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# A review of UAV positioning in LAIN: toward a 5G-core “space–air–ground” integrated and cooperative architecture

**Key words:** Low-altitude intelligent network (LAIN); Unmanned aerial vehicle (UAV); Integrated positioning; Integrated communication and navigation; Space–air–ground collaboration

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# LAE tendency and challenges

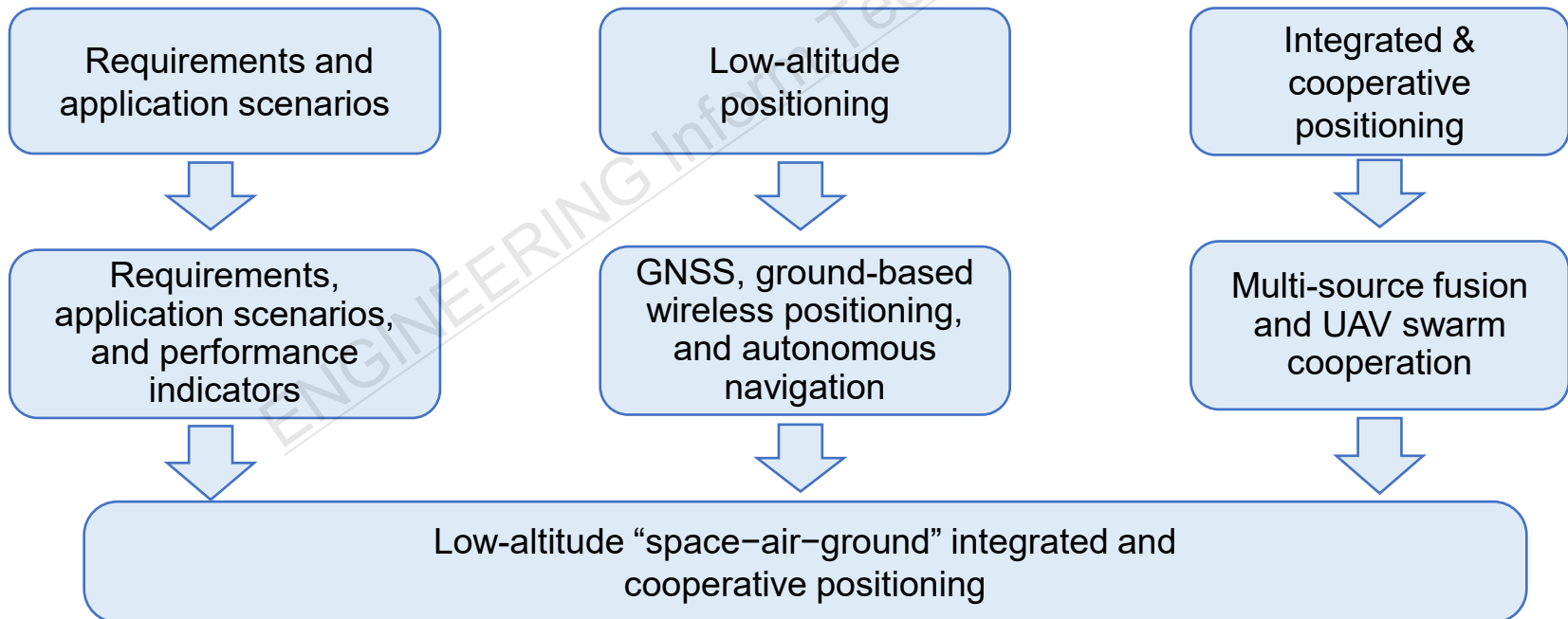
- The rapid expansion of the low-altitude economy (LAE) is driving strong demand for highly accurate and reliable positioning technologies to support diverse aerial operations.
- Single positioning technology cannot meet the diverse and demanding requirements of the LAE.
- The current positioning infrastructure is fragmented and lacks sufficient coverage to support large-scale and continuous low-altitude operations.

