The Low-Altitude Network by Integrated Sensing and Communication

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01 Executive Summary

With the steady deployment of 5G networks in China and in the rest of the world, all eyes are on possible new applications that can take advantage of new technologies to lift cellular service providers out of their business saturations. While the concept of the integrated sensing and communication (ISAC) was proposed as a 6G vision, this paper will show that the technology using ISAC will most likely be kicked off in the 5G era to respond to the rapid growth of the drone industry with the following conclusions:

01 While the recent regional conflicts around the world have demonstrated the potential for drones, the real growth opportunities in the world ecosystem will be in the commercial sectors with a clear market driven trend. Multiple mainstream consulting companies have projected the market values of the drone sector to be in the hundreds of billions.

02 The expected rapid growth of the drone sector can fuel progress of the digital economy in many fields including agriculture, energy, mining, environment, smart city, tourism, and 3D charting & mapping. Many of these applications will require video backhauls that represent high-end Internet of Things (IoT) applications expected to bring relatively high Average Revenue Per User (ARPU) to operators.

03 In addition to video backhauls, another major category of drone services will be through the cellular coverage in low altitude airspace to connect all drones for autonomous flights. The size of this type of market has also been projected to be comparable in size as the video backhauls in various vertical sectors.

04 Currently, the number of drones in China is already in the order of millions. With the takeoff of the sector, the number is expected to grow to the order of tens of millions. Together with the relatively projected high ARPU, the progress in this sector has the potential to bring a few percentages of annual revenue growth for operators.

05 To support services for the drone sector, the cellular operators need to extend their current ground coverage to low altitude airspaces with a network architecture that can support communication, sensing, and computing. In this paper, extensive discussions are made in depth covering the technical aspects of channel models, waveform designs, sensing, interference management, drone detections and identifications, reliability, drone collision control, and navigation platforms for drones.

While the effort to extend the cellular coverage to low altitude airspace is just starting, operators, equipment, terminal, and chipset vendors are all hopeful and excited by the opportunity. With the expected rapid progress in this field, this new engine is expected to fuel new growth in the cellular industry and elevate the world digital economy to the next level.

02 Introduction

The digital economy is the cornerstone of global economic development and one of the key focus of China's economic growth. The low-altitude economy, relying on low-altitude networks and focusing on the Unmanned Aerial Vehicle (UAV) industry. It establishes a comprehensive economic system covering city management, express logistics, geographic surveying and mapping, agriculture and plant protection, emergency rescue and other fields. With substantial support from policies, regulations, markets, and technology, the low-altitude economy will become a new important driver of the global economy. Therefore, it can bring innovation, efficiency improvements and new business opportunities.

China Telecom is currently collaborating with industry partners to construct a low-altitude coverage based on cellular mobile networks through ISAC, aiming to achieve the goal of "ubiquitous connectivity, global sensing, and intelligent computing". Low-altitude network by ISAC will provide regulatory authorities with convenient, comprehensive and intelligent low-altitude airspace management solutions. It aims to guide equipment manufacturers and service providers to form a global industrial chain for the low-altitude UAV industry. It offers industry users intelligent and diversified experiences in low-altitude airspace. This initiative aims to fuel the rapid development of the emerging low-altitude economy.

03

Drivers for low-altitude economy and industries

The low-altitude economy is on the verge of a rapid expansion, propelled by diverse driving forces. UAVs not only have great value in the military field, but also are expected to have a remarkable future in commercial applications.

Accelerating economic development has become critical for countries around the world after Covid-19. From a broad perspective across multiple industries, the global low-altitude economy is poised for rapid growth. Nations worldwide are increasingly acknowledging the importance and future possibilities of UAV applications. They recognize that UAVs play a significant role in the digital economy and have the potential to boost overall economic growth. Market and technology have become the "power sources" of the low-altitude economy. After cultivating the consumer market, the low-altitude economy has rapidly expanded into various industrial markets. Policies and regulations serve as "boosters" for the healthy and sustainable development of the low-altitude economy. By free use ofairspace, low-altitude economy is poised to become a new engine for economic growth.

3.1 Market driver

UAVs will be widely used in various civilian fields, such as consumer entertainment, delivery and transportation, agricultural meteorology, industrial production, infrastructure surveillance, geographical energy, and smart cities. UAV is becoming an integral part of the core production and operational processes in various traditional industries. They offer several advantages, including enhanced efficiency, cost reduction, and minimized risks, when compared to traditional methods. In addition to increasing the market value of UAV equipment, the low-altitude economy, as an essential part of new infrastructure, also contributes to the overall development of traditional industries. Emerging business models such as 'UAVs+ Agriculture', 'UAVs+ Healthcare' and 'UAVs+ Logistics' have brought significant benefits to traditional industries. In the future, with the synchronous development of numerous technologies like 5G/6G and artificial intelligence, the low-altitude economy will unlock new growth opportunities across a diverse range of industries.

