

The Convergence of UAV D2X Communication and Intelligent Networking

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Abstract—Drone-to-Everything (D2X) communication represents a paradigm shift in aerial connectivity, enabling UAVs to seamlessly exchange information with heterogeneous entities such as other UAVs, ground vehicles, infrastructure, cloud platforms, and edge servers. Unlike traditional UAV networking models, D2X integrates multiple communication paradigms — air-to-air, air-to-ground, and air-to-network — under a unified intelligent framework. With the rapid deployment of UAVs for logistics, surveillance, emergency management, and urban mobility, reliable D2X communication has become a critical enabler of safety, efficiency, and autonomy. This paper systematically analyzes the architecture, enabling technologies, application scenarios, and development challenges of UAV D2X systems. We propose a four-layer architecture encompassing infrastructure, networking, intelligence, and application layers, detail key enabling technologies such as 5G/6G URLLC, millimeter-wave and terahertz links, non-terrestrial networks (NTN), reconfigurable intelligent surfaces (RIS), and AI-native control, and explore advanced applications in logistics, intelligent transportation, and emergency response. Furthermore, we identify critical challenges in safety, regulations, spectrum allocation, and cybersecurity, and suggest strategies to overcome them. Comparative analysis with the United States, EU, Singapore, and other leading regions highlights best practices. Finally, we outline future research directions including quantum-safe D2X, satellite-terrestrial integrated networking, and digital twin-based airspace management.

Keywords—Drone-to-Everything (D2X), UAV communication, multi-agent collaboration, intelligent networking, low-altitude economy

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have evolved from niche applications such as aerial photography to mission-critical platforms supporting logistics, intelligent transportation, environmental monitoring, and emergency response. As the density of UAV operations in low-altitude airspace (below 1,000 meters, extendable to 3,000 meters) increases, the need for reliable, ultra-low-latency, and high-capacity communication becomes paramount. Traditional UAV networking models based solely on UAV-to-ground (U2G) or UAV-to-UAV (U2U) links cannot fully satisfy the requirements of large-scale, heterogeneous, and highly dynamic UAV ecosystems [1] – [3].

A. From V2X to D2X: Conceptual Evolution

The Drone-to-Everything (D2X) paradigm is inspired by the success of Vehicle-to-Everything (V2X) communication in ground intelligent transportation systems. While V2X primarily connects vehicles with infrastructure (V2I), networks (V2N), and other vehicles (V2V), D2X extends these links into three-dimensional space, integrating:

UAV-to-UAV (U2U): For collaborative sensing, formation flight, and swarm coordination.

UAV-to-Infrastructure (U2I): For real-time navigation and air traffic management.

UAV-to-Vehicle (U2V): For aerial-ground data relay in intelligent transportation.

UAV-to-Network/Cloud (U2N/U2C): For edge-cloud computing and AI-driven decision-making.

This holistic approach enables continuous connectivity, context-aware decision-making, and coordinated mission execution [4], [5].

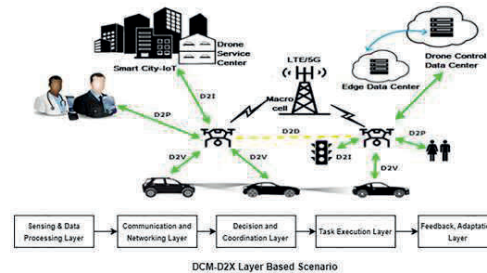


Fig. 1. Decentralized Cooperative Multi-Layer Drone to Everything [6]

B. Market Growth and Strategic Importance

The global UAV market is expected to grow from \$30 billion in 2023 to over \$90 billion by 2030, with D2X communication serving as its backbone [7]. In China, national strategies for developing the low-altitude economy project a market size of 2 trillion yuan by 2030, where UAVs will drive logistics, emergency response, and industrial monitoring [8]. The Asia-Pacific region, led by China, Japan, and South Korea, is expected to dominate due to dense urbanization and proactive regulatory reforms [9].

C. Technical Motivation for D2X

Current UAV communication relies heavily on direct radio links or cellular 4G/5G networks, which face limitations:

Coverage Gaps: Terrestrial base stations are optimized for ground users, not aerial nodes.

High Mobility: UAVs experience fast-changing link quality, requiring intelligent handover.

Spectrum Congestion: UAVs share bands with terrestrial devices, causing interference.

Limited Intelligence: Legacy networks lack context-aware decision-making for swarms.