Table 1 Overview of UAV localization surveys

Paper	Focus area	Key contribution
Couturier and Akhloufi (2021)	Absolute visual localization	Reviews absolute visual localization, comparing methods by trajectory length, environment size, and error.
Gyagenda et al. (2022)	GNSS-independent navigation	Surveys non-GNSS navigation techniques, analyzing their strengths/weaknesses and fusion approaches.
Xin et al. (2022)	Visual autonomous landing	Summarizes visual landing, covering sensor setups, algorithms, and challenges like lighting/occlusion.
Arafat et al. (2023)	Visual navigation	Reviews visual navigation systems and addresses key challenges (e.g., environmental changes and real-time performance).
Tang P et al. (2024)	Visual detection and navigation for emergency rescue	Reviews visual detection and navigation for UAVs in emergency missions, focusing on real-time and robustness needs.
Gu et al. (2025)	Visual localization	Surveys visual methods (monocular, stereo, SLAM), comparing their accuracy and computational complexity.
Kramarić et al. (2025)	UWB	Surveys short-range localization technologies (UWB), analyzing their accuracy and deployment factors.

# Motivation

- ❑ High-precision, robust, and highly reliable positioning can support safe flight of unmanned aerial vehicles (UAVs) in complex low-altitude environments.
- ❑ This work focuses on the application scenarios, 5G positioning, and integrated 5G+GNSS technologies for UAV positioning.
- ❑ It advances the theory of multi-source integrated positioning and guides the technical planning of low-altitude intelligent network (LAIN) infrastructure.



# 1 Positioning requirements and applications

- ❑ Positioning accuracy requirements vary across flight phases and also differ across different LAE application scenarios.
- ❑ Positioning technology for LAE is applied in three scenarios: UAV navigation, operational supervision by authorities, and spatial benchmark construction for infrastructure.
- ❑ Performance indicators of low-altitude positioning technology: accuracy, coverage, real-time capability, robustness, power consumption, and cost.

Table 2 Comparison of positioning requirements for four typical low-altitude applications

Application	Requirement dimension				
	Sphere of activity	Accuracy	Real-time requirements	Cost sensitivity	Typical solution
Logistics transportation	Fixed route	Submeter-to-centimeter level	High	Medium	GNSS + INS + Visual
Agricultural and forestry plant protection	Wide-area farmland/forest area	Meter-to-submeter level	Medium	High	GNSS
Emergency rescue	Disaster scene	Meter level	High	Low	GNSS + INS + SLAM
Drone aerial display	Fixed performance airspace	Submeter level	Extremely high	Medium	GNSS + Visual

# 2 Low-altitude positioning

- ❑ GNSS is the most mature and widely used positioning method for UAVs, but is inoperable in complex environments.
- ❑ 5G can be deeply integrated with GNSS to achieve seamless indoor-outdoor positioning for UAVs, and enable cooperative localization for UAV clusters.

