Movable Antennas Meet Low-Altitude Wireless Networks: Fundamentals, Opportunities, and Future Directions

Wenchao Liu, Xuhui Zhang, Chunjie Wang, Jinke Ren, and Weijie Yuan

***Abstract*—With the rapid development of low-altitude applications, there is an increasing demand for low-altitude wireless networks (LAWNs) to simultaneously achieve high-rate communication, precise sensing, and reliable control in the low-altitude airspace. In this paper, we first present a typical system architecture of LAWNs, which integrates three core functionalities: communication, sensing, and control. Subsequently, we explore the promising prospects of movable antenna (MA)-assisted wireless communications, with emphasis on its potential in flexible beamforming, interference management, and spatial multiplexing gain. Furthermore, we elaborate on the integrated communication, sensing, and control capabilities enabled by MAs in LAWNs, and illustrate their effectiveness through representative examples. A case study demonstrates that MA-enabled LAWNs achieve significant performance improvements over traditional fixed-position antenna-based LAWNs in terms of communication throughput, sensing accuracy, and control stability. Finally, we outline several promising directions for future research, including the MA-assisted unmanned aerial vehicle (UAV) communication/sensing, the MA-assisted reliable control, and the MA-enhanced physical layer security.**

I. Introduction

As an emerging strategic economic paradigm, the low-altitude economy primarily refers to various manned and unmanned flight operations conducted within the airspace below 1,000 meters above ground level, along with the associated industrial development driven by such activities [1]. In recent years, propelled by advancements in unmanned aerial vehicle (UAV) technologies and fifth-generation (5G) wireless communications, the low-altitude economy has experienced rapid growth and has become a key driver in reshaping modern society and promoting industrial transformation [2].

As a critical enabler of the low-altitude economy, low-altitude wireless networks (LAWNs) provide integrated information services for various manned and unmanned aerial vehicles, encompassing key functionalities such as real-time command and control, navigation enhancement, and cooperative monitoring [3]. This is accomplished through a unified and dynamic management architecture that spans the low-altitude airspace. The central objective of this framework is to achieve seamless integration of key functionalities, specifically communication, sensing, and control, thereby ensuring flight safety, operational efficiency, and high-precision environmental awareness.

However, LAWNs face highly dynamic radio channels in dense air-ground traffic and complex urban environments. Multipath interference, signal attenuation, and rapidly varying propagation conditions severely limit high-rate communication, precise sensing, and reliable intelligent control, posing major challenges to flight safety and operational efficiency. To address these challenges, movable antenna (MA) technology, also known as fluid antenna system, has emerged as a promising innovation, spurring extensive research efforts [4], [5]. By enabling flexible adjustment of antenna positions within a constrained three-dimensional space, the MAs can dynamically adapt to varying channel conditions, thereby enhancing signal quality, suppressing interference, and improving spectral efficiency through intelligent resource reuse [6]. Integrating the MAs into the LAWN architecture not only helps mitigate the effects of complex and uncertain propagation environments, but also significantly enhances communication capacity, sensing accuracy, and energy efficiency, providing a solid technological foundation for intelligent and fine-grained management of the low-altitude airspace.

This study provides a systematic review of the fundamental principles of LAWNs and MAs. Building on this analysis, we explore the key application potentials of MAs within the LAWN architecture. Furthermore, we present a case study demonstrating an integrated system that combines communication, sensing, and control functionalities through the use of MA technology. The results indicate that MAs significantly outperform fixed-position antennas in enhancing overall system efficiency. Finally, we discuss potential directions for future research and offer conclusions in the final section.

II. Fundamentals of LAWNs

As a foundational infrastructure supporting the development of the low-altitude economy, LAWNs encompass a range of key enabling technologies, including autonomous formation control and cooperative scheduling of UAV swarms, air traffic planning and management within the low-altitude airspace,

Wenchao Liu and Weijie Yuan are with the School of System Design and Intelligent Manufacturing, Southern University of Science and Technology, Shenzhen 518055, China (e-mail: wc.liu@foxmail.com; yuanwj@sustech.edu.cn).

Xuhui Zhang and Jinke Ren are with the Shenzhen Future Network of Intelligence Institute, the School of Science and Engineering, and the Guangdong Provincial Key Laboratory of Future Networks of Intelligence, The Chinese University of Hong Kong, Shenzhen, Guangdong 518172, China (e-mail: xu.hui.zhang@foxmail.com; jinkeren@cuhk.edu.cn).

