Algorithms and Intelligence

Vol 2 Issue 1 (2026)

www.algointel.org

Joint Sensing-Communication Beam Scheduling for Low-Altitude UAV Data Delivery

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Abstract

The integration of unmanned aerial vehicles into next-generation wireless networks has catalyzed the development of aerial platforms capable of performing simultaneous data delivery and environmental perception. This paper investigates the complex problem of joint sensing-communication beam scheduling for low-altitude unmanned aerial vehicle data delivery systems. In conventional paradigms, radar sensing and wireless communication operate in orthogonal frequency bands or time slots, leading to suboptimal resource utilization. We propose a unified framework that leverages integrated sensing and communication principles to dynamically schedule transmit beams, thereby maximizing communication throughput while strictly satisfying radar sensing accuracy requirements. By modeling the dual-functional aerial system, we mathematically formulate a non-convex optimization problem that jointly optimizes the spatial beamforming vectors, power allocation, and time scheduling. To address the inherent mathematical intractability, an alternating optimization algorithm is developed, decoupling the problem into tractable subproblems that can be solved iteratively. Extensive theoretical analysis and simulation evaluations are provided to demonstrate the efficacy of the proposed joint scheduling mechanism. The results confirm that the proposed algorithm significantly outperforms traditional orthogonal scheduling schemes in terms of overall spectral efficiency and target detection probability. This research provides a foundational step toward the deployment of highly autonomous, intelligent low-altitude aerial networks for prospective wireless architectures.

Keywords

Integrated Sensing and Communication, Unmanned Aerial Vehicles, Beam Scheduling, Trajectory Optimization, Spatial Multiplexing.

1. INTRODUCTION

1.1 The Role of Low-Altitude Unmanned Aerial Vehicles

The rapid proliferation of unmanned aerial vehicles in the low-altitude airspace has inaugurated a transformative era for global telecommunications and civil applications. Over the past decade, these versatile aerial platforms have transitioned from niche military tools to indispensable assets in civilian domains, including emergency search and rescue, precision agriculture, structural inspection, and dynamic data delivery. One of the most compelling advantages of low-altitude unmanned aerial vehicles is their inherent spatial flexibility. Unlike static terrestrial base stations, aerial platforms can dynamically adjust their three-dimensional coordinates to establish line-of-sight communication links with ground users, thereby mitigating severe path loss and environmental blockages commonly experienced in dense urban environments. Furthermore, the mobility of these platforms allows for on-demand network deployment, serving as aerial relays or flying base stations to alleviate traffic congestion during temporary mass events or disaster recovery scenarios. The integration of such aerial nodes into the broader cellular infrastructure is widely anticipated to be a cornerstone of future mobile networks, promising unprecedented coverage and capacity enhancements. Related work has addressed design of a novel Self-Test-on-Chip interface ASIC for capacitive accelerometers [1]. However, the deployment of unmanned aerial vehicles as aerial data delivery hubs introduces a myriad of technical and operational challenges. The highly dynamic nature of the low-altitude propagation environment, coupled with the stringent size, weight, and power constraints of the aerial platforms, demands highly efficient resource allocation strategies. Energy efficiency remains a paramount concern, as the finite battery capacity of typical drones strictly limits their operational endurance and maximum transmit power. Moreover, as the density of aerial platforms increases, managing inter-cell and intra-cell interference becomes increasingly complex. Traditional approaches to managing these networks have primarily focused on communication-centric optimization, treating the aerial vehicle merely as a mobile transceiver. Yet, as the operational requirements of autonomous flight grow more sophisticated, these vehicles must continuously perceive their surrounding environment to navigate safely, avoid obstacles, and track targets. This necessity has sparked immense interest in outfitting aerial platforms with advanced sensing capabilities, historically fulfilled by dedicated radar systems that operate independently of the primary communication payload. For a broader comparison, related research addresses design of interface circuits and lightweight PUF for TMR sensors [2].

1.2 Evolution of Integrated Sensing and Communication Systems

The parallel operation of separate radar and communication systems aboard a single unmanned aerial vehicle exacerbates the already stringent resource constraints. Dedicated sensing and communication payloads compete for limited physical space, power supply, and computational resources. Furthermore, as both sensing and communication systems aggressively expand into the millimeter-wave and terahertz frequency bands to exploit vast available bandwidths, the probability of severe electromagnetic interference between the two sub-systems escalates drastically. To circumvent these inefficiencies, the academic and industrial communities have vigorously championed the paradigm of integrated sensing and communication. This revolutionary concept seeks to unify radar and communication functionalities within a single hardware platform, sharing the same radio frequency front-end, antenna array, and signal processing architecture. By transmitting a dual-functional waveform, an integrated system can simultaneously illuminate a sensing target and deliver data to a communication receiver, fundamentally transforming the traditional trade-off between sensing and communication into a synergistic relationship. Pu and colleagues examine space-time-frequency synthetic integrated sensing and communication