TABLE I. LIMITATIONS OF EXISTING UAV COMMUNICATION MODELS

Model	Advantages	Limitations
U2G (direct to ground)	Simple deployment	Limited by base station height, urban shadowing
U2U (ad-hoc UAV links)	Flexible topology	Short range, no global coordination
Cellular UAV (4G/5G)	Wide coverage	Not optimized for aerial mobility, spectrum contention
Satellite links	Global coverage	High latency, expensive bandwidth

D2X addresses these issues by integrating heterogeneous links (air-to-air, air-to-ground, satellite, and edge-cloud), applying AI for decision-making, and building a unified communication-control architecture [10], [11].

D. Objectives and Paper Contributions

This paper provides a comprehensive review of UAV D2X communication systems. The major contributions are:

Propose a four-layer D2X architecture (infrastructure, networking, intelligence, and application).

Analyze enabling technologies, including 5G/6G, non-terrestrial networks (NTN), reconfigurable intelligent surfaces (RIS), semantic knowledge sharing, and digital twins.

Explore practical application scenarios, such as UAV logistics, cooperative transportation, and emergency rescue, with data-supported case studies.

Identify key challenges—including safety, regulations, spectrum allocation, and cybersecurity—and provide development countermeasures.

Compare international practices from the United States, EU, Singapore, Japan, and South Korea, offering strategic insights for global deployment.

II. TECHNICAL ARCHITECTURE OF UAV D2X

The UAV Drone-to-Everything (D2X) communication framework must integrate air-to-air (A2A), air-to-ground (A2G), air-to-network (A2N), and air-to-infrastructure (A2I) links in a multi-layered, AI-driven architecture to achieve seamless connectivity, ultra-reliability, and autonomous decision-making.

This section proposes a four-layer D2X architecture consisting of Infrastructure Layer, Networking Layer, Intelligence Layer, and Application Layer, each providing different capabilities but operating cohesively.

A. Infrastructure Layer: Physical and Spectrum Resources

The foundation of D2X communication is built on physical assets, radio spectrum, and positioning infrastructure. This layer includes:

Communication infrastructure: 5G-Advanced base stations, low-altitude UAV nodes, and LEO satellite gateways.

Navigation systems: BeiDou, GPS, and Galileo for high-precision positioning (with error ≤ 10 cm using RTK).

Energy supply: UAV charging pads, battery-swapping stations, and wireless power transfer (WPT) nodes to extend mission endurance.

Airspace infrastructure: Vertiports and UAV traffic corridors for take-off/landing.

TABLE II. INFRASTRUCTURE COMPONENTS FOR UAV D2X

Component	Function	Representative Technology
Spectrum resources	Provide URLLC/mMTC channels	Licensed C-band, mmWave, THz
Base stations	Air-ground connectivity	5G-A/6G gNodeB
Satellite nodes	Beyond-line-of-sight control	LEO (Starlink, OneWeb)
Navigation	Positioning and timing	GNSS + RTK/PPP
Energy systems	Extend flight endurance	WPT, solar UAV, battery swap

B. Networking Layer: Connectivity and Routing

The networking layer ensures continuous link quality and robust information exchange between UAVs, ground vehicles, and cloud platforms.

Key design features include:

Hybrid link integration: Seamless switching between A2A, A2G, and satellite links to guarantee coverage in dense urban or remote areas.

Reconfigurable Intelligent Surfaces (RIS): Dynamically manipulate radio propagation to overcome shadowing in urban canyons [12].

Software-Defined Networking (SDN) and Network Function Virtualization (NFV): Enable programmable UAV networks that adapt topology and resource allocation in real time.

Edge-assisted routing: UAVs act as mobile base stations or relays to enhance local coverage during high traffic demand.

C. Intelligence Layer: AI-Driven Control and Knowledge Sharing

The intelligence layer upgrades D2X communication from mere data exchange to context-aware, cooperative decision-making:

Knowledge graphs: UAVs locally generate semantic maps from multi-sensor data, compressed and shared with peers to reduce bandwidth [13].

Federated learning: UAV swarms jointly train navigation and control models without raw data aggregation, improving privacy and scalability [14].

Multi-agent reinforcement learning (MARL): Allows UAVs to dynamically adjust flight paths, allocate tasks, and avoid collisions in real-time [15].

AI-native networking: Deep neural networks optimize handover decisions, interference mitigation, and spectrum management in unpredictable conditions.

D. Application Layer: Mission-Oriented Services

The application layer translates D2X network intelligence into mission-level operations, including:

Logistics and parcel delivery: Reliable A2G/A2N communication for urban last-mile delivery.

Intelligent transportation integration: UAVs act as aerial relays for connected vehicles (U2V).