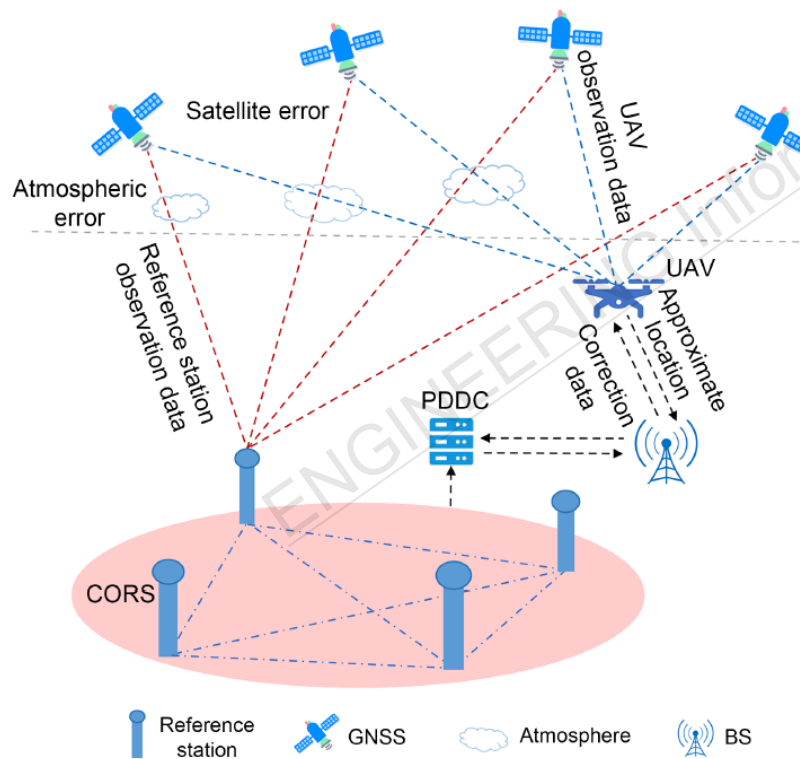


Fig. 2 Schematic diagram of RTK positioning

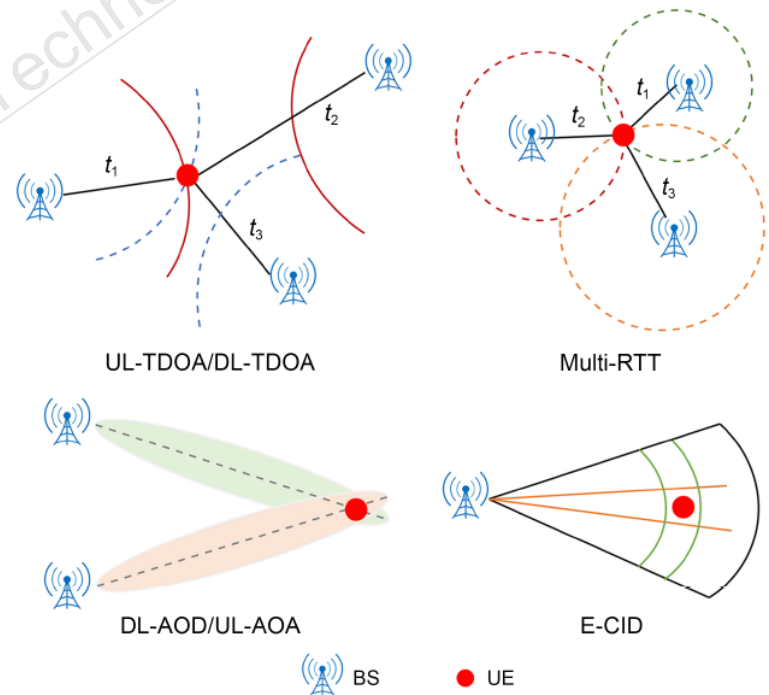


Fig. 3 Schematic diagram of six 5G positioning methods. Reproduced from Jin et al. (2023), with permission from the editorial office of *GNSS World of China*

# 2 Low-altitude positioning

- GNSS offers clear advantages for wide-area spatial positioning, while other positioning technologies contribute complementary capabilities. No single positioning technique satisfies all requirements for complex low-altitude operations; therefore, practical systems should integrate multiple technologies.

Table 4 Comparison of performance indicators of main low-altitude positioning technologies

Positioning technology	Accuracy	Coverage	Real-time capability	Robustness	Power consumption	Cost
GNSS	SPP: ~10 m	PPP: Global	PPP: Low	Medium	Medium	Low
	RTK: Centimeter level	RTK: Wide	RTK: High			
5G	Centimeter level	Wide	High	High	Medium	Low
UWB	Centimeter level	Small-scale	High	Medium	Medium	High
INS	Centimeter level (short-term)	Unrestricted	High	High	Medium	Medium
Visual localization	Submeter-to-meter level	Unrestricted	Medium	Medium	High	Medium
SLAM	Laser SLAM	Unrestricted	High	High	High	High
	Visual SLAM	Submeter-to-meter level	Unrestricted	Medium	Medium	Medium
Geomagnetic positioning	Meter level	Global	Medium	Medium	Low	Low

# 3 Integrated positioning

- Integrated positioning enhances UAV's capabilities by combining heterogeneous sensors and leveraging their complementary strengths; this approach addresses limitations in accuracy, continuity, and reliability, enabling seamless high-precision positioning across broad outdoor areas to confined indoor spaces.