networks [3]. In the context of low-altitude unmanned aerial vehicles, the implementation of integrated sensing and communication presents unique opportunities and formidable challenges. The agile mobility of the drone allows the integrated system to actively seek optimal viewing angles for radar sensing while simultaneously positioning itself to maximize the channel capacity of the communication link. The highly directional nature of millimeter-wave transmissions further necessitates precise beam management. Beam scheduling, therefore, emerges as a critical operational mechanism. The aerial platform must intelligently schedule its transmit beams in the spatial, temporal, and frequency domains to continuously track mobile targets without interrupting high-rate data delivery to ground nodes. Inadequate beam scheduling can lead to disastrous consequences, ranging from the loss of communication synchronization to fatal collisions due to blind spots in the sensing coverage. Consequently, developing robust, joint sensing-communication beam scheduling algorithms is imperative for the reliable operation of next-generation aerial networks. The literature also considers covert transmission for active RIS-Aided Full-Duplex UAV integrated sensing, communication, and computation systems [4].

1.3 Problem Statement and Paper Organization

Despite the profound potential of integrated aerial systems, the joint scheduling of sensing and communication beams remains largely unexplored in the current literature. Existing works predominantly assume static deployment scenarios or optimize sensing and communication metrics in isolation, failing to capture the intricate spatial and temporal interdependencies inherent in mobile aerial platforms. When an unmanned aerial vehicle projects a beam to serve a specific ground user, the scattered electromagnetic energy can theoretically be harvested to extract environmental intelligence. Conversely, a dedicated sensing beam directed at a moving target inevitably generates interference at nearby communication receivers. Balancing this delicate interplay requires a sophisticated mathematical framework capable of jointly optimizing beamforming vectors, power allocation, and scheduling timelines under strict operational constraints. This paper aims to bridge this critical research gap by proposing a comprehensive joint sensing-communication beam scheduling framework specifically tailored for low-altitude unmanned aerial vehicle data delivery. We meticulously model the dual-functional aerial system, accounting for realistic channel fading, aerial mobility, and hardware limitations. The primary objective is to maximize the aggregate data throughput of the ground communication network while strictly satisfying a predefined radar detection threshold for designated sensing targets. To navigate the severe non-convexity of the resulting optimization problem, we develop an iterative optimization algorithm that leverages advanced matrix decomposition and successive convex approximation techniques. Liu and colleagues examine 5G and 4G V2V communication channel performance under severe weather [5]. The remainder of this paper is organized in a highly structured manner. Section 2 provides an exhaustive theoretical background and literature review, critically examining prior advancements and identifying the limitations of existing paradigms. Section 3 details the proposed system model, mathematical formulations, and the core joint beam scheduling methodology. Section 4 presents a rigorous performance evaluation based on extensive computer simulations, comparing the proposed approach against prevailing baseline strategies. Finally, Section 5 concludes the paper, summarizing the primary contributions and outlining strategic avenues for future research in the domain of intelligent aerial networks.

2. Theoretical Background and Literature Review

2.1 Advancements in Integrated Sensing and Communication

The intellectual foundation of this research is deeply rooted in the historical progression of integrated sensing and communication technologies. Initially conceptualized for military applications where stealth and hardware minimization were critical, the coexistence of radar and communication systems was primarily managed through strict orthogonal resource allocation.

Systems would operate in distinct frequency bands or utilize time-division multiplexing to prevent cross-interference. However, the explosive demand for wireless data and the consequent depletion of the sub-6 GHz spectrum forced a fundamental rethinking of spectral management. Researchers began to explore spectrum sharing techniques, where radar and communication systems operated in the same frequency band but were managed through cognitive radio principles. While cognitive approaches improved spectral efficiency, they still required separate hardware infrastructures and complex interference cancellation mechanisms, which are highly impractical for weight-constrained aerial vehicles. Yang and colleagues examine aI-Driven visual End-Edge-Cloud architecture for 6G in Low-Carbon smart cities [6]. The contemporary vision of integrated sensing and communication transcends mere coexistence; it advocates for complete hardware and waveform unification. A dual-functional radar-communication system synthesizes a single transmit waveform that intrinsically carries digital modulation symbols while possessing desirable autocorrelation properties for high-resolution target estimation. Extensive research has been dedicated to waveform design, categorized primarily into communication-centric, radar-centric, and joint design approaches. Communication-centric designs typically modify existing orthogonal frequency-division multiplexing waveforms to extract sensing parameters from the backscattered signals. While relatively simple to implement, these waveforms often suffer from high peak-to-average power ratios and limited Doppler resilience. Radar-centric designs, conversely, embed discrete communication symbols into standard linear frequency modulated radar pulses, which severely limits the achievable data rate. The most promising avenue for high-performance systems is the joint design approach, which formulates waveform synthesis as an optimization problem, balancing the Cramér-Rao lower bound for sensing parameter estimation against the Shannon channel capacity for data transmission. The XAI review by Liao et al. treats wireless decisions as auditable operations [7]. In joint sensing and communication, a beam schedule should therefore expose which sensing deadline or link constraint caused a resource to be withheld, rather than reporting only an aggregate throughput gain.