Chunjie Wang is with Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China, and also with University of Chinese Academy of Sciences, Beijing 100049, China (e-mail: cj.wang@siat.ac.cn)

Corresponding author: Weijie Yuan

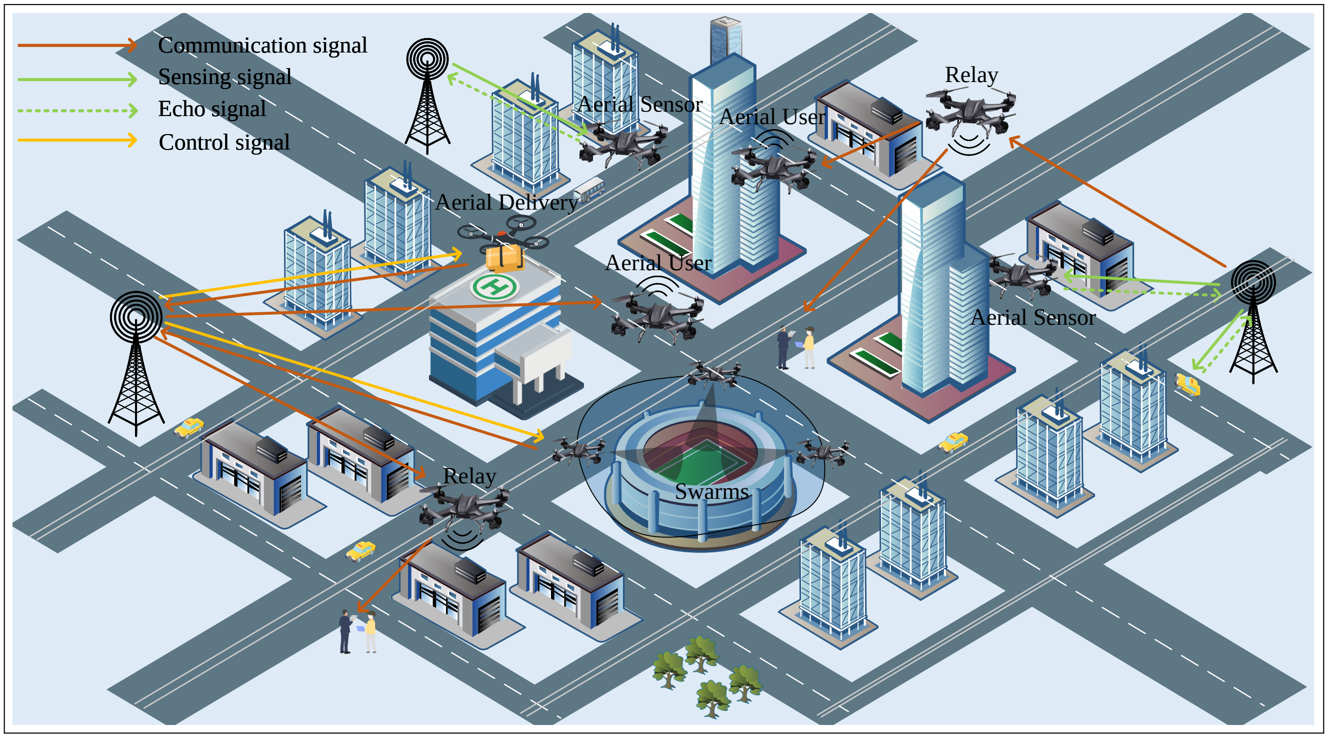

Fig. 1: Typical scenario of LAWN for communication, sensing, and control.

intelligent detection of unauthorized UAVs, and smart real-time navigation, as illustrated in Fig. 1. This section provides a systematic analysis of the technical architecture of LAWNs from three fundamental perspectives: communication, sensing, and control.

A. Communication Perspective

In LAWNs, stringent communication performance requirements must be satisfied to support the autonomous control, mission execution, and multi-agent coordination of UAVs. Due to the complexity of tasks and the dynamic nature of the operational environment, the LAWN must provide low latency, high bandwidth, strong interference resistance, and robust information security mechanisms. By classifying communication signals based on their application purposes and technical characteristics, efficient and reliable communication support can be achieved.

