Researches on Dynamic Metasurface Antenna based Wireless Communication System

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***Abstract*—The dynamic metasurface antenna (DMA) architecture is defined by Lorentzian amplitude-phase coupling and waveguide-induced attenuation. This summary reviews DMA-based downlink and uplink beamforming, categorized by objective (sum-rate vs. energy efficiency) and phase control (continuous vs. discrete). Representative methods use alternating optimization combining WMMSE-based digital updates with manifold or projected-gradient updates of DMA weights. Power-aware designs apply fractional programming and convex approximation. For switched meta-atoms, structure-aware quantization mitigates low-resolution loss, while DMA-specific channel estimation with combiner co-design enables efficient reception with few RF chains.**

***Index Terms*—Dynamic Metasurface Antenna, Beamforming, Precoding, Lorentzian Constraint**

I. INTRODUCTION

Next-generation 6G wireless communication system aim to achieve high spectral efficiency (SE) and energy efficiency (EE) through simple baseband processing enabled by extremely massive MIMO systems, incorporating hundreds to thousands of antenna elements [1]–[3]. However, implementing fully digital phased arrays significantly increases the number of RF chains, power consumption, cost, and imposes stringent size and shape constraints. As a result, hybrid beamforming has emerged as a promising alternative [4].

Hybrid beamforming combines low-level digital precoding at the baseband with analog precoding in the RF domain. This architecture reduces the number of RF chains for large-scale antenna arrays, thereby lowering power consumption and and cost, while supporting multi-stream transmission and enhancing beam gain. The digital stage is responsible for multi-user interference management, stream splitting, and power distribution using a limited number of RF chains. The analog stage consists of phase shifters, variable gain amplifiers, and a distribution/combination network to provide beam directionality and focus. Howeverm, key limitations in the analog stage include frequency-flat behavior, a nearly constant-modulus nature, and challenges associated with quantized phase, insertion loss, and calibration. In contrast, the digital stage offers flexibility but is limited by the number of RF chains [5].

Two primary analog architectures are fully-connected and partially-connected topologies. In fully-connected topologies, each RF chain is connected to all antennas via a splitter/combiner network, enabling maximum beamforming gain and high flexibility for multi-stream transmission [6]. However, this approach requires a large number of phase shifters, resulting in increased losses, power consumption, area, and calibration complexity. On the other hand, partially-connected topologies assign each RF chain to a subset of antennas (subarrays), which reduces the number of required phase shifters and associated losses, thereby improving scalability and power efficiency and simplifying hardware implementation. Nevertheless, weak coupling between subarrays in partially-connected architectures limits the maximum achievable array gain and precise multi-user separation [7].

A. Dynamic Metasurface Antenna

From a system power model perspective, phased arrays used in hybrid beamforming suffer from accumulated power and insertion losses due to phase shifters. As an alternative, the Dynamic Metasurface Antenna (DMA) has attracted significant attention [8]. DMA is a transceiver architecture that supports large-scale arrays with low power and cost by feeding multiple sub-wavelength metamaterial elements into a waveguide and performing beam shaping and analog signal processing in the RF domain. In the context of 6G, DMA is considered a promising candidate due to its ability to scale up large arrays with simpler hardware compared to conventional antenna architectures [8].

The physical foundation of DMA is the waveguide-fed metasurface model [9]. Metamaterial elements are modeled as polarizable dipoles arranged along a reference wave path supplied by the waveguide. Each element controls the coupling between the reference and radiated waves by adjusting its resonance characteristics, such as through a varactor [9]. This structure allows for beam steering and shaping without active phase shifters and is analytically tractable enough to enable a closed-form expression of the array factor during the initial design stage. In other words, DMA achieves hybrid beamforming by leveraging the tunable resonance of the elements themselves, eliminating the need for bulky external phase shifters or combiners.

However, since the polarizability of the elements follows Lorentzian characteristics, amplitude–phase coupling arises and imposes design constraints. Nonetheless, high-quality beamforming can still be achieved using sub-wavelength sampling and phase control of the reference wave [10].

As a result, DMA enables a reduction in RF chains and savings in power and area. Its structure resembles the partially connected hybrid beamforming architecture, where one RF chain is connected to each end of the waveguide [11]. Additionally, from a system power model viewpoint, while conventional phased arrays accumulate insertion and power losses due to phase shifters, DMAs require lower varactor driving power, suffer reduced losses, and feature a smaller distribution network. This results in a relatively short transmission power loss path. Based on this, the EE model supports lower transmission power requirements for achieving equivalent SE, ultimately providing an EE advantage [12].

II. DMA based Beamforming

In DMA-based downlink multi-user multiple-input single-output (MU-MISO) systems, the digital precoder and DMA weights at the base station (BS) are jointly optimized. Since the reference signal propagates through a waveguide, filters capturing the waveguide's attenuation and phase propagation must be considered. Furthermore, due to the Lorentzian nature of the effective polarizability of DMA elements, the complex weights of each element involve phase–amplitude coupling. Unlike conventional phase shifter arrays that independently control only phase, the design of DMA-based systems must account for Lorentzian constraints and waveguide-induced attenuation.