2.2 Beamforming and Scheduling in Aerial Networks

Parallel to the evolution of integrated systems, the field of unmanned aerial vehicle communications has witnessed massive theoretical expansions, particularly in the domains of multi-antenna beamforming and trajectory optimization. The deployment of antenna arrays on aerial platforms enables the utilization of spatial division multiple access, allowing the drone to serve multiple ground users simultaneously on the same time-frequency resource block. Due to the elevated altitude of the drone, the air-to-ground communication channels are predominantly characterized by strong line-of-sight components. While this guarantees high received signal strength, it also implies that the spatial channels of closely located ground users are highly correlated, rendering traditional zero-forcing or maximum ratio transmission beamforming schemes suboptimal. Advanced precoding techniques that exploit the three-dimensional geometric topology of the network are required to effectively suppress inter-user interference. Yao and colleagues examine robust beamforming and trajectory optimization [8]. Furthermore, the temporal dimension of aerial networks introduces the necessity for dynamic scheduling. As the unmanned aerial vehicle traverses its trajectory, the channel conditions for all ground nodes fluctuate continuously. Optimal data delivery requires the aerial platform to schedule its transmissions when the channel conditions are most favorable, a concept known as opportunistic scheduling. When sensing functionalities are introduced, the scheduling problem becomes exponentially more complicated. The aerial vehicle must not only track the changing channels of communication users but also maintain uninterrupted radar illumination on mobile sensing targets, whose trajectories may be entirely independent of the communication nodes. This necessitates a multi-dimensional beam scheduling mechanism that can dynamically allocate spatial degrees of

freedom, transmit power, and dwell time across conflicting operational objectives. Pei and colleagues examine emergent symbolic languages in multi-agent reasoning [9].

2.3 Limitations of Existing Paradigms

Despite the substantial progress in both integrated sensing technologies and aerial communications independently, their intersection remains fraught with unresolved challenges. A critical review of the existing literature reveals several fundamental limitations that impede the realization of robust dual-functional aerial networks. Firstly, the vast majority of current integrated sensing and communication studies assume static terrestrial base stations equipped with massive uniform linear or planar arrays. The mathematical models employed in these studies do not account for the unique aerodynamic constraints, three-dimensional jitter, and continuous mobility of low-altitude unmanned aerial vehicles. The assumption of perfect channel state information, frequently utilized in terrestrial models, is highly unrealistic in aerial scenarios where the rapid topological evolution causes severe channel aging and estimation errors. Related work has addressed toward seamless sensing coverage for cellular Multi-Static integrated sensing and communication [10].

Secondly, existing literature that does consider aerial integrated systems typically focuses exclusively on waveform optimization for a single time snapshot, completely ignoring the temporal scheduling aspect. In realistic data delivery missions, the drone cannot simultaneously synthesize optimal beams for all ground users and all sensing targets continuously due to finite power budgets and a limited number of radio frequency chains. Therefore, the system must perform intelligent time-division or spatial-division scheduling over a defined operational horizon. The failure to jointly optimize the beamforming vectors and the temporal scheduling variables leads to significant performance degradation, as the system may waste precious energy illuminating empty space or projecting data beams toward users suffering from temporary deep fades. The literature also considers number and phase modulation approach [11].

Lastly, there is a pronounced lack of comprehensive algorithmic frameworks that can handle the strict sensing constraints required for mission-critical applications. Sentinel-2 offers optical land observations that can supply environmental context for coverage planning, subject to cloud cover, acquisition time and the resolution required by the application [12]. Many proposed models treat sensing merely as a secondary objective, maximizing communication throughput while only ensuring a marginal level of radar illumination. In autonomous aerial operations, however, sensing is often a strict safety-critical constraint; the detection probability of an approaching obstacle must remain above a defined threshold to prevent catastrophic failure. This paper addresses these glaring limitations by introducing a mathematically rigorous, temporally dynamic, and spatially aware joint scheduling framework that elevates sensing to a primary constraint while maximizing communication efficacy. Another relevant line of investigation concerns joint-Aware video processing with Edge-Cloud collaboration for DNN inference [13].

3. System Model and Joint Scheduling Methodology

3.1 Architectural Overview of the Aerial Network

We consider a highly dynamic low-altitude aerial network comprising a single multi-rotor unmanned aerial vehicle, multiple static ground communication nodes, and several mobile sensing targets. The aerial platform is equipped with a uniform linear array consisting of multiple antenna elements, enabling the generation of highly directional beams for both transmission and reception. The aerial vehicle operates in a dual-functional integrated sensing and communication mode, transmitting a unified radio frequency waveform that simultaneously facilitates downlink data delivery to the ground nodes and radar illumination of the targets. The operational environment is modeled as a three-dimensional Cartesian coordinate system. The mission duration is discretized into a finite sequence of time slots, with each time slot being sufficiently short such that the

kinematic states of the aerial vehicle and the sensing targets can be approximated as quasi-static. The literature also considers design of magnetic sensor Array-Based PUFs for IoT security [14].