- Mission-oriented communication is primarily utilized to transmit various types of data collected by UAVs during task execution, such as images, video streams, and sensor measurements [7]. While the latency requirements for this type of communication are relatively relaxed, it typically demands higher levels of data security, particularly in scenarios involving sensitive missions or critical operations.
- Air-to-air communication among UAVs plays a pivotal role in multi-agent coordination and formation flight missions [8]. Such communication not only need to meet stringent requirements for low latency and strong interference resistance, but also needs to offer high reliability and good dynamic adaptability, in order to effectively address the rapidly changing relative positions between UAVs and the complex and varying airspace environment.
- Air-to-ground communication is primarily utilized to enable information exchange between UAVs and base stations, supporting critical functions such as remote command transmission, status feedback, and mission coordination. This type of communication imposes requirements on both security and stability, in order to ensure the reliability of remote operations.
- Emergency communication serves as a dedicated mechanism activated when an UAV encounters sudden malfunctions or hazardous situations, primarily for transmitting critical control commands or distress signals. This type of communication is assigned the highest priority and must be supported by robust reliability and comprehensive security measures to ensure the timely and effective delivery of essential information under extreme conditions.

B. Sensing Perspective

In addition to communication, sensing plays a crucial role in LAWNs, particularly in scenarios involving UAVs. By acquiring and analyzing external environmental data as well as internal system states, sensing technologies can significantly enhance autonomous decision-making capabilities and environmental adaptability, thereby providing robust technical support for flight control and mission execution. From a functional perspective, the sensing capabilities integrated within LAWNs can be systematically categorized into three types: control-related sensing, mission-oriented sensing, and radio-based sensing.

- Control-related sensing refers to the perception of an aircraft's own motion and navigation states, including parameters such as position, velocity, acceleration, and attitude. These signals are typically obtained from inertial measurement units (IMUs), global navigation satellite systems (GNSS), and onboard flight sensors, playing a critical role in ensuring safe navigation, flight stability, and formation maintenance.
- Mission-oriented sensing encompasses data acquisition mechanisms specifically designed for particular tasks, including but not limited to optical and infrared imaging, LiDAR scanning, and environmental parameter monitoring (e.g., temperature and air quality). This type of sensing enables a wide range of aerial operations, such as terrain mapping, target detection and tracking, and real-time environmental surveillance.
- Radio-based sensing utilizes the physical propagation characteristics of electromagnetic waves to perceive the surrounding environment. This can be achieved either through dedicated radar systems or by reusing communication signal waveforms. Such an approach offers notable advantages under degraded visual conditions and serves as a foundational element of the emerging integrated sensing and communication (ISAC) paradigm [9].

C. Control Perspective

In LAWNs, the control link serves as a core mechanism for ensuring flight safety and mission execution [10]. Its functionalities encompass not only real-time aircraft control but also environmental state awareness, navigation coordination, and operational scheduling. To accommodate the communication requirements of various control tasks, a systematic classification of control signals with clearly defined performance specifications must be established during the design of the communication link. These control signals can be categorized into three critical types based on their operational objectives:

- Flight control commands are generated by the ground control center and transmitted to UAVs for real-time adjustment of their flight trajectory, speed, and attitude. Although the data volume is typically small, these commands impose stringent communication requirements, including ultra-low end-to-end latency, extremely high transmission reliability, and robust security mechanisms.
- Status feedback information is periodically transmitted from the UAV to report its operational state, such as altitude, speed, and attitude. This type of data imposes relatively high requirements on communication reliability and latency, and is typically suitable for transmission over medium-rate to low-rate uplink channels.
- Task and management control are primarily utilized in non-real-time control scenarios, such as mission updates. Although it exhibits a higher tolerance to latency, it still requires secure data transmission and a certain level of reliability to ensure the effective operation of system management and task scheduling.

III. Fundamentals of MA

Driven by the demand for higher data rates and spectral efficiency, multiple-input multiple-output (MIMO) and its extension, massive MIMO, have emerged as core technologies in wireless networks. They exploit spatial diversity and multiplexing to significantly enhance channel capacity and spectrum utilization. However, as frequencies shift toward millimeter-wave bands, hardware complexity and power consumption increase exponentially, leading to higher computational costs and stricter energy efficiency requirements that limit their practical deployment [11].

Recently, MA technology has emerged as a promising approach to enhance wireless system performance. By dynamically adjusting the position or orientation of individual antenna elements, it can adapt to spatial channel variations, enabling real-time channel optimization and improved spatial multiplexing gain with minimal hardware overhead. As illustrated in Fig. 2, MA arrays are mainly categorized into two types based on movement modes: those performing 3D translational motion and those using rotational movement for spatial orientation adjustments [12], [13]. These movement capabilities support key benefits such as flexible beamforming, effective interference management, and enhanced spatial multiplexing.

