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Low-altitude UAV swarm ISAC: new opportunities and challenges

Key words: Unmanned aerial vehicle (UAV) swarm; Integrated sensing and communication (ISAC); Sparse extremely-large multiple-input multiple-output (XL-MIMO); Reconfigurable antenna arrays; Sparse time–frequency resource allocation; Channel knowledge maps (CKMs)

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Research status and challenges

- UAVs will evolve into swarms in 6G networks; thus, ISAC for low-altitude UAV swarms will face challenges, stemming from their low–slow–small target characteristics, high density, large quantity, complex low-altitude environments, and high swarm coordination requirements.

Table 1 Comparison of existing magazine/survey papers on UAV ISAC

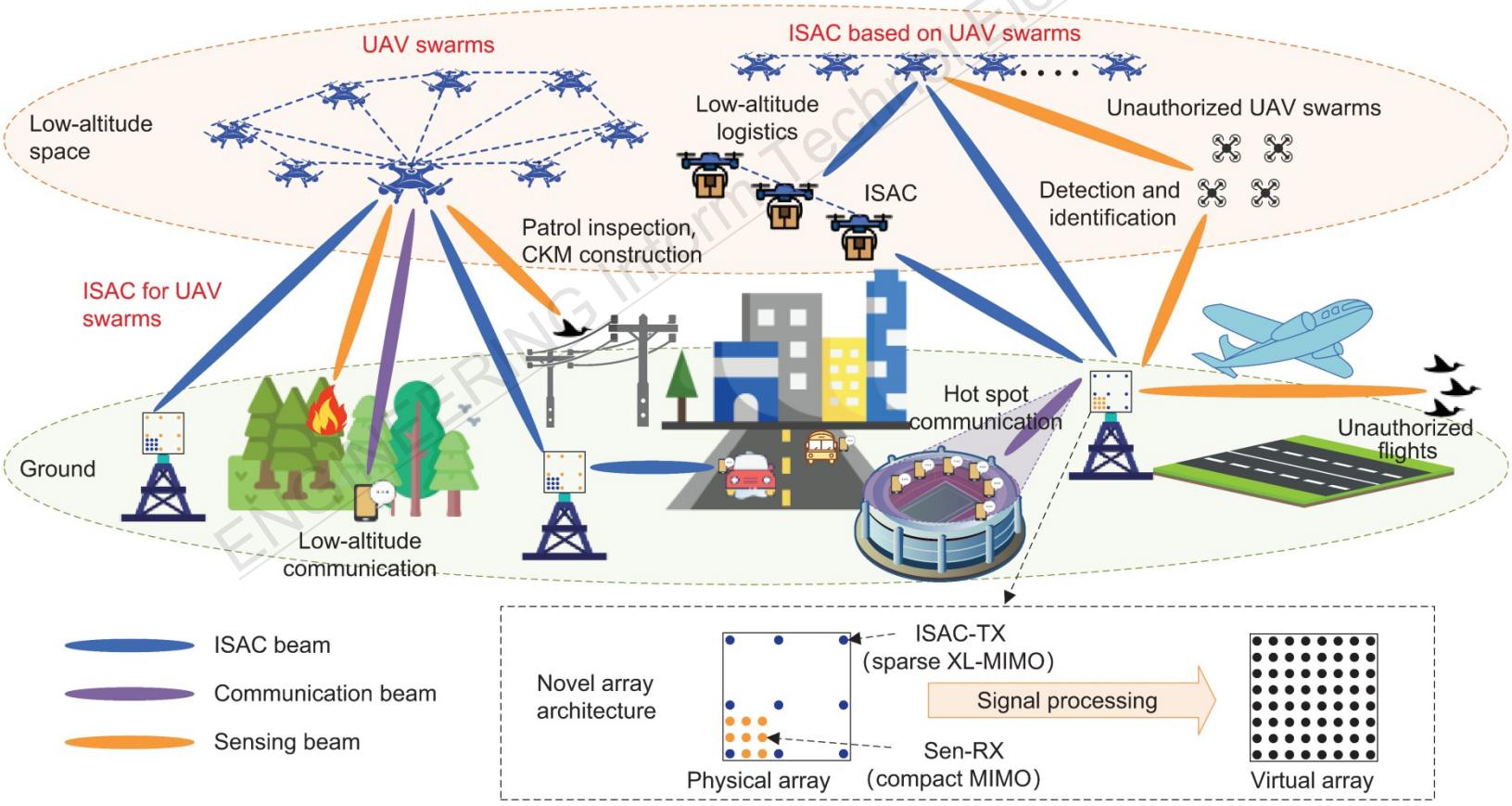
Reference	System model			Communication and sensing enhancement				
	UAV swarm	ISAC for UAVs	ISAC based on UAVs	Array architecture	Time–frequency resource allocation	Prior information	NLoS	Cooperative
Cui YP et al. (2023)	×	✓	✓	×	×	×	×	✓
Fei et al. (2023)	×	×	✓	×	×	×	×	✓
Mu et al. (2023)	✓	✓	✓	×	×	×	×	✓
Meng et al. (2024)	×	×	✓	✓	✓	×	✓	✓
Zhang YB et al. (2024)	✓	×	✓	×	×	✓	×	✓
Xu JL et al. (2024)	×	×	✓	×	×	×	✓	×
Song et al. (2025)	✓	✓	✓	×	×	✓	✓	✓
Wang XY et al. (2025)	×	✓	✓	×	✓	×	✓	✓
Mao et al. (2026)	×	×	✓	✓	×	×	×	✓
Zhao YJ et al. (2026)	×	×	✓	✓	×	×	✓	×
Luo et al. (2026)	×	✓	×	×	×	✓	✓	✓
This paper	✓	✓	✓	✓	✓	✓	✓	✓