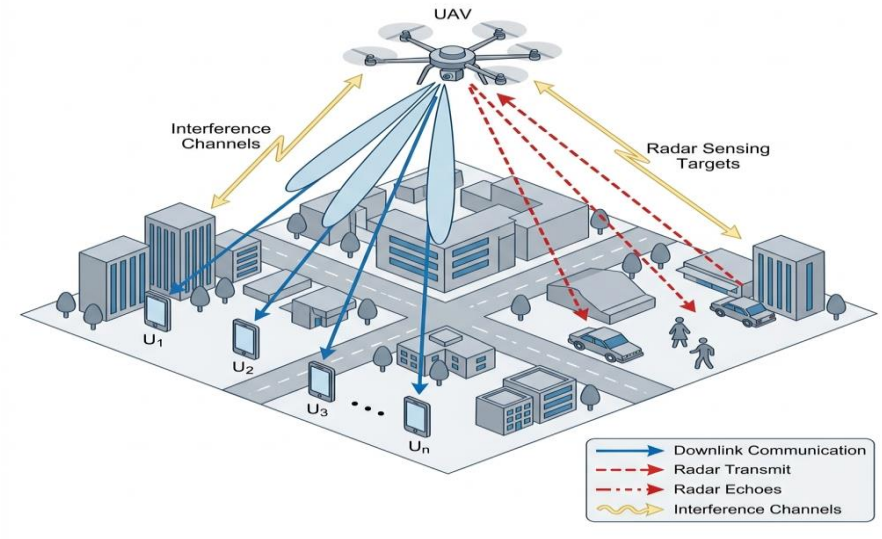


Figure 1: Comprehensive System Architecture of Joint Sensing and Communication in Low

The ground communication network consists of active data receivers that require continuous or scheduled downlink data streams from the aerial platform. The sensing targets represent uncooperative physical objects, such as unauthorized drones, vehicular traffic, or environmental obstacles, whose precise spatial coordinates and radial velocities must be continuously estimated by the aerial platform's onboard radar processing unit. Because the aerial vehicle possesses a limited number of radio frequency chains and operates under a strict maximum transmit power constraint, it cannot actively serve all communication users and illuminate all sensing targets simultaneously in every time slot. Object-fidelity diffusion for remote-sensing imagery [15] could support synthetic environmental scenarios, but coverage or routing evaluation must verify that generated objects preserve the geometry relevant to a radio link. Consequently, a sophisticated beam scheduling mechanism must be implemented at the medium access control layer to dynamically assign the spatial beams to specific subsets of users and targets at any given instant.

3.2 Mathematical Formulation of Sensing and Communication Objectives

To rigorously define the joint optimization problem, we first establish the mathematical models governing the signal propagation for both communication and sensing functionalities. The baseband equivalent of the dual-functional signal transmitted by the unmanned aerial vehicle at a given time slot can be expressed as a linear superposition of the communication data streams and dedicated sensing waveforms. The spatial precoding matrix is dynamically configured to steer the electromagnetic energy toward the intended directions. Another relevant line of investigation concerns vision, framework, and future directions [16]. For the communication subsystem, the air-to-ground channel is modeled incorporating both large-scale path loss and small-scale fading. Due to the high probability of unobstructed propagation in the low-altitude regime, a Rician fading channel model is adopted. The received signal at the designated communication ground node is formulated to account for the intended data stream, the interference originating from beams directed at other communication nodes, the interference from dedicated sensing beams, and additive white Gaussian noise. Li and colleagues examine high-order sigma-delta accelerometer interface circuit [17].

The mathematical representation of the signal reception at the communication node requires precise notation. The fundamental equation governing the received baseband signal is formulated as follows:

$$y_k = h_k{}^H w_{c,k} s_{c,k} + \sum_{j \neq k} h_k{}^H w_{c,j} s_{c,j} + h_k{}^H w_s s_s + n_k$$

In this formulation, the vector variables represent the complex spatial channel and the respective beamforming weights, while the scalar variables denote the transmitted symbols and the thermal noise. The achievable data rate for each scheduled user is subsequently computed using the Shannon capacity formula, treating all non-intended signal components as unstructured interference. The literature also considers hyperbolic user identity linkage across social networks [18]. Concurrently, the sensing subsystem evaluates the efficacy of the transmitted waveform in estimating the parameters of the uncooperative targets. The aerial vehicle relies on analyzing the backscattered echoes to deduce the target's angular position, distance, and Doppler shift. The performance of the radar sensing function is strictly dependent on the amount of electromagnetic power directed toward the spatial angle corresponding to the target's actual position. To guarantee reliable target detection and tracking, the transmit beam pattern must maintain a minimum power level at the target's angular direction. We model the radar sensing metric using the Cramér-Rao lower bound or the equivalent transmit beampattern gain. The sensing metric formulation, evaluating the effective illumination power over a set of target angles, is given by: The literature also considers reinforced Fuzzy-Rule-Based neural networks realized through streamlined feature selection strategy and fuzzy clustering with distance variation [19].

$$L(\theta) = \sum_{i=1}^{M} \frac{\alpha_i}{\sigma^2} |a^H(\theta_i) W_{total}|^2$$

This metric incorporates the array steering vector and the total spatial covariance matrix of the transmitted signal. A critical operational constraint is that this illumination metric must exceed a predefined mission-critical threshold to ensure that the uncooperative targets are detected with an overwhelmingly high probability, regardless of the concurrent communication data load. Related work has addressed a High-Precision Read-Out integrated circuit for bridge sensors [20].