Public safety and emergency response: Real-time high-definition video streaming to command centers.

Urban inspection and governance: UAVs equipped with multispectral sensors monitor traffic, pollution, and infrastructure health.

Digital twin management: UAV data feeds virtual airspace replicas for predictive conflict resolution.

E. Integrated Architecture Overview

The four layers interact to create a closed-loop system:

Infrastructure supplies communication, positioning, and power.

Networking ensures robust data exchange among UAVs, ground stations, and cloud nodes.

Intelligence converts raw data into actionable decisions using AI.

Applications deploy these capabilities for real-world missions.

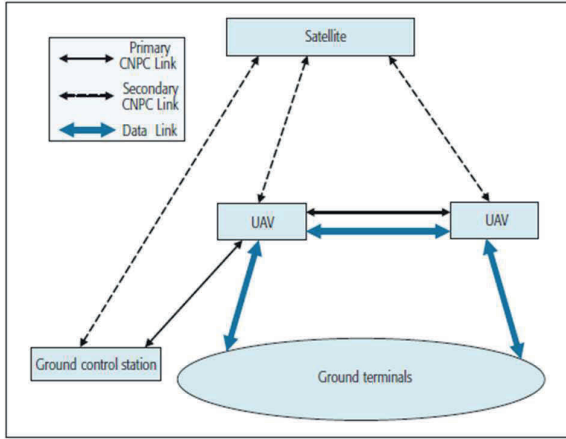


Fig. 2. Basic networking architecture of UAV-aided wireless communications. [16]

III. ENABLING TECHNOLOGIES

The performance of UAV Drone-to-Everything (D2X) communication depends on a set of emerging technologies that jointly provide ultra-reliable low-latency communications (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) capabilities. These technologies include advanced wireless systems, intelligent

networking paradigms, and cyber-physical integration platforms.

This section analyzes five categories of key technologies: (A) 5G/6G and beyond, (B) Non-Terrestrial Networks (NTN), (C) Reconfigurable Intelligent Surfaces (RIS), (D) AI-native control and collaborative learning, and (E) Digital twin and edge-cloud convergence.

A. 5G/6G and Beyond: Ultra-Reliable Low-Latency Links

5G-Advanced (5G-A) provides 1 ms latency, Gbps throughput, and network slicing, enabling dedicated UAV communication channels. 6G further extends these capabilities with sub-millisecond latency, Tbps data rates, and native AI control loops [17].

Key enablers include:

Terahertz (THz) bands: Provide ultra-high bandwidth but require line-of-sight (LOS) links and adaptive beamforming.

Massive MIMO: Improves link reliability through spatial diversity.

Network slicing: Allocates exclusive UAV communication resources to avoid interference with terrestrial devices.

TABLE III. COMPARISON OF 4G/5G/6G FOR UAV COMMUNICATION

Feature	4G LTE	5G-A	6G
Latency	~30 - 50 ms	~1 ms	<0.1 ms
Data rate	<100 Mbps	~1 - 10 Gbps	>1 Tbps
Mobility support	Limited	High-speed handover	AI-native dynamic handover
AI integration	None	External	Native AI-driven
Latency	~30 - 50 ms	~1 ms	<0.1 ms

B. Non-Terrestrial Networks (NTN): Ubiquitous Coverage

NTN architectures integrate LEO satellites, stratospheric platforms (HAPS), and terrestrial 5G/6G networks, providing beyond-line-of-sight (BLOS) connectivity [18]. This is critical for UAV missions in rural, maritime, or disaster-stricken areas.

Key technologies include:

Dynamic beam steering: Maintains stable air-to-satellite links for high-mobility UAVs.

Hybrid satellite-cellular handover: Seamlessly switches between ground stations and satellite gateways.

Delay-tolerant networking (DTN): Handles intermittent connectivity in sparse environments.

TABLE IV. TERRESTRIAL VS. NON-TERRESTRIAL UAV LINKS

Metric	Terrestrial (5G/6G)	Non-Terrestrial (LEO/HAPS)
Coverage	Limited to BS range	Global
Latency	Low (<10 ms)	Medium (20 - 50 ms)
Cost	Lower	Higher
Use case	Urban swarm control	Remote area BLOS missions
Latency	~30 - 50 ms	~1 ms

C. Reconfigurable Intelligent Surfaces (RIS): Propagation Control

RIS consists of programmable meta-surfaces that dynamically alter the wireless propagation environment by reflecting, refracting, or focusing radio waves. This enables UAVs to maintain high-quality links in:

Dense urban canyons with severe multipath fading.