Motivation

- Most UAV ISAC studies focus on single or medium-to-large UAV platforms; dedicated research on swarm-oriented ISAC remains insufficient.
- Existing standards and performance metrics cannot fully characterize the actual requirements of future low-altitude UAV swarm ISAC. Future UAV swarms require more stringent communication and sensing capabilities. A set of key performance metrics should be redefined.
- To realize the ambitious “Ten Ones” performance metrics for future UAV swarm ISAC system, several promising technologies need to be introduced, such as novel array architectures including XL-MIMO, sparse XL-MIMO, and RAAs, sparse time–frequency resource allocation, and CKMs.

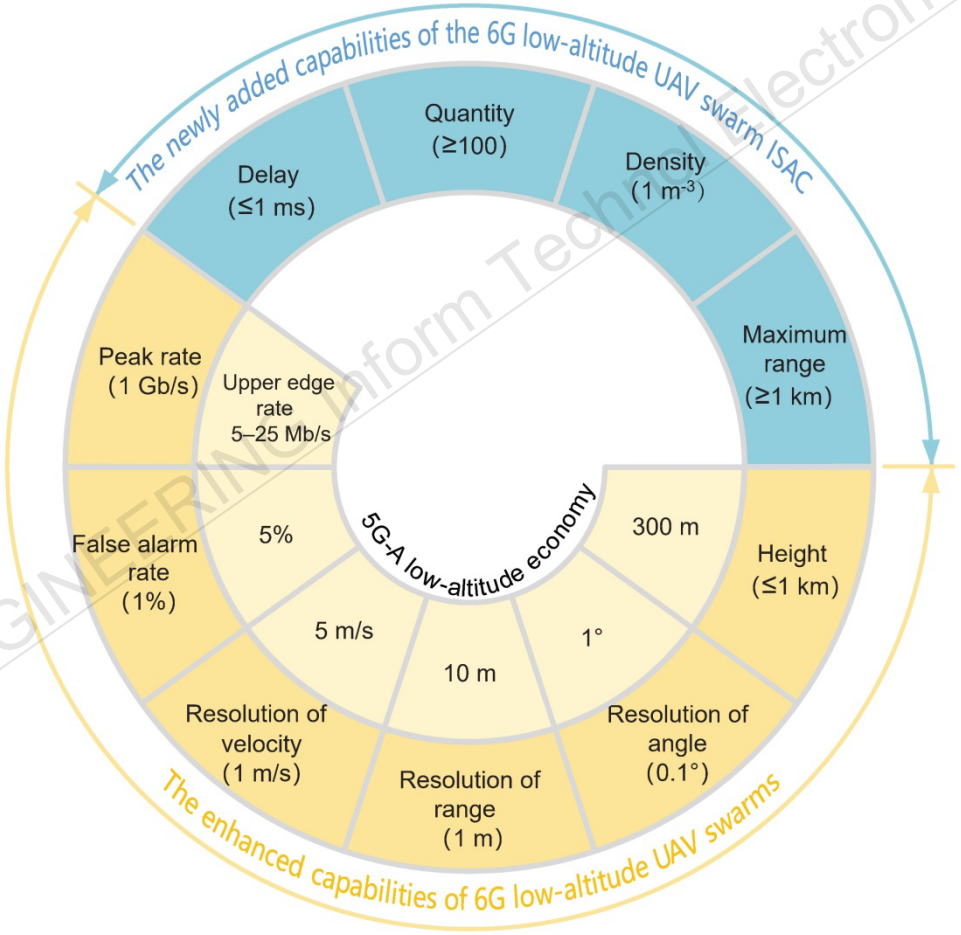
Future vision

- ISAC for low-altitude UAV swarms: realize UAV detection, localization, classification, and tracking.
- ISAC based on low-altitude UAV swarms: UAV swarms are leveraged as airborne ISAC platforms.



“Ten Ones” performance metrics