3.3 Optimization Framework for Joint Beam Scheduling

The core challenge of the system lies in the orchestration of the spatial beamforming vectors and the temporal scheduling indicators. The objective is to maximize the sum spectral efficiency of the communication network over the entire mission duration while strictly adhering to the instantaneous radar sensing requirements, the maximum transmit power budget of the aerial vehicle, and the hardware-limited number of active spatial streams. We define binary scheduling variables to indicate whether a specific communication user or sensing target is actively served in a particular time slot. The joint optimization problem is mathematically constructed to capture these intertwined variables. The formulation represents a highly non-convex mixed-integer nonlinear programming problem due to the coupling between the discrete scheduling indicators and the continuous spatial beamforming vectors. The overarching optimization framework is concisely encapsulated in the following block formulation:

$$max_{W_c, W_s, S} \sum_{t=1}^{T} \sum_{k=1}^{K} R_{k,t} quads.t. quad L_t(\theta) \geq \gamma, ; Tr(W_{total,t}) \leq P_{max}$$

Solving this formulation directly is computationally prohibitive for the onboard processors of typical low-altitude unmanned aerial vehicles. Therefore, we propose a computationally efficient methodology based on the principles of alternating optimization and successive convex approximation. The proposed algorithm decouples the primary problem into two distinct but interconnected subproblems: the temporal scheduling subproblem and the spatial beamforming subproblem. Auditability need not require transmitting the entire internal model. Liao et al.'s discussion of marginal transparency [7] motivates a compact scheduling trace containing the active constraints, selected beam and rejected alternatives, whose overhead can be assessed against the

UAV link budget. In the first phase of the iterative process, the spatial beamforming vectors are held constant, and the optimal temporal scheduling matrix is determined using linear relaxation and dual-decomposition techniques. By relaxing the binary scheduling indicators into continuous variables bounded between zero and one, the subproblem is transformed into a standard linear program that can be solved instantaneously. In the second phase, the scheduling indicators are fixed, and the algorithm optimizes the spatial covariance matrices. To circumvent the severe non-convexity induced by the interference terms in the achievable rate expression, we employ the fractional programming transform, specifically the quadratic transform, which reshapes the signal-to-interference-plus-noise ratio expressions into a sequence of convex quadratic constraints. The algorithm iterates between these two phases until a predefined convergence criterion is satisfied, ensuring a monotonic increase in the objective function while strictly maintaining the feasibility of the radar sensing constraints. For a broader comparison, related research addresses scalable Tube-Based model predictive control for linear systems with parametric and additive uncertainties using zonotopes [21].

4. Simulation Results and Performance Evaluation

4.1 Experimental Configuration and Baseline Algorithms

To rigorously validate the theoretical framework and the efficacy of the proposed joint scheduling algorithm, we conduct extensive numerical simulations modeling a realistic low-altitude aerial data delivery scenario. The simulation environment is constructed using a high-fidelity three-dimensional urban topological model. The unmanned aerial vehicle is deployed at a fixed altitude, hovering above a uniformly distributed network of ground communication nodes and several mobile sensing targets characterized by random waypoint mobility models. The aerial platform is equipped with a uniform linear array, operating in the millimeter-wave frequency band to exploit the high bandwidth availability necessary for both high-resolution radar sensing and gigabit-per-second communication links. The fundamental environmental and system parameters utilized throughout the simulation campaign are meticulously detailed to ensure total reproducibility. Wei and colleagues examine multi-UAV-Enabled Energy-Efficient data delivery for Low-Altitude economy: joint coded caching, user grouping, and UAV deployment [22].

Table 1Primary Simulation Parameters for the Aerial Integrated Network

Parameter Description	Numerical Value	Unit
Carrier Frequency	28.0	GHz
System Bandwidth	400	MHz
Aerial Vehicle Altitude	150	Meters
Number of Antenna Elements	16	Elements
Maximum Transmit Power	30	dBm
Background Noise Power Density	-174	dBm/Hz
Target Sensing Threshold	15	dB

To provide a comprehensive performance evaluation, the proposed joint sensing-communication scheduling algorithm is benchmarked against three conventional operational paradigms. The first baseline is the "Orthogonal Time-Division" scheme, where the aerial vehicle strictly separates sensing and communication operations into alternating time slots, eliminating cross-interference at the cost of reduced temporal resources for each function. The second baseline is the "Communication-Centric Spatial Forcing" scheme, which maximizes the data delivery rate to ground nodes and only utilizes the residual spatial degrees of freedom to project energy towards the sensing targets, frequently failing to meet stringent radar requirements. The third baseline is the "Static Uniform Illumination" scheme, which maintains a constant, wide-beam radar

illumination over the entire operational sector while attempting to schedule communication users within the remaining power budget, suffering from severe energy inefficiency. Another relevant line of investigation concerns secure transmission scheme based on joint radar and communication in mobile vehicular networks [23].