A. Downlink

Chen *et al.* formulated a nonconvex problem for maximizing the weighted sum rate (SINR) of a receiver based on the digital precoder and DMA weights [13]. A solution was obtained by alternately updating the DMA-related weights and the digital precoder through alternating optimization, a commonly used technique. Specifically, Riemannian manifold optimization was employed to update the DMA weights under a continuous-phase assumption. However, this method was found to be computationally intensive. To address this, a projected gradient descent (PGD)-based algorithm was proposed, achieving performance comparable to the Riemannian method with significantly reduced computational complexity [13].

Chen *et al.* also addressed the EE maximization problem, formulating it as a fractional objective with the total power consumption (i.e., launch power and hardware power) in the denominator. Joint optimization of the digital precoder and DMA weights was performed under both power budget and Lorentzian constraints [14].The DMA weights were updated within the alternating optimization (AO) framework using manifold optimization and quadratic transform, while the digital precoder was updated using successive convex approximation (SCA) after equalization [14].

Methods for directly handling discrete phase constraints have been proposed for the switched meta-atom structure of DMA in [15]. Representative examples include (i) Closest Point Projection (CPP), which projects a continuous solution onto a nearest-neighbor grid, and (ii) Optimal M-Phase Beamforming (OMPB), which finds a global optimum for a given M-phase set in polynomial time. The average performance loss for uniform phase quantization is reported to be approximately 3.74dB for 1-bit, 0.87dB for 2-bit, and 0.22dB for 3-bit, demonstrating good agreement between theory and simulation. The analysis includes Lorentz constraints and waveguide attenuation.

DMA elements sample a reference wave supplied by a waveguide. Due to the Lorentzian response of the resonant meta-atom, the phase tuning range is limited and amplitude-phase coupling is inevitable. This characteristic fundamentally differs from traditional phased arrays, which control only phase, and is overcome by holographic beam synthesis, which utilizes both subwavelength sampling and reference-wave phase propagation [9]. Additionally, the systematic advantages of DMA are summarized, such as enabling large-scale arrays with simple hardware while providing a functional layout similar to a hybrid A/D structure [8].

B. Uplink

In a DMA-based uplink, signals transmitted by users are sequentially processed by the analog and digital combiners of the DMA. As the DMA architecture involves subwavelength meta-elements that sample and radiate a reference wave propagating through a waveguide, the element response follows Lorentzian characteristics. Consequently, attenuation and phase advancement inherently occur along the waveguide path. DMA provides a functional structure similar to analog/digital (A/D) hybrid systems but uses simpler hardware. However, it offers limited flexibility in combining signals, as it lacks the per-antenna access available in fully digital systems [8]. Uplink performance is typically evaluated from a multiple access channel (MAC) perspective. It has been reported that DMAs can achieve a summation rate closer to that of fully connected hybrid systems, even when using the same number of RF chains [12].

Studies in [9] and [8] summarized the DMA reception model and uplink architecture. In a DMA-based uplink, the analog combiner first aggregates the signal transmitted by the user, followed by digital combining that precisely separates user interference. DMA performs this operation by combining subwavelength meta-elements on a reference wave supplied through a waveguide. Due to the Lorentzian response of these meta-elements, phase and amplitude are inherently coupled, and attenuation and phase progression caused by waveguide propagation are superimposed on the received signal. Unlike traditional phased arrays, which control only the phase, DMA employs a holographic beamforming strategy that simultaneously uses subwavelength sampling and reference wave propagation. While this enables simpler hardware and a functional structure akin to an A/D hybrid, the degree of combining freedom remains lower than that of fully digital architectures.

Channel estimation and combiner design strategies were introduced in [16] and [17]. In this approach, each user transmits a pilot signal, and the analog and digital combiners are jointly optimized. Due to the limited number of RF chains in DMAs, the number of received samples is small. To address the underdetermined channel dimension, virtual channel projection is applied within a hybrid MIMO framework, incorporating DMA-specific constraints. Additionally, to improve the effective number of received samples without increasing pilot overhead, a method was proposed that utilizes the high-speed switching of the DMA to repeat measurements across multiple states within one symbol duration. During combiner design, a noise model incorporating antenna noise, RF chain noise, and structural attenuation is used to derive a combiner close to practical implementation.

[15] proposed a method to directly handle discrete phase constraints. In practical DMAs using switched metaelements, phases are selected only from a limited set, so instead of simply quantizing continuous solutions, phase design or structure-friendly projection techniques that guarantee global optima are used to minimize performance degradation even at low resolutions. In general, the average loss of uniform phase quantization is largest at 1 bit and smallest at 3 bits, and the resolution gain increases as the number of elements increases, but the improvement is limited if waveguide attenuation is excessive. Therefore, a trade-off between phase resolution, hardware complexity, and propagation loss is key even in the uplink.