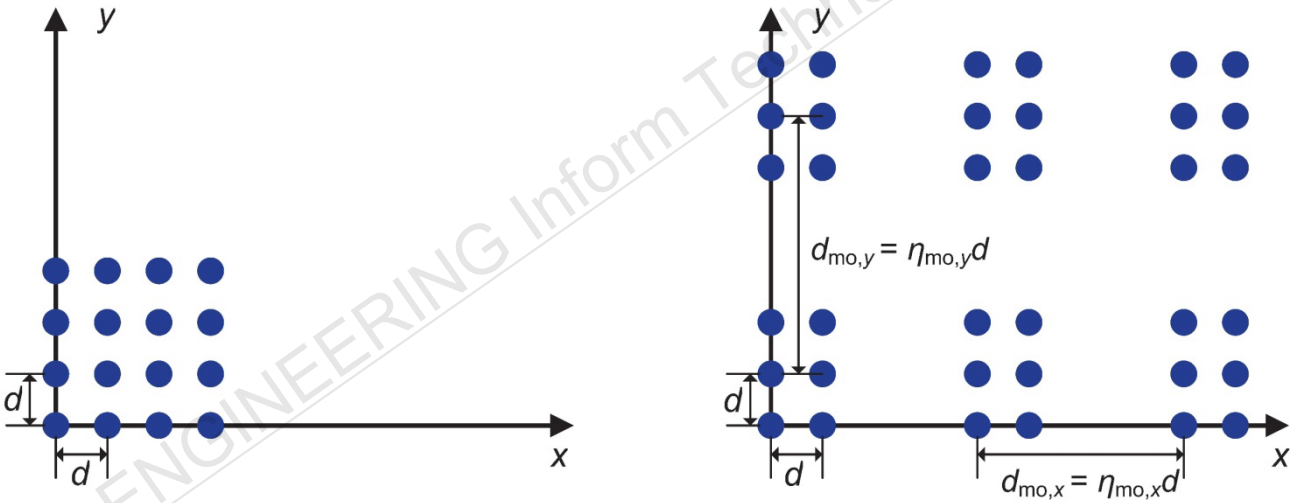
- Taking a ground-based (or low-height, tower-mounted) ISAC BS as the origin, for a hemispherical airspace with a radius of 1 km, the communication and sensing metrics are established.



“Ten Ones” performance metrics for low-altitude UAV swarm ISAC

Key enabling technologies

- Sparse XL-MIMO: adjacent antenna spacings ≥ half-wavelength
- Advantages: higher spatial resolution, more sensing degrees of freedom, larger near-field region, smaller mutual coupling effects, more flexible array arrangement, more economical hardware, and lower energy and signal processing overhead



Comparison of array architectures between conventional compact MIMO (left) and sparse XL-MIMO (right)

Key enabling technologies

- RAAs: flexibly adjust radiation patterns, resonant frequencies, and polarization states by changing the surface current distribution
- Advantages: adapt to dynamically changing low-altitude complex environments