**Table 5 Comparative analysis of integrated positioning schemes for low-altitude UAVs**

Integrated scheme	Advantage	Disadvantage
GNSS + INS	<ul style="list-style-type: none"> <li>- Complementary accuracy and reliability</li> <li>- Enhanced anti-spoofing and anti-interference capability</li> </ul>	<ul style="list-style-type: none"> <li>- INS error accumulation over time</li> <li>- Implementation challenges of deep coupling</li> </ul>
GNSS + 5G	<ul style="list-style-type: none"> <li>- Ubiquitous high-precision positioning services</li> <li>- Reduced CORS deployment and maintenance costs</li> </ul>	<ul style="list-style-type: none"> <li>- Dependence on 5G BS coverage</li> <li>- Multi-source signal stability challenges</li> <li>- Urban canyon positioning optimization requirements</li> </ul>
GNSS + Visual	<ul style="list-style-type: none"> <li>- Suppression of Visual-Inertial Odometry drift via absolute position constraints</li> <li>- Improved continuity in complex environments</li> </ul>	<ul style="list-style-type: none"> <li>- Complex initialization for coordinate system alignment</li> <li>- Difficult feature extraction in low-texture environments</li> </ul>
GNSS + UWB	<ul style="list-style-type: none"> <li>- Seamless indoor-outdoor positioning</li> <li>- Centimeter-level accuracy</li> </ul>	<ul style="list-style-type: none"> <li>- High deployment cost for UWB BS</li> <li>- NLOS-induced accuracy degradation</li> </ul>
GNSS + INS + Visual	<ul style="list-style-type: none"> <li>- Simultaneous suppression of INS drift and visual scale ambiguity</li> <li>- Enhanced robustness in degraded GNSS or low-texture scenes</li> </ul>	<ul style="list-style-type: none"> <li>- High computational load from visual processing</li> <li>- Complex sensor calibration and initialization</li> <li>- Environmental texture and lighting dependence</li> </ul>
GNSS + INS + UWB	<ul style="list-style-type: none"> <li>- Seamless indoor-outdoor positioning</li> <li>- High robustness in NLOS environments</li> </ul>	<ul style="list-style-type: none"> <li>- High system integration complexity and cost</li> <li>- Performance degradation in dense NLOS settings</li> </ul>
Cooperative positioning	<ul style="list-style-type: none"> <li>- Reduced dependence on single-node accuracy and infrastructure</li> <li>- Enhanced swarm fault tolerance</li> <li>- Compatibility with large-scale swarm operations</li> </ul>	<ul style="list-style-type: none"> <li>- High demands on communication reliability</li> <li>- Complex data fusion and network synchronization</li> <li>- Security vulnerabilities</li> </ul>

# 3 Integrated positioning

□ UAV positioning technology has shifted from single technique solutions to multi-source integration and cooperative approaches.

- Integrated positioning fuses two or more sources using Kalman filtering, graph optimization, or other estimation methods, and adapts strategies according to context to exploit complementary strengths.
- Cooperative positioning extends this idea to multiple agents, improving swarm-level accuracy and fault tolerance via information sharing and collaborative algorithms.

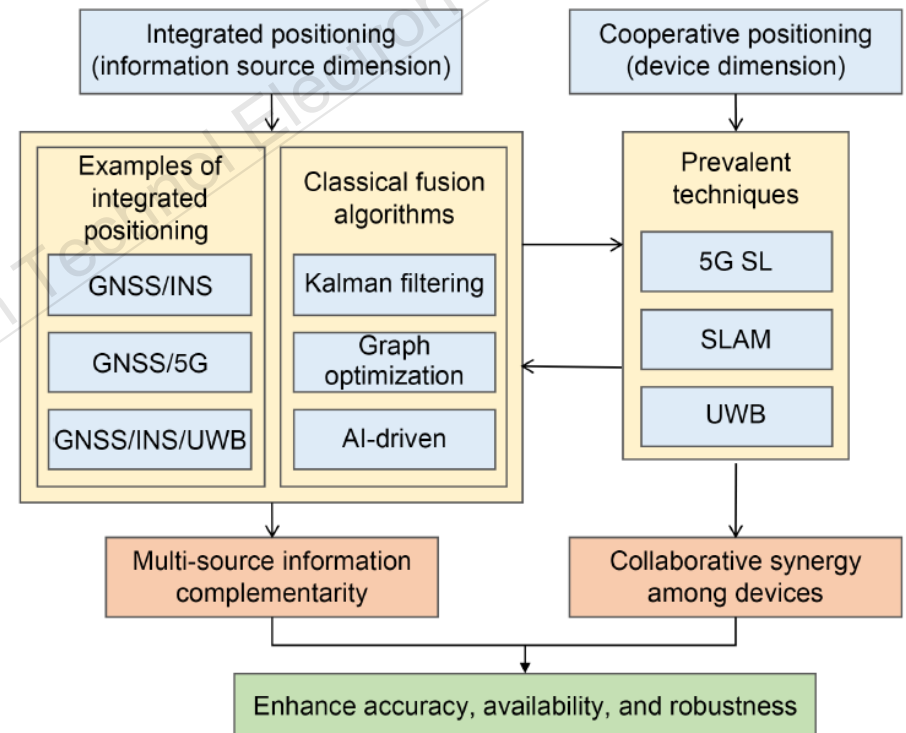


Fig. 6 Schematic diagram of the relationship between integrated positioning and cooperative positioning

# 4 Integrated and cooperative positioning for LAIN

- We propose a 5G-centered, GNSS-enhanced, space–air–ground integrated and cooperative positioning architecture that integrates 5G aircraft-to-everything (A2X)/sidelink (SL) plus low Earth orbit (LEO) satellites for redundancy and coverage extension.