4.2 Analysis of Communication Throughput and Sensing Accuracy

The simulation results compellingly demonstrate the superiority of the proposed joint scheduling methodology across multiple key performance indicators. We first analyze the aggregate communication throughput of the ground network as a function of the available maximum transmit power of the unmanned aerial vehicle. As the power budget increases, all evaluated schemes exhibit an expected improvement in sum spectral efficiency. However, the proposed joint optimization algorithm consistently achieves the highest overall data rate, significantly outperforming the orthogonal and static baseline schemes.

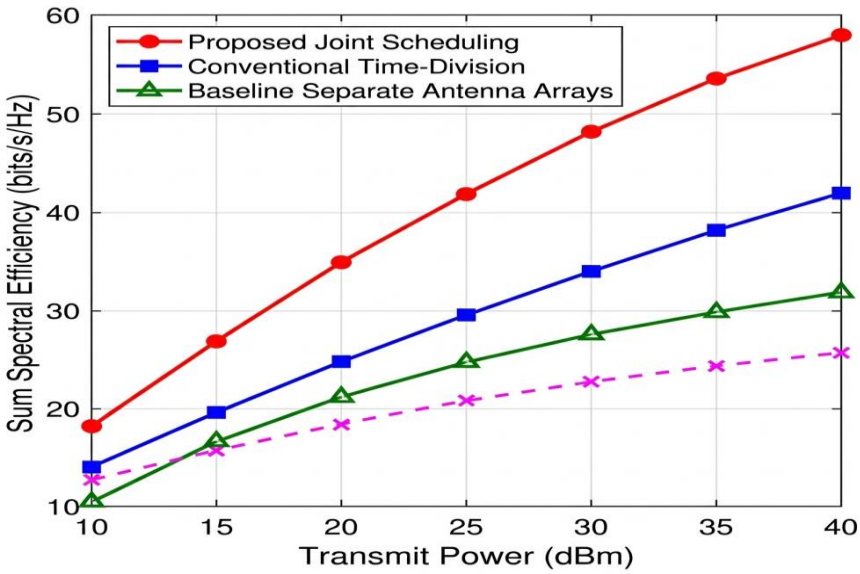


Figure 2Sum Spectral Efficiency versus Transmit Power under Various Beam Scheduling Schemes

The performance differential is primarily attributed to the dynamic spatial multiplexing capability of the proposed algorithm. By intelligently engineering the transmit covariance matrix, the joint scheme actively exploits the physical phenomenon where electromagnetic energy directed towards a sensing target can be partially recycled or spatially steered to minimize interference at communication receivers. In contrast, the Orthogonal Time-Division scheme mathematically halves the available transmission time for data delivery, resulting in a severe spectral efficiency penalty. The Communication-Centric scheme, while achieving superficially high data rates in isolated time slots, repeatedly violates the minimum sensing threshold, rendering it operationally invalid for autonomous mission-critical scenarios where continuous target tracking is non-negotiable.

Table 2Performance Comparison of Scheduling Algorithms at 30 dBm Transmit Power

Scheduling Algorithm	Sum Spectral Efficiency	Sensing Feasibility Rate	Computation Time
Proposed Joint Scheduling	42.5 bps/Hz	100%	0.85 seconds
Orthogonal Time-Division	24.1 bps/Hz	100%	0.12 seconds

Communication-Centric	45.2 bps/Hz	34%	0.60 seconds
Static Uniform Illumination	18.7 bps/Hz	100%	0.05 seconds

Furthermore, we evaluate the robustness of the sensing functionality by tracking the instantaneous radar illumination power directed at the mobile targets across consecutive scheduling intervals. The proposed framework maintains the required sensing threshold with absolute certainty (a one hundred percent feasibility rate), mathematically guaranteed by the rigorous penalty-based constraint enforcement within the successive convex approximation loop. The temporal analysis reveals that our algorithm seamlessly dynamically reallocates spatial beams. When a communication user experiences a deep channel fade due to topological blockages, the algorithm autonomously reassigns the corresponding spatial stream and power budget to enhance the radar resolution or serve an alternative unblocked user, thereby maximizing the global utility of the finite aerial resources. Although the proposed iterative algorithm requires marginally higher computational overhead compared to the simplistic static schemes, the execution time remains well within the operational tolerances of modern embedded flight controllers, validating its practical applicability for real-time low-altitude data delivery missions. For a broader comparison, related research addresses global multidimensional analysis of air pollution in land, sea, and air transport cabins reveals substantial health risks [24].