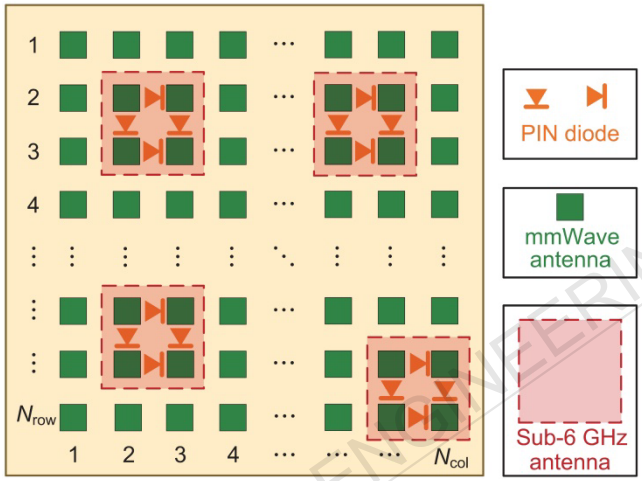


Illustration of the dual-band reconfigurable antenna array (DBRAA)

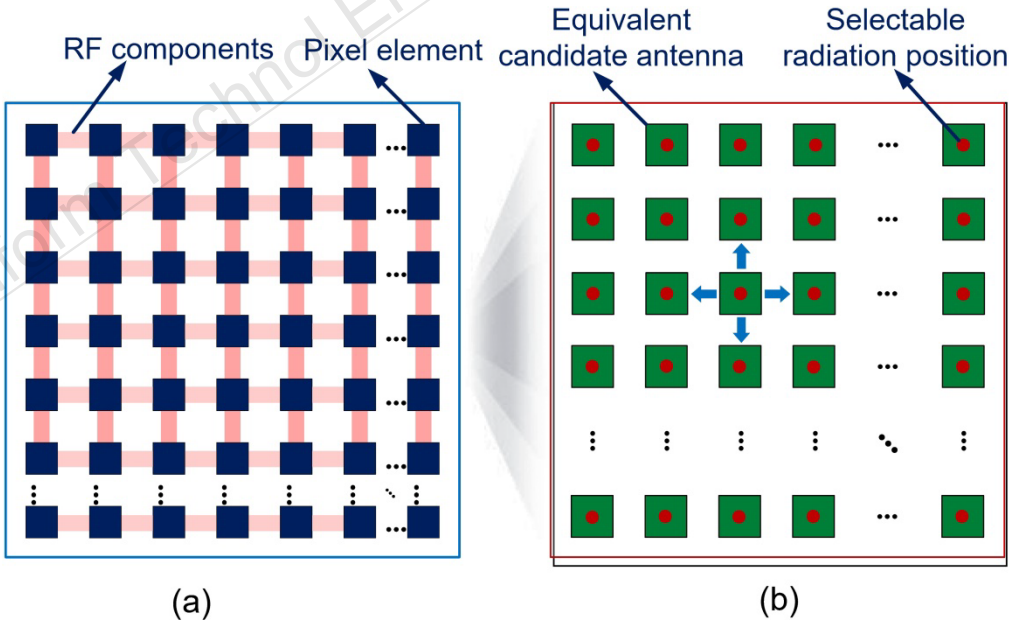
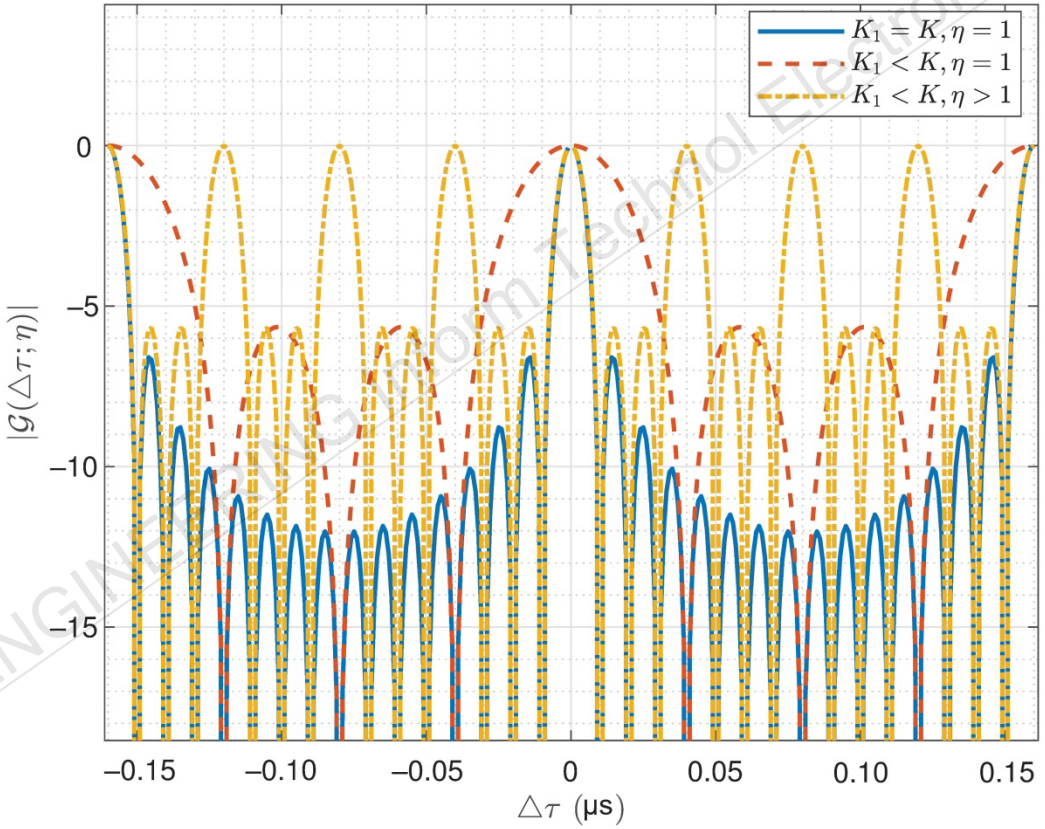