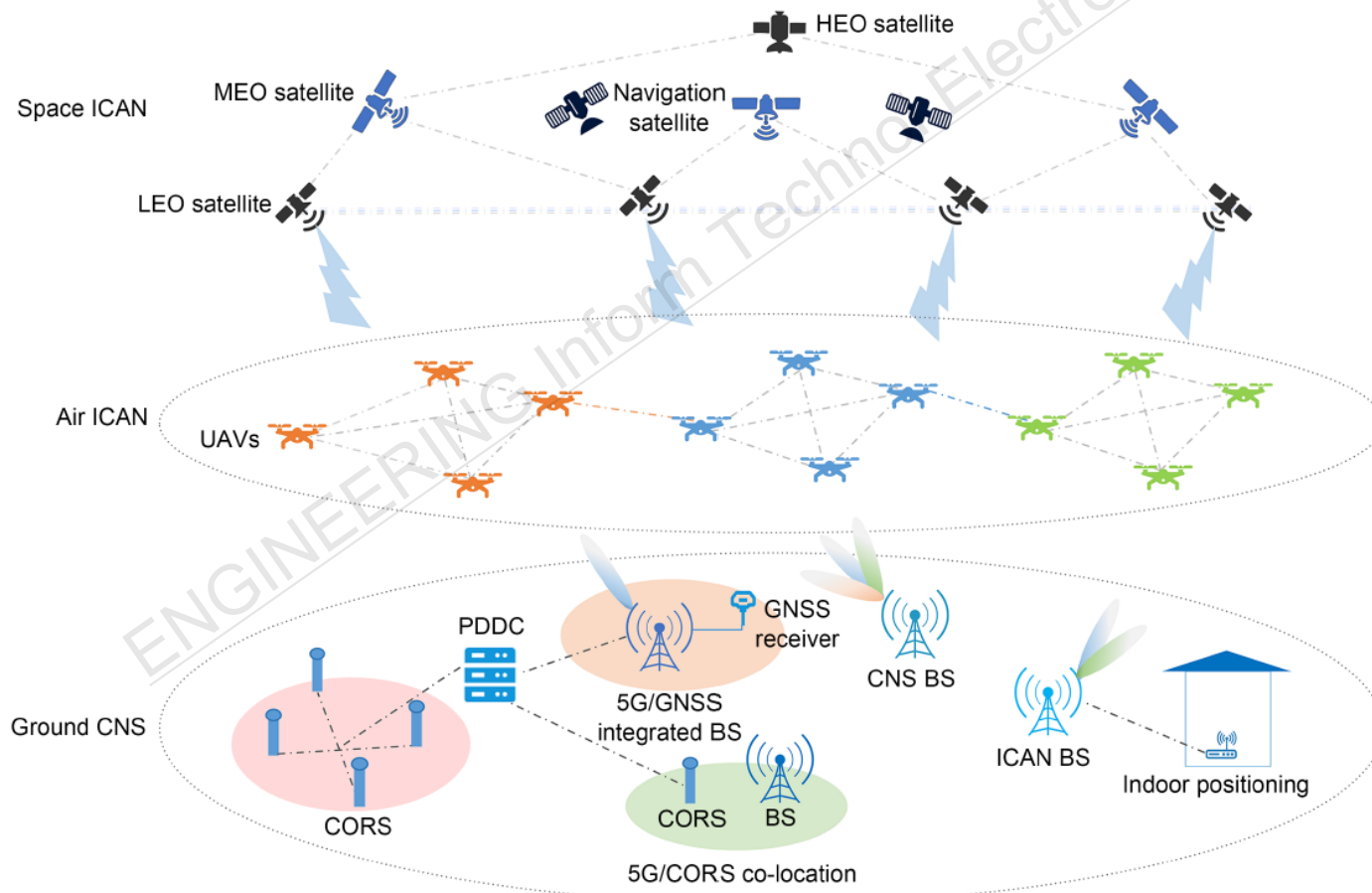


Fig. 7 Schematic diagram of low-altitude “space–air–ground” integrated and cooperative positioning scheme

# 4 Integrated and cooperative positioning for LAIN

- ❑ Ground communication, navigation, and sensing (CNS): integrating 5G and GNSS to deliver seamless indoor–outdoor high-precision positioning.
- ❑ Air integrated communication and navigation (ICAN): using 5G A2X/device-to-device (D2D) and 5G SL technology to establish direct communication links and relative positioning within UAV clusters.
- ❑ Space ICAN: integrating LEO satellites, BeiDou Navigation Satellite System (BDS) short-message services, and future 6G capabilities with next-generation GNSS.