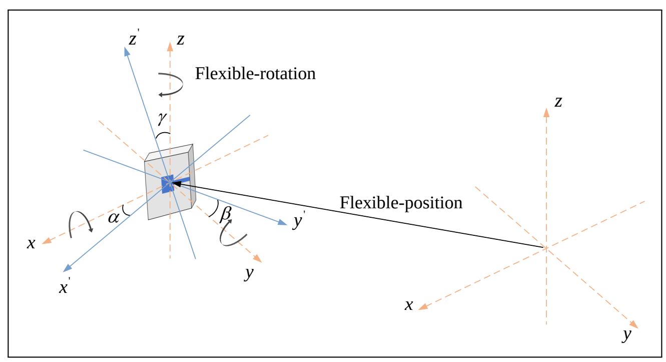

Fig. 2: Element architecture of MA.

- Flexible beamforming: Compared to conventional fixed antenna arrays, MA arrays represent a significant advancement in beamforming technology. While traditional beamforming mainly relies on adjusting antenna weights to control the phase and amplitude of individual elements, MA arrays introduce spatial freedom through dynamic adjustment of antenna positions, enabling distinct radiation patterns for each element. This facilitates more flexible beam power allocation via joint optimization of beamforming and antenna placement. Consequently, the system can adapt to dynamic environments by directing beam power to areas of highest need, thereby enhancing both flexibility and performance.
- Interference management: MA systems significantly enhance interference management by dynamically adjusting antenna positions to reconfigure the spatial signal geometry. Fixed antennas rely on digital beamforming to generate directional nulls for suppressing interference, but their effectiveness is constrained by factors such as the aperture size, the number of antenna elements, and the

accuracy of channel estimation. In contrast, MA systems can physically move antennas to locations with minimal spatial correlation to interfering sources. When integrated with beamforming techniques, this capability enables the formation of narrower and deeper nulls, leading to improved suppression of spatial interference.
- Spatial multiplexing gain: In conventional fixed-antenna systems, spatial multiplexing gain is typically achieved by exploiting multipath signals in scattering, reflective, or diffractive environments to enable simultaneous data transmission and improve system capacity. However, in environments with limited scattering, strong mutual coupling, or dominant line-of-sight (LoS) links, this gain is significantly reduced. In contrast, MA systems can dynamically search for and move to positions that capture the strongest and most independent signal paths. Even in weakly scattering environments, MAs can adjust their positions to identify better path combinations, thereby maintaining high multiplexing performance.

IV. Applications of MA in LAWNs

In LAWNs, as illustrated in Fig. 3, base stations or edge servers are required to perform formation control for a large number of UAVs, while simultaneously maintaining reliable communication with numerous ground and aerial users. Moreover, the system must be capable of detecting and identifying unauthorized targets within the low-altitude airspace in real time. The realization of these functionalities relies on complex signal processing, resource allocation, and environmental sensing mechanisms, which impose a significant energy consumption burden on the infrastructure. This presents a major challenge for the sustainable operation and performance assurance of LAWNs.

By integrating MA technology into LAWNs, it is possible to achieve performance that is comparable to or even superior to that of traditional fixed-antenna systems, while significantly reducing system energy consumption. Compared to fixed antennas, MAs provide spatial flexibility, enabling dynamic adjustment of their positions and orientations in response to varying channel conditions and operational requirements. This capability results in improved signal gain, effective interference suppression, and enhanced communication link stability. In this section, we present a systematic analysis of the application potential and technical advantages of MAs in LAWNs, focusing on three fundamental aspects: communications, sensing, and control.

A. Communication Perspective

Unlike conventional fixed-antenna systems, MA technology introduces a novel communication paradigm by enabling dynamic reconfiguration of the physical signal propagation environment. Through intelligent control of antenna position and orientation, MA systems can actively optimize signal transmission paths and significantly enhance channel quality. This capability enables MAs to effectively address several key challenges in LAWN, particularly in mitigating terrain-induced shadowing and performance degradation caused by the high mobility of UAVs.

In practical deployments, MA systems can be flexibly integrated into various platforms based on specific application scenarios. For instance, in urban environments characterized by dense obstructions, UAV-mounted MAs can be utilized to rapidly establish high-rate communication links. MAs deployed on ground-based robotic platforms are capable of providing real-time tracking and stable connectivity for low-altitude UAVs. Furthermore, base stations equipped with MA arrays that support both position and orientation adjustments can dynamically reconfigure their placements to achieve targeted coverage and performance improvements in designated areas.