Non-line-of-sight (NLOS) conditions where conventional links fail.

Advantages:

Low energy consumption: RIS is nearly passive.

Cost-effective coverage improvement: No need for dense base station deployment.

Adaptive beamforming: Redirects UAV signals in real time.

D. AI-Native Control and Collaborative Learning

AI-native networks integrate machine learning at the network core, enabling UAV swarms to self-organize, self-optimize, and self-heal.

Key methods:

Multi-Agent Reinforcement Learning (MRL): UAVs learn cooperative policies to allocate spectrum, plan routes, and avoid collisions.

Federated Learning (FL): UAVs train shared models without centralizing sensitive data, improving privacy and scalability.

Semantic communication: Instead of sending raw data, UAVs transmit task-relevant semantic information, reducing bandwidth consumption.

E. Digital Twin and Edge-Cloud Convergence

A digital twin is a real-time virtual representation of UAV networks and airspace. It enables:

Predictive air traffic management (ATM): Simulates UAV trajectories to prevent conflicts.

Real-time UAV health monitoring: Tracks battery status, sensor faults, and communication reliability.

Mission rehearsal and optimization: UAV swarms test flight plans virtually before execution.

Edge-cloud collaboration ensures low-latency AI processing at the edge while maintaining global situational awareness in the cloud.

IV. APPLICATION SCENARIOS

The integration of AI and the low-altitude economy has demonstrated significant potential across a wide range of fields. The following sections expand on both existing and emerging application scenarios, illustrating how AI-driven unmanned systems are transforming industries and public services.

A. Logistics and Distribution

Drone logistics represent one of the most mature applications of the low-altitude economy [19]. Companies like

JD.com and SF Express have pioneered the use of drones for parcel delivery, especially in remote and geographically challenging regions such as the Qinghai-Tibet Plateau. These systems leverage AI for route optimization, obstacle avoidance, and autonomous landing. In urban settings, however, drone logistics face complex challenges including regulatory restrictions, public acceptance, and safety management. AI helps mitigate these risks through real-time monitoring, predictive maintenance, and dynamic no-fly zone updates. Future developments may include hub-and-spoke drone networks integrated with ground logistics, enabling fully automated last-mile delivery.

B. Urban Governance

Drones are increasingly deployed as intelligent tools in urban management. In addition to traffic monitoring — exemplified by Songshan Lake's AI "aerial police" that reduce accident response time to 90 seconds—drones are used for infrastructure inspection, pollution monitoring, and public security [19]. AI-powered image recognition allows automatic detection of illegal construction, garbage accumulation, and sewerage leaks. Some cities are experimenting with persistent drone surveillance networks that provide real-time urban operation dashboards, facilitating data-driven decision-making for city administrators.

C. Emergency Rescue

In disaster response, drones equipped with thermal imaging, gas sensors, and communication relays can access hazardous areas beyond human reach. During earthquakes, floods, or wildfires, drone swarms can perform rapid area scanning, identify survivors, and deliver emergency supplies [20]. AI enhances these capabilities through collaborative search algorithms, real-time data fusion, and adaptive mission re-planning. For instance, in the western Sichuan earthquake, tethered drones provided continuous communication coverage, significantly improving rescue coordination.

D. Cultural Tourism and Education

Drones are opening new avenues in experiential education and cultural promotion. Schools and universities are incorporating drone technology into STEM curricula, allowing students to learn about robotics, aerodynamics, and coding through hands-on activities. In tourism, drones offer immersive experiences such as aerial virtual tours, light shows, and interactive heritage site reconstructions. AI-generated content and real-time video analytics further enrich these applications, creating personalized and engaging user experiences.

E. Agricultural and Environmental Applications

Beyond the scenarios discussed above, AI-enhanced drones are widely used in precision agriculture. They enable crop health monitoring, automated pesticide spraying, and soil analysis, greatly improving yield and reducing resource waste [21]. In environmental protection, drones monitor wildlife, track deforestation, and detect illegal fishing or mining activities. AI algorithms process multispectral and hyperspectral imagery to provide actionable insights for sustainable management.

F. Industrial Inspection and Maintenance

Drones are reducing costs and risks in industries such as energy, transportation, and telecommunications. They inspect power lines, wind turbines, bridges, and pipelines with high-

resolution cameras and LiDAR. AI supports defect recognition, predictive maintenance, and automated reporting. This not only improves safety by reducing the need for human inspectors in dangerous environments but also increases the frequency and accuracy of inspections [22].