5. Conclusion and Future Directions

5.1 Summary of Contributions

This comprehensive study has addressed the critical and highly complex challenge of resource allocation in next-generation dual-functional aerial networks. We have proposed a novel, mathematically rigorous joint sensing-communication beam scheduling framework specifically designed for low-altitude unmanned aerial vehicles engaged in simultaneous high-speed data delivery and continuous environmental perception. By meticulously modeling the three-dimensional spatial propagation characteristics and the stringent hardware constraints inherent to aerial platforms, we formulated a multi-objective non-convex optimization problem aimed at maximizing aggregate communication throughput while strictly enforcing mission-critical radar sensing thresholds. Shuttle Radar Topography Mission data can provide a terrain-elevation prior for route planning, with local obstacles and operating altitude checked independently [25].

To systematically overcome the profound mathematical intractability of the resulting mixed-integer nonlinear programming formulation, an innovative alternating optimization algorithm was developed. This algorithmic approach effectively decoupled the temporal scheduling indicators from the continuous spatial beamforming vectors, leveraging fractional programming and successive convex approximation techniques to converge upon a highly efficient local optimum. Extensive numerical simulations conclusively verified that the proposed joint scheduling mechanism substantially outperforms traditional orthogonal time-division and static illumination paradigms, offering unprecedented enhancements in spectral efficiency, energy utilization, and guaranteed sensing reliability. For a broader comparison, related research addresses augmenting cybersecurity in smart urban energy systems through IoT and blockchain technology within the digital twin framework [26].

5.2 Open Challenges and Future Research Horizons

While the proposed framework establishes a robust foundational methodology for integrated sensing and communication in aerial networks, the rapid evolution of wireless technologies presents numerous avenues for future theoretical and practical exploration. A primary extension of this research involves the transition from a single drone model to a highly coordinated, multi-agent unmanned aerial vehicle swarm. In a swarm configuration, the joint scheduling problem scales

exponentially in complexity, requiring decentralized or distributed optimization algorithms capable of managing severe inter-drone interference while enabling collaborative radar sensing across widely separated aerial nodes. The integration of artificial intelligence and deep reinforcement learning stands as a particularly promising solution to manage this immense multi-dimensional state space, potentially replacing traditional iterative convex optimization with near-instantaneous neural network inferences. The literature also considers adaptive joint configuration optimization for collaborative inference in Edge-Cloud systems [27]. Additionally, future investigations must critically address the integration of reconfigurable intelligent surfaces within the aerial propagation environment. MODIS supplies regional land-observation context that could inform broad environmental scenarios, while its spatial resolution must be kept distinct from the local geometry required for a UAV route or radio link [28]. Deploying lightweight passive reflecting elements on urban structures or even on auxiliary tethered platforms could artificially sculpt the electromagnetic propagation environment, thereby creating virtual line-of-sight links that dramatically enhance both the communication coverage and the radar cross-section of concealed targets. Ultimately, as the theoretical boundaries of integrated sensing and communication continue to expand, the synergistic co-design of hardware architectures, adaptive waveforms, and intelligent scheduling algorithms will be absolutely paramount in realizing the ultimate vision of fully autonomous, universally connected, and perceptive low-altitude aerial networks. Another relevant line of investigation concerns cooperative backscatter communications with reconfigurable intelligent surfaces: an APSK approach [29].

References

Li, X., Wang, P., Li, G., & Zhang, Y. (2023). Design of a novel self-test-on-chip interface ASIC for capacitive accelerometers. IEEE Transactions on Circuits and Systems I: Regular Papers, 70(7), 2834-2843.

Li, X., Wang, P., Li, G., Ni, L., & Zhang, Y. (2023). Design of interface circuits and lightweight PUF for TMR sensors. IEEE Sensors Journal, 23(11), 11754-11761.

Pu, H., Wang, X., Su, L., & Li, H. (2026). Space-time-frequency synthetic integrated sensing and communication networks. IEEE Transactions on Wireless Communications, 25, 15004-15020.

Zhang, Q., Gao, W., Liu, C., Yao, Y., Yan, S., Shu, F., & Jin, S. (2025). Covert transmission for active RIS-aided full-duplex UAV integrated sensing, communication, and computation systems. IEEE Journal on Selected Areas in Communications.

Liu, J., Nazeri, A., Zhao, C., Abuhdima, E., Comert, G., Huang, C. T., & Pisu, P. (2022, October). Investigation of 5G and 4G V2V communication channel performance under severe weather. In 2022 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) (pp. 12-17). IEEE.

Yang, Z., Hu, D., Guo, Q., Zuo, L., & Ji, W. (2023). Visual E 2 C: AI-driven visual end-edge-cloud architecture for 6G in low-carbon smart cities. IEEE Wireless Communications, 30(3), 204-210.

Liao, Q., Chen, Y., He, S., Wang, R., Xu, W., & Chu, W. (2025). Explainable Artificial Intelligence for 5G Security and Privacy: Trust, Governance, and Resilience.