B. Sensing Perspective

Traditional radar sensing systems typically rely on fixed antenna arrays, and consequently face inherent limitations such as coverage blind spots, uneven spatial resolution, and susceptibility to environmental noise interference. In contrast, radar systems enabled by MAs overcome these challenges by flexibly adjusting antenna positions to dynamically optimize the sensing geometry. Compared to static deployment approaches, this technology offers superior spatial adaptability, allowing the system to actively approach target areas, reduce detection distances, enhance SNR, and significantly improve target feature extraction capabilities.

In practical applications, MA-based radar systems demonstrate diverse deployment configurations. For example, radar modules mounted on UAVs can perform circumnavigation around targets to acquire multi-angle observations. Ground-based mobile platforms can collaboratively form dynamic radar arrays to enhance spatial resolution. Vehicular radars equipped with height-adjustable mechanisms can adapt to varying terrain conditions for continuous and stable monitoring.

C. Control Perspective

Traditional control systems typically rely on fixed base stations, which often encounter challenges such as high command transmission latency, reduced control accuracy, and unstable link conditions when applied to high-speed target control and complex electromagnetic interference environments. In contrast, MA-based control systems construct dynamic control networks through intelligent adjustment of antenna positions, significantly enhancing the reliability and real-time performance of command delivery.

These systems exhibit strong adaptability, enabling them to actively approach controlled entities in order to reduce signal propagation delay, and to optimize spatial deployment for interference avoidance, thereby ensuring stable and efficient control links. In practical deployments, MA systems can be flexibly configured according to specific application scenarios. For instance, MA arrays integrated into ground base stations can provide wide-area command coverage for UAV swarms operating over extended regions, while MAs

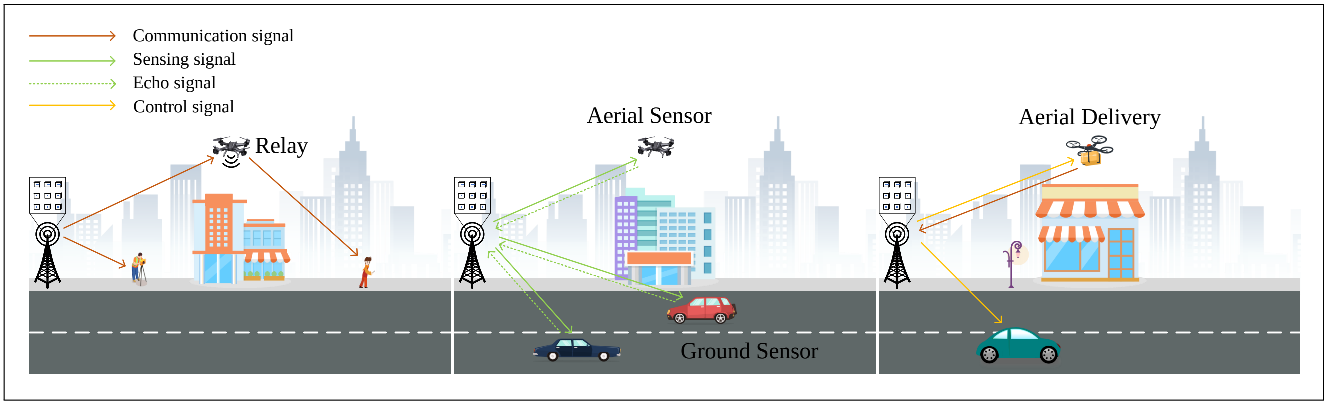

Fig. 3: The MA empowered LAWN for communication, sensing, and control.

mounted on mobile platforms can continuously track low-altitude unauthorized targets to maintain uninterrupted signal connectivity.

V. Case Study: MA-Enhanced LAWNs

In this section, we present a case study, which includes the system model, the proposed methodology, and the corresponding numerical results. In the numerical analysis, we examine the performance advantages of MAs over fixed antennas from the perspective of communication, sensing, and control.

A. System Model and Proposed Solution

Communication links, sensing links, and control links all play critical roles in LAWNs. To enhance the generality of the study, we consider the communication users, sensing targets, and controlled UAVs as distinct and independent entities. As illustrated in Fig. 4, the base station transmits communication signals to K users, sensing signals to M targets, and control commands to N controlled UAVs. The base station is equipped with T_x transmit MAs and is capable of two-dimensional mobility within an $A \times A$ area. The framework assumes that the CSI is perfectly known at the base station. Moreover, the channel models between the base station, users, and controlled UAVs follow a Rician distribution, which consists of both LoS and non-line-of-sight (NLoS) components.