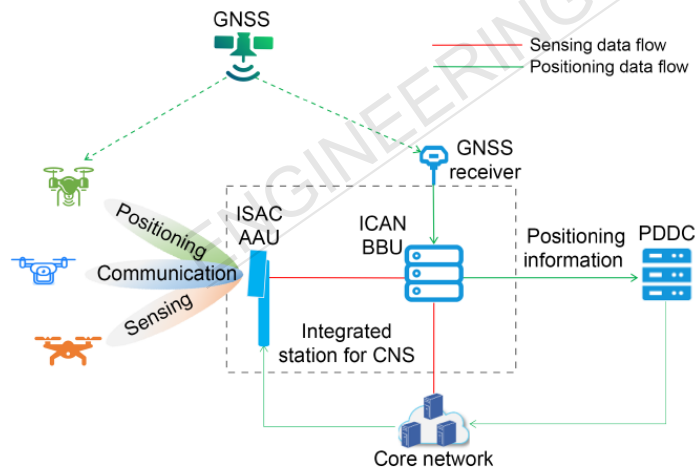


Fig. 8 Schematic diagram of integrated CNS based on 5G BS  
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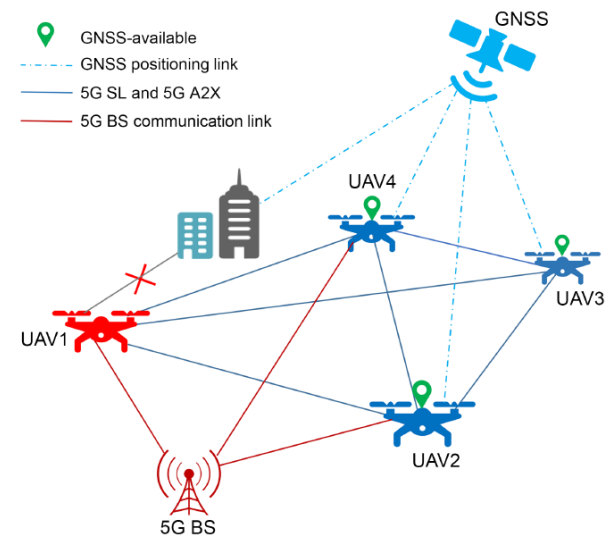


Fig. 9 Schematic diagram of collaborative UAV cluster positioning

# Future outlook

Low-altitude positioning	Outlook
Multi-source intelligent fusion	<ul style="list-style-type: none"><li>• Prioritize tight coupling for multi-source fusion</li><li>• Build tight-coupled factor-graph models integrating multi-modal sensors</li><li>• Optimize fusion and improve robustness and adaptivity with artificial intelligence</li></ul>
Cluster-level collaborative positioning	<ul style="list-style-type: none"><li>• Realize UAV cluster positioning via distributed information sharing</li><li>• Adopt decentralized architectures and consensus mechanisms for real-time complex-environment collaboration</li><li>• Enhance cluster stability and reliability using geometric relations</li></ul>
Communication – navigation–sensing integration	<ul style="list-style-type: none"><li>• Reduce cost and improve efficiency through hardware and network integration</li><li>• Provide unified multi-service on a single platform with 5G-A and GNSS</li><li>• Enable flexible and resilient full coverage by employing hybrid networks</li></ul>
“Space–air–ground” integration	<ul style="list-style-type: none"><li>• Promote space–air–ground CNS integration powered by 6G, GNSS, and LEO satellites</li><li>• Support high-precision positioning and enhanced inter-satellite communication</li><li>• Ensure reliable LAE CNS services with anti-interference technologies</li></ul>

# Author Bio

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Zhongliang DENG is a professor and doctoral supervisor at Beijing University of Posts and Telecommunications, and an academician of the Chinese Academy of Engineering. His research interests include indoor and outdoor seamless positioning, global navigation satellite systems, satellite communications, MEMS, and multimedia.



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