G. Healthcare and Medical Delivery

In the medical field, drones deliver blood, vaccines, and medicines to remote clinics or disaster zones. Companies like Zipline have demonstrated how AI-planned routes and autonomous navigation can save lives in regions with poor road infrastructure. Future systems may include integrated cold-chain management and emergency response coordination, making healthcare more accessible and efficient.

V. CONCLUSION AND FUTURE PERSPECTIVES

This paper has provided a comprehensive analysis of the convergence of artificial intelligence and the low-altitude economy, highlighting its technical architecture, key enabling technologies, and diverse application scenarios. As a strategically emerging industry, the low-altitude economy is transitioning from localized pilots to large-scale, systematic deployment, with AI serving as a core driver for intelligent and autonomous operations.

The proposed four-layer framework — perception, cognition, decision-making, and execution — offers a structured approach to understanding how AI integrates with and enhances low-altitude systems. Multi-agent collaboration, supported by knowledge graphs, semantic compression, and distributed decision-making, significantly improves the efficiency, robustness, and scalability of drone operations. Practical applications in logistics, urban governance, emergency response, cultural tourism, agriculture, healthcare, and industrial inspections already demonstrate tangible social and economic benefits.

However, the development of the low-altitude economy still faces several challenges, including safety management, regulatory alignment, technical bottlenecks, and talent shortages. Addressing these will require coordinated efforts among governments, enterprises, academic institutions, and international bodies. Policy innovation, R&D investment, standardization, and industry-education integration are all critical to building a safe, open, and sustainable low-altitude ecosystem.

Looking ahead, we anticipate that emerging technologies such as digital twins, blockchain, and next-generation communication (e.g., 6G) will further integrate with the low-altitude economy, enabling more sophisticated applications such as urban air mobility (UAM), large-scale autonomous swarms, and real-time airspace digitalization. International

cooperation will be essential to establish unified standards and foster global market growth.

In conclusion, the deep integration of AI and the low-altitude economy is not only inevitable but also imperative for building a smart, efficient, and resilient society. With continued innovation and collaboration, the low-altitude economy will become a cornerstone of future economic development and social transformation.

REFERENCES

- [1] Y. Shi et al., "AI technologies in UAV applications," *IEEE Access*, 2023.
- [2] L. Fu et al., "UAV industry analysis," *Aerospace Science*, 2021.
- [3] J. Euchi, "Drones for smart cities: A survey," *Sustainable Cities and Society*, 2021.
- [4] ICAO, "UTM Framework 2023," [Online]. Available: <https://www.icao.int/>
- [5] P. Zhou, "Communication challenges in UAV swarms," *IEEE Trans. Wireless Commun.*, 2023.
- [6] A. Dixit and S. K. Singh, "DCM-D2X: An Effective Communication Mobility Model for Decentralized Cooperative Multi-Layer Drone to Everything," *IEEE Access*, vol. 12, pp. 37326-37348, 2024.
- [7] M. Radovic, "Deep vision in UAVs," *IEEE Trans. Aerospace*, 2023.
- [8] R. Singh, "Computer vision applications in UAVs," *Pattern Recognition Letters*, 2023.
- [9] J. Li, "Edge computing for drone networks," *IEEE Trans. Mobile Computing*, 2022.
- [10] W. Dong, "RL for UAV coordination," *Autonomous Agents*, 2022.
- [11] L. Chen, "Reinforcement learning for autonomous UAVs," *IEEE Access*, 2023.
- [12] A. Kumar, "Federated learning in UAV networks," *IEEE Communications Surveys*, 2022.
- [13] K. Zhang, "Edge-cloud collaboration for UAVs," *IEEE IoT Journal*, 2023.
- [14] S. Gupta, "Digital twins for urban airspace," *IEEE Access*, 2023.
- [15] X. Yang, "Digital twin for air mobility," *Automation in Construction*, 2023.
- [16] Y. Zeng, R. Zhang and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 36-42, May 2016.
- [17] M. Brown, "Certification challenges for AI systems," *IEEE Trans. Systems*, 2023.
- [18] FAA, "Part 107 - Small Unmanned Aircraft Systems," *Federal Aviation Administration*, 2022.
- [19] T. Williams, "Regulatory Sandboxes for Advanced Air Mobility," *J. Air Transport Management*, 2023.
- [20] SESAR JU, "U-space Architecture and Services Definition," *SESAR Report*, 2023.
- [21] L. H. Tan, "Privacy and Security Framework for Urban UAVs," *Computers & Security*, 2023.
- [22] A. Wong, "Droneports and Urban Infrastructure," *Sustainable Cities and Society*, 2023.