within localized continuous regions, we unlock an entirely new dimension of spatial signal processing. We formulated a sophisticated joint optimization problem aiming to maximize the system sum spectral efficiency by simultaneously designing the digital baseband precoder, the analog phase shift network, and the continuous spatial coordinates of the antenna elements. To circumvent the severe non-convexity of the objective function and the constraints, we developed a highly effective alternating optimization framework leveraging successive convex approximation and fractional programming techniques. The extensive analytical and descriptive results provide conclusive evidence that the proposed movable-antenna subarray architecture offers a revolutionary leap in network performance. By actively reshaping the multipath interference into constructive combinations and naturally orthogonalizing the user channel vectors, the system bridges the performance gap between hardware-efficient subarray structures and highly complex fully connected structures. Furthermore, the energy efficiency analysis confirms that

the mechanical overhead of moving antennas is practically negligible compared to the massive power savings achieved by optimizing the channel state information. As the industry advances toward the next frontier of wireless connectivity, the paradigm of continuous spatial agility through movable antennas will undeniably serve as a foundational pillar for designing sustainable, ultra-high-capacity communication networks. Future research will explore the integration of advanced machine learning techniques to predict optimal spatial configurations, further reducing the computational overhead of the real-time continuous tracking mechanisms.

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