Illustration of the reconfigurable pixel antenna (RPA) (a) and RPA-based electronic movable antenna (REMA) (b)

Key enabling technologies

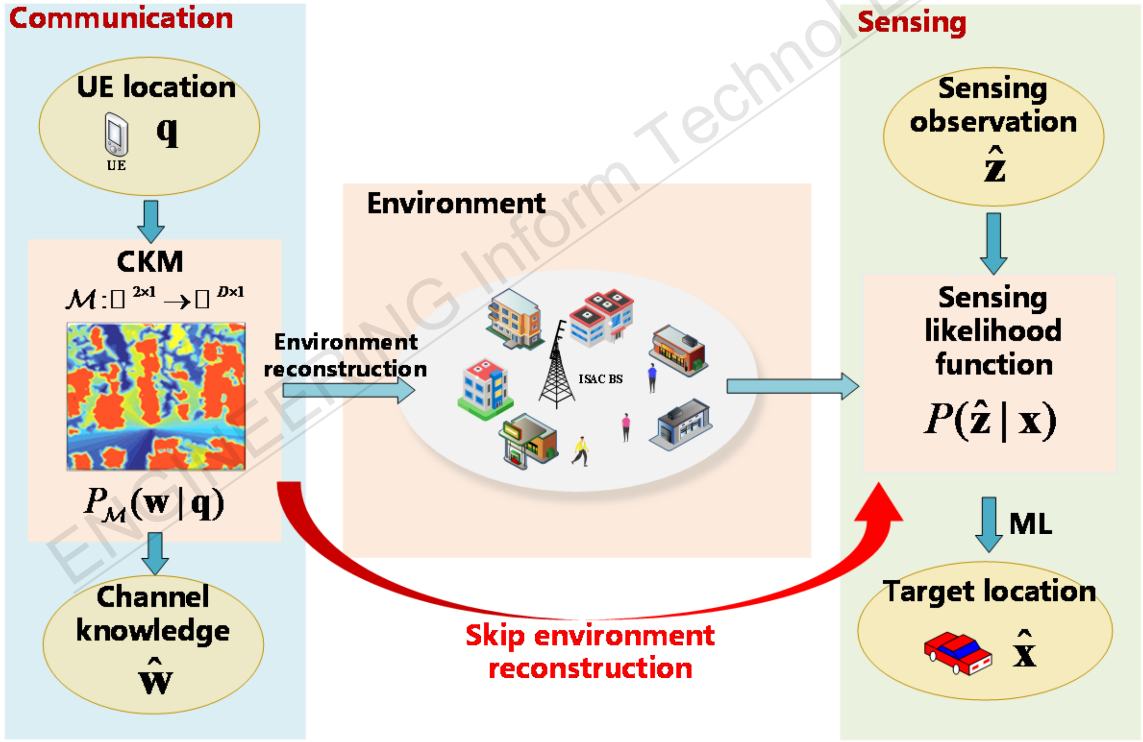
- Sparse time–frequency resource selection
- Advantages: achieve full-bandwidth delay resolution and unambiguous detection range using only partial bandwidth