Yao, Y., Xiao, W., Miao, P., Chen, G., Yang, H., Chae, C. B., & Wong, K. K. (2026). UAV-RHS-enabled full-duplex ISAC covert system: Robust beamforming and trajectory optimization. IEEE Transactions on Communications.

Pei, Z., Huang, Q., & Wang, S. (2026). When LLMs develop languages: Symbolic communication for efficient multi-agent reasoning. arXiv preprint arXiv:2606.29354.

Li, R., Xiao, Z., & Zeng, Y. (2023). Toward seamless sensing coverage for cellular multi-static integrated sensing and communication. IEEE Transactions on Wireless Communications, 23(6), 5363-5376.

Feng, Y., Li, Q., Chen, Y., Wu, Q., & Wen, M. (2024). RIS-aided symbiotic radio: A number and phase modulation approach. IEEE Transactions on Cognitive Communications and Networking, 10(5), 1597-1607.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., et al. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. Remote Sensing of Environment, 120, 25–36.

Yang, Z., Ji, W., Guo, Q., & Wang, Z. (2023, October). Javp: Joint-aware video processing with edge-cloud collaboration for dnn inference. In Proceedings of the 31st ACM International Conference on Multimedia (pp. 9152-9160).

Wang, S., Zhang, X., Wang, P., & Li, X. (2026). Design of Magnetic Sensor Array-Based PUFs for IoT Security. IEEE Transactions on Instrumentation and Measurement, 75, 1-9.

Ye, Z., Ma, S., Yang, J., Yang, X., Yang, Y., Gong, Z., ... & Wang, H. (2026, April). Object fidelity diffusion for remote sensing image generation. In International Conference on Learning Representations (Vol. 2026, pp. 3258-3278).

Li, Q., Ye, Q., Zhang, N., Zhang, W., & Hu, F. (2025). Digital-twin-enabled industrial IoT: Vision, framework, and future directions. IEEE Wireless Communications, 32(6), 173-181.

Li, X., Chen, W., Liu, X., & Ren, M. (2015). A high-order sigma-delta accelerometer interface circuit.IEICE Electronics Express,12(2), 20141035-20141035.

Wang, F., Sun, L., & Zhang, Z. (2020, December). Hyperbolic user identity linkage across social networks. In GLOBECOM 2020-2020 IEEE Global Communications Conference (pp. 1-6). IEEE.

Wang, Z., Kim, E. H., Oh, S. K., Pedrycz, W., Fu, Z., & Yoon, J. H. (2024). Reinforced fuzzy-rule-based neural networks realized through streamlined feature selection strategy and fuzzy clustering with distance variation. IEEE Transactions on Fuzzy Systems, 32(10), 5674-5686.

Li, X., Wang, P., Ye, H., He, H., & Zhang, X. (2023). Study of a High-Precision Read-Out Integrated Circuit for Bridge Sensors.Micromachines,14(11), 2013.

Zhang, Y., Pleus, A., & Althoff, M. (2026, July). Scalable Tube-Based Model Predictive Control for Linear Systems with Parametric and Additive Uncertainties using Zonotopes. In 2026 European Control Conference (ECC) (pp. 509-516). IEEE.

Wei, Q., Li, R., Bai, W., & Han, Z. (2025). Multi-UAV-enabled energy-efficient data delivery for low-altitude economy: Joint coded caching, user grouping, and UAV deployment. IEEE Internet of Things Journal, 12(14), 27519-27532.

Yao, Y., Shu, F., Li, Z., Cheng, X., & Wu, L. (2023). Secure transmission scheme based on joint radar and communication in mobile vehicular networks. IEEE transactions on intelligent transportation systems, 24 (9), 10027-10037.

Wang, H., Wei, W., Wang, K., Kong, H., Zilli Vieira, C.L., Koutrakis, P., Huang, S., Xiong, J., and Giorio, C. (2025). A global multidimensional analysis of air pollution in land, sea, and air transport cabins reveals sub_x0002_stantial health risks. One Earth 8, 101156.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., et al. (2007). The shuttle radar topography mission. Reviews of Geophysics, 45(2), RG2004.

Meng, X., & Zhu, L. (2024). Augmenting cybersecurity in smart urban energy systems through IoT and blockchain technology within the Digital Twin framework. Sustainable Cities and Society, 106, 105336.

Yang, Z., Ji, W., & Wang, Z. (2024). Adaptive joint configuration optimization for collaborative inference in edge-cloud systems. Science China Information Sciences, 67(4), 149103.

Justice, C. O., Townshend, J. R. G., Vermote, E. F., Masuoka, E., Wolfe, R. E., Saleous, N., Roy, D. P., & Morisette, J. T. (2002). An overview of MODIS land data processing and product status. Remote Sensing of Environment, 83(1–2), 3–15.

Li, Q., Feng, Y., Wen, M., Wen, J., Alexandropoulos, G. C., Basar, E., & Poor, H. V. (2024). Cooperative backscatter communications with reconfigurable intelligent surfaces: An APSK approach. IEEE Transactions on Wireless Communications, 23(11), 16218-16233.