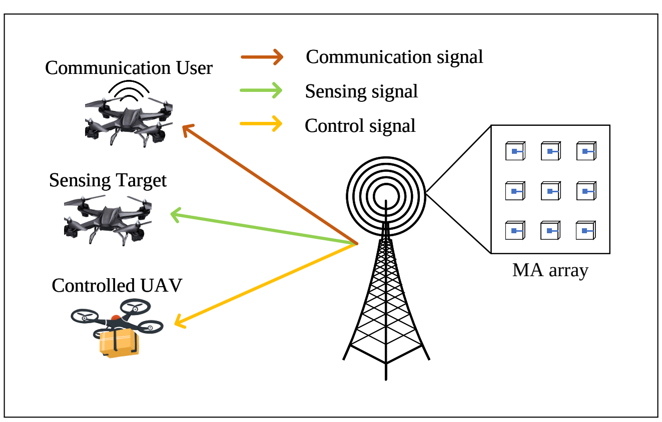

Fig. 4: System architecture of an MA-empowered LAWN.

The proposed framework aims to minimize the total transmit power by jointly optimizing the transmit beamforming and the positions of MAs within the transmit area, while satisfying constraints on users' communication rate thresholds, beam gain pattern specifications towards the targets, and the linear quadratic regulator (LQR) cost associated with the controlled UAVs. Due to the non-convex nature of the optimization problem and the presence of highly coupled high-dimensional vector variables, the problem becomes computationally challenging. To address this, we develop a particle swarm optimization (PSO)-based double-loop iterative algorithm to obtain a sub-optimal solution. Specifically, in the inner loop, given fixed MA positions, the transmit beamforming is optimized using a successive convex approximation (SCA)-based algorithm. In the outer loop, the MA positions within the transmit area are optimized through the PSO algorithm.

B. Numerical Results and Discussion

The numerical results of the proposed framework are obtained based on the average performance over 10 independent realizations. For comparative analysis, we also consider a conventional fixed-antenna system as the baseline framework to evaluate the performance gains achieved by the proposed MA-empowered LAWN. Unless otherwise stated, the simulation parameters are set as follows: the number of communication users is $K = 3$, the number of sensing targets is $M = 3$, and the number of controlled UAVs is $N = 2$. The base station is equipped with $T_x = 10$ transmit antennas. The MA area is set to $5\lambda \times 5\lambda$. The noise power at the receiver is -100 dBm, and the channel power gain at the reference distance of 1 m is -60 dBm. The communication rate threshold for each user is 1 bps/Hz, the beampattern gain threshold towards the target direction is -10 dBm, and the LQR cost threshold for the controlled UAVs is 10.58. The Rician factor is set to 31.3.

Fig. 5 (a) depicts the transmit power requirement versus the communication rate threshold (in bps/Hz). As the threshold increases from 0.8 to 1.6 bps/Hz, the transmit power of both systems rises. However, the fixed-antenna system exhibits a sharp increase in power consumption, exceeding 65 W at the highest threshold. In contrast, the MA system demonstrates a significantly lower and more gradually increasing power profile. This performance gain is attributed to the reconfigurable