[18] Design considerations and systematic advantages from a physical-layer perspective were summarized in [18]. Due to the resonant behavior of the meta-elements, a degradation region exists within the tunable phase range, necessitating combiner/pilot designs that account for this effect. On the other hand, DMAs can implement large-scale arrays with relatively simple hardware by leveraging subwavelength sampling and reference wave propagation. The combination of appropriately designed combiners and quantization-aware optimization demonstrates that close-to-optimal summation performance can be achieved, even with a limited number of RF chains, as supported by uplink studies.

III. Conclusion

This paper surveyed DMA-based beamforming for downlink and uplink, emphasizing the Lorentzian amplitude-phase coupling and waveguide-induced attenuation that distinguish DMAs from conventional phased arrays. We organized recent methods by two core objectives-weighted sum rate and energy efficiency-and two implementation regimes-continuous and discrete phase-highlighting alternating-optimization frameworks that pair WMMSE-type digital updates with manifold/PGD-based DMA weight updates, as well as fractional programming and sequential convex approximation for power aware designs.

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References

[1] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, "An overview of massive mimo: Benefits and challenges," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 742–758, 2014.

[2] M. A. L. Sarker, P. Selvaprabhu, V. B. Kumaravelu, S. Chinnadurai, B. Senouci, and D. S. Han, "Hybrid beamforming with branchwise phase shifters for ris-assisted 6g wireless communications," *ICT Express*, vol. 11, no. 4, pp. 618–623, 2025.

[3] M. Choi, J. Kim, and J. Moon, "Wireless video caching and dynamic streaming under differentiated quality requirements," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 6, pp. 1245–1257, 2018.

[4] F. Sohrabi and W. Yu, "Hybrid digital and analog beamforming design for large-scale antenna arrays," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, no. 3, pp. 501–513, 2016.

[5] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 831–846, 2014.

[6] S. Wan, H. Zhu, K. Kang, and H. Qian, "On the performance of fully-connected and sub-connected hybrid beamforming system," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 10, pp. 11 078–11 082, 2021.

[7] P. L. Cao, T. J. Oechtering, and M. Skoglund, "Transmit beamforming for single-user large-scale miso systems with sub-connected architecture and power constraints," *IEEE Communications Letters*, vol. 22, no. 10, pp. 2096–2099, 2018.

[8] N. Shlezinger, G. C. Alexandropoulos, M. F. Imani, Y. C. Eldar, and D. R. Smith, "Dynamic metasurface antennas for 6g extreme massive mimo communications," *IEEE Wireless Communications*, vol. 28, no. 2, pp. 106–113, 2021.

[9] D. R. Smith, O. Yurduseven, L. P. Mancera, P. Bowen, and N. B. Kundtz, "Analysis of a waveguide-fed metasurface antenna," *Physical Review Applied*, vol. 8, p. 054048, Nov 2017.

[10] M. Boyarsky, T. Sleasman, M. F. Imani, J. N. Gollub, and D. R. Smith, "Electronically steered metasurface antenna," *Scientific reports*, vol. 11, no. 1, p. 4693, 2021.

[11] L. You, J. Xu, G. C. Alexandropoulos, J. Wang, W. Wang, and X. Gao, "Energy efficiency maximization of massive mimo communications with dynamic metasurface antennas," *IEEE Transactions on Wireless Communications*, vol. 22, no. 1, pp. 393–407, 2023.

[12] J. Carlson, M. R. Castellanos, and R. W. Heath, "Hierarchical codebook design with dynamic metasurface antennas for energy-efficient arrays," *IEEE Transactions on Wireless Communications*, vol. 23, no. 10, pp. 14 790–14 804, 2024.

[13] J.-C. Chen and C.-H. Hsu, "Beamforming design for dynamic metasurface antennas-based massive multiuser miso downlink systems," *IEEE Open Journal of the Communications Society*, vol. 5, pp. 1387–1398, 2024.

[14] G. Chen, R. Zhang, H. Zhang, C. Miao, Y. Ma, and W. Wu, "Energy-efficient beamforming for downlink multi-user systems with dynamic metasurface antennas," *IEEE Communications Letters*, vol. 29, no. 2, pp. 284–288, 2025.

[15] X. Pei, H. Yin, L. Cao, and R. Song, "Dynamic metasurface antennas with discrete phase shifts: Performance analysis and beamforming methods," *IEEE Transactions on Communications*, pp. 1–1, 2025.

[16] M. Rezvani and R. Adve, "Channel estimation for dynamic metasurface antennas," *IEEE Transactions on Wireless Communications*, vol. 23, no. 6, pp. 5832–5846, 2024.

[17] J. Xu, L. You, G. C. Alexandropoulos, J. Wang, W. Wang, and X. Gao, "Dynamic metasurface antennas for energy efficient uplink massive mimo communications," in *2021 IEEE Global Communications Conference (GLOBECOM)*, 2021, pp. 1–6.

[18] R. J. Williams, P. Ramírez-Espinosa, J. Yuan, and E. de Carvalho, "Electromagnetic based communication model for dynamic metasurface antennas," *IEEE Transactions on Wireless Communications*, vol. 21, no. 10, pp. 8616–8630, 2022.