Delay resolution and unambiguous range versus the number of allocated subcarriers K_1 and frequency-domain downsampling interval η

Key enabling technologies

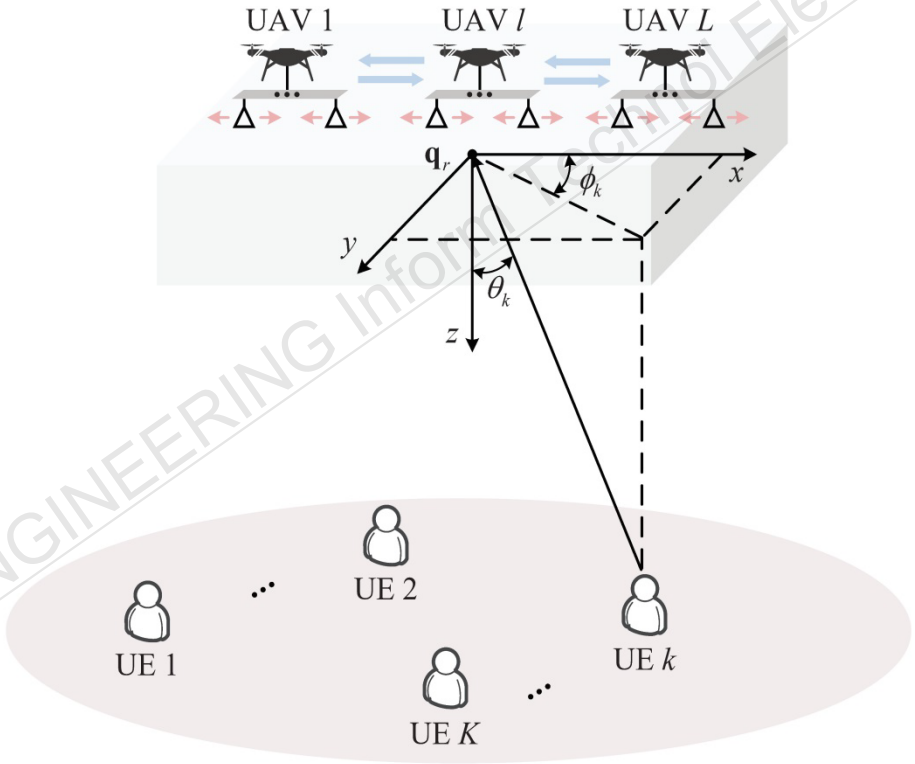
- CKM: a mapping database indexed primarily from transceiver positions to channel knowledge
- Advantages: prior acquisition of wireless channel environment information, enhanced cognition of wireless environment, supporting environment-aware communication and sensing



CKM-enabled ISAC that uses the same CKM developed for communication to achieve environment-aware sensing

Key enabling technologies

- ISAC based on low-altitude UAV swarms: treat UAV swarms as aerial BSs or anchor points
- Advantages: expanded communication and sensing coverage, higher line-of-sight (LoS) probability, enhanced deployment flexibility



ISAC based on a low-altitude UAV swarm system

Future outlook

Research direction	Outlook
Low-altitude UAV swarm 3D ISAC	• Novel array architecture modeling for 3D ISAC • Beamforming and interference management in 3D airspace • 3D trajectory planning and resource co-optimization
Low-altitude UAV swarm near-field ISAC	• Near-field signal processing for novel array modeling • Near-field beam modes for NLoS coverage and sensing
CKM-based low-altitude UAV swarm ISAC	• Multimodal CKM fusion for UAV swarm ISAC • CKM-assisted sensing and localization for NLoS scenarios • ISAC-driven online CKM update and refinement
Low-altitude UAV swarm ISAC super-resolution low-complexity algorithms	• Super-resolution multi-target tracking in ultra-dense swarm scenarios • Low-complexity real-time algorithm implementation
AI-based low-altitude UAV swarm ISAC	• AI-enhanced channel modeling and dynamic prediction • Multi-agent RL for cooperative swarm beam and resource management • Generative AI for CKM completion and clutter suppression