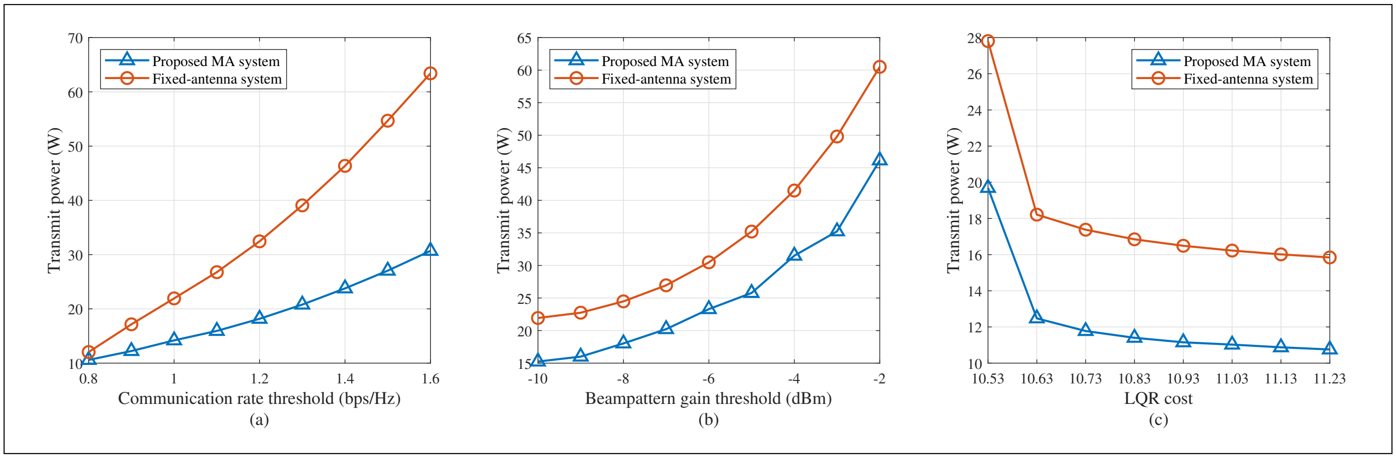

Fig. 5: (a) Transmit power versus the communication rate threshold; (b) Transmit power versus the beampattern gain threshold; (c) Transmit power versus the LQR cost threshold.

nature of the MA system, which can dynamically adjust the antenna position to enhance channel conditions, thereby reducing the required transmission power. These results validate the superior energy efficiency of the MA system in fulfilling high-rate communication demands.

Fig. 5 (b) presents the transmit power consumption versus the beampattern gain threshold (in dBm), which corresponds to a higher sensing performance requirement. As the threshold increases from -10 dBm to -2 dBm, both systems require higher transmit power due to the increased signal focusing requirements. Nevertheless, the MA system consistently consumes less power than the fixed-antenna counterpart across the entire range, particularly under stringent gain requirements (e.g., above -5 dBm). This indicates that the MA system maintains high sensing accuracy with reduced power expenditure, thereby demonstrating its effectiveness in supporting advanced sensing tasks with improved energy efficiency.

Fig. 5 (c) investigates the impact of the LQR cost threshold, a metric for control performance [14], on transmit power. As the LQR cost increases from 10.53 to 11.23, the MA system achieves a rapid decline in transmit power, eventually stabilizing below 11 W. In comparison, the fixed-antenna system experiences a relatively moderate reduction and maintains higher power levels throughout. These results suggest that the MA system can better accommodate closed-loop control requirements for controlled UAVs, while minimizing energy consumption through flexible beam management and adaptive channel optimization.

VI. Future Reaserch Directions

The integration of MA technology into LAWNs opens up several promising research opportunities that have the potential to significantly enhance network performance while reducing operational overhead. The following directions outline prospective areas for future research in this field.

A. MA-Assisted UAV Communication/Sensing

MAs can be deployed on UAVs and serve as a key component of LAWNs. In the presence of UAV-mounted MAs, designing an efficient MA-assisted UAV communication/sensing architecture is a valuable research direction. For instance, the joint optimization of MA positioning and beamforming can significantly enhance the communication coverage and achievable data rates of UAV systems. Furthermore, UAVs-mounted MAs can be flexibly positioned near base stations to act as relays for computation offloading from ground users, thereby improving edge computing capabilities and overall service quality.

B. MA-Assisted Reliable Control

In LAWNs, the transmission of control signals is critical to the safety and stable operation of unmanned systems. Compared to traditional data communication links, control links are more sensitive to packet loss probability and latency; even minor channel fluctuations can lead to significant performance degradation. Therefore, leveraging MA technology to dynamically adjust antenna positions and orientations enables real-time optimization of link quality, thereby enhancing the reliability of control channels and reducing end-to-end delay. In this scenario, the spatial deployment of MAs plays a crucial role in maintaining control stability. By jointly optimizing the MA placement and transmit beamforming, the robustness of the control link can be effectively improved while minimizing the probability of link outages.

C. MA-Enhanced Physical Layer Security

Physical layer security has emerged as a critical research direction in wireless communication security, aiming to ensure the confidentiality and integrity of information transmission by exploiting the physical characteristics of wireless channels. Its primary objective is to maximize the achievable data rate for legitimate users while minimizing the probability of information interception.

However, in complex and dynamic communication environments, fixed antenna arrays often struggle to adapt to time-varying channel conditions, thereby limiting their anti-eavesdropping capabilities. The introduction of MA technology offers a promising new approach to enhancing physical layer security [15]. By dynamically controlling the antenna's movement trajectory, MA systems can achieve time-varying beamforming, actively steering beams away from potential eavesdroppers and significantly reducing the risk of information leakage. Compared to conventional fixed antenna systems, MAs offer superior flexibility and environmental adaptability. They are capable of dynamically adjusting beam directions and coverage areas in response to changing channel conditions, thereby effectively improving the security and robustness of wireless communications.

VII. Conclusions

The integration of the MAs into the LAWNs represents a transformative advancement for next-generation aerial communication, sensing, and control co-design systems, establishing their potential to overcome the limitations of conventional fixed-antenna architectures. We first introduced the fundamental principles of the LAWNs and the MAs. Then, we investigated the advancements of the MA-empowered LAWNs. Through an in-depth case study, we demonstrated how MA-enhanced LAWNs can achieve significant improvements in communication, sensing, and control performance compared to traditional systems. Three key research directions emerge for future exploration: (1) MA-assisted UAV communication/sensing, (2) MA-based reliable control, and (3) MA-enhanced physical layer security. These future directions highlight the versatility of MA technology in addressing diverse challenges across the low-altitude domain. By bridging theoretical analysis with practical insights, this work provides a foundation for developing adaptive and intelligent wireless infrastructures tailored for the emerging 3D LAWNs. The MA paradigm represents a significant step toward realizing robust, efficient, and secure networks for future low-altitude applications.

References

[1] G. Cheng, X. Song, Z. Lyu, and J. Xu, "Networked ISAC for low-altitude economy: Coordinated transmit beamforming and UAV trajectory design," *IEEE Trans. Commun.*, to appear, 2025.

[2] M. Song, Y. Lin, J. Wang, G. Sun, C. Dong, N. Ma, D. Niyato, and P. Zhang, "Trustworthy intelligent networks for low-altitude economy," *IEEE Commun. Mag.*, to appear, 2025.

[3] D. He, W. Yuan, J. Wu, and R. Liu, "Ubiquitous UAV communication enabled low-altitude economy: Applications, techniques, and 3GPP's efforts," *IEEE Network*, to appear, 2025.

[4] Z. Kuang, W. Liu, C. Wang, Z. Jin, J. Ren, X. Zhang, and Y. Shen, "Movable-antenna array empowered ISAC systems for low-altitude economy," in *Proc. IEEE/CIC Int. Conf. Commun. China Workshops (ICCC Workshops)*, Hangzhou, China, Aug. 2024, pp. 776–781.

[5] W.-J. Lu, C.-X. He, Y. Zhu, K.-F. Tong, K.-K. Wong, H. Shin, and T. J. Cui, "Fluid antennas: Reshaping intrinsic properties for flexible radiation characteristics in intelligent wireless networks," *IEEE Commun. Mag.*, vol. 63, no. 5, pp. 40–45, May 2025.

[6] L. Zhu, W. Ma, and R. Zhang, "Movable Antennas for Wireless Communication: Opportunities and Challenges," *IEEE Commun. Mag.*, vol. 62, no. 6, pp. 114–120, Jun. 2024.

[7] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: The communication perspective," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2322–2358, 4th Quart. 2017.

[8] Y. Ping, T. Liang, H. Ding, and T. Zhang, "Communication and control co-design for distributed UAV formation," in *Proc. IEEE Glob. Commun. Conf. (GLOBECOM)*, Cape Town, South africa, Dec. 2024, pp. 5006–5011.

[9] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun. 2022.

[10] H. Chen, X.-m. Wang, and Y. Li, "A survey of autonomous control for uav," in *Proc. Int. Conf. Artif. Intell. Comput. Intell. (AICI)*, vol. 2, Shanghai, China, Nov. 2009, pp. 267–271.

[11] L. Zhu, W. Ma, B. Ning, and R. Zhang, "Movable-antenna enhanced multiuser communication via antenna position optimization," *IEEE Trans. Wireless Commun.*, vol. 23, no. 7, pp. 7214–7229, Jul. 2024.

[12] X. Shao and R. Zhang, "6DMA Enhanced Wireless Network with Flexible Antenna Position and Rotation: Opportunities and Challenges," *IEEE Wireless Commun.*, vol. 63, no. 4, pp. 121–128, Apr. 2025.

[13] B. Ning, S. Yang, Y. Wu, P. Wang, W. Mei, C. Yuen, and E. Bjornson, "Movable antenna-enhanced wireless communications: General architectures and implementation methods," *IEEE Wireless Commun.*, to appear, 2025.

[14] C. Lei, W. Feng, J. Wang, S. Jin, and N. Ge, "Control-oriented power allocation for integrated satellite-UAV networks," *IEEE Wireless Commun. Lett.*, vol. 12, no. 5, pp. 883–887, May 2023.

[15] Z. Cheng, C. Ouyang, and X. Zhang, "Movable antenna aided physical layer security with no eavesdropper CSI," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, Hyderabad, India, Apr. 2025, pp. 1–5.