Based on current trends, the global UAV market is expected to reach a scale of 700 to 1,000 billion RMB (100 to 140 billion USD) by 2030.Significantly, the Chinese market is expected to account for around half of this total market value[10]. According to Morgan Stanley, the global Urban Air Mobility (UAM) market could reach about 7 trillion RMB (1,000 billion USD) by 2040 and 64 trillion RMB (9,000 billion USD) by 2050][24] . Industrial UAVs are expected to account for up to 52% of this market, representing the largest segment.

Combining data from other consulting firms, the global UAV market is expected to be between 300 to 500 billion RMB (43 to 71 billion USD) in 2025 and reach 500 to 800 billion RMB (71-115 billion USD) by 2030. For instance, Drone Industry Insights predicts [1] that by 2030, the global drone hardware market will be around 390 billion RMB (55 billion USD), with a Compound Annual Growth Rate (CAGR) of 7.7%. The application and service market will be around 398 billion RMB (56 billion USD)[2] , with a CAGR of 7.4%.

3.2 Technology driver

The healthy development of the low-altitude economy is inseparable from the innovation drive of technology. In recent years, with the rapid growth of UAV technology, the number of UAVs has increased dramatically and their tasks have become increasingly complex. UAV swarming technology has emerged to help meet the operational needs of multiple UAVs. Significant advances in low-altitude network technology have laid a solid foundation for managing UAV swarms and developing the low-altitude economy.

First, high-reliability, low-latency communication technology provides essential communication support for UAV swarm control. This technology can meet the basic requirements of low-altitude UAV for receiving flight control signals, reporting supervision data, allowing inter-device communications, and enabling the precise control of UAV swarms.

Second, the integrated sensing and communication technology provided by terminal and radio access networks enables the ability to monitor UAV flights and enforce regulatory measures, thus empowering industry development. This technology can satisfy both the communication and sensing needs of low-altitude UAVs. Moreover, mobile communication networks can rapidly expand the service range of low-altitude networks, even achieving seamless coverage in key areas.

Third, low-altitude supervision platform provides a new opportunity for unified management of UAVs. The low-altitude network enables the platform to process meteorological data, airspace information, flight plans, surveillance information, and perform comprehensive computing. Thus, it achieves management objectives for UAV visualization, dispatchability, and monitorability.

Fourth, advances in artificial intelligence technology and computing power enhance low-altitude UAVs' detection and tracking capabilities. AI technology can be used to discriminate between different types of targets. It can not only detect inappropriate or illegal activities such as "reckless flying" or "unauthorized flying", but also optimize the performance of UAV anti-collision systems and low-altitude supervision platforms. This provides efficient, safe, and controllable flight management and control solutions for low-altitude UAV, laying a solid foundation for their safe operation.

3.3 Policy driver

For over a decade, multiple countries and regions, led by the United States and the European Union, have been shaping policies to foster the commercialization of the low-altitude economy. Starting around 2013, these nations began implementing regulations for managing low-altitude airspace and initiated pilot projects to encourage the commercial use of UAVs. This active promotion has been instrumental in driving the development of the low-alti tude economy. China also places high importance on developing the low-altitude economy and implementing supportive and encouraging policies.

The United States has continuously promoted the application of UAV in the commercial sector, with a focus on commercializing passenger Autonomous Aerial Vehicle (AAV). In 2013, "the Federal Aviation Administration(FAA) Modernization and Reform Act" introduced the idea of integrating UAVs into the U.S. National Airspace System (NAS). This act marked the beginning of the commercialization of UAVs and established a critical regulatory and policy framework that would support the growth of the low-altitude economy. In 2017, the FAA launched the Unmanned Aircraft Systems Integration Pilot Program (IPP). This program was designed to strength collaboration among local governments, the private sector, and the federal government. The aim was to investigate the safety and effectiveness of UAV technology and to speed up its application in transportation, public safety, and agriculture. In 2018, the National Aeronautics and Space Administration (NASA) proposed an evolutionary road-map from Unmanned Aircraft System Traffic Management (UTM) to UAM and then to Advanced Air Mobility (AAM),further promoting the innovative development of the UAV industry[19].

The European Union, from both regulatory and technological perspectives, actively explores advanced air traffic management systems to promote the commercial development of UAVs. In 2014, The European Union launched the "European Drone Strategy 1.0," establishing a basic UAV operation framework and promoting the application of UAV technology in civilian fields. In 2017, the U-Space plan was proposed to establish an air traffic management system supporting large-scale UAV operations. By 2022, the European Commission passed the "European Drone Strategy 2.0," introducing more advanced safety frameworks and technical requirements. It aims to create an innovative and competitive UAV industry using critical technologies like artificial intelligence, robotics, and mobile communications [3].

Since 2013, China has laid out comprehensive plans for the low-altitude economy and implemented various policies to support the development of the UAV industry. In 2016, the State Council's "13th Five-Year National Strategic Emerging Industries Development Plan" identified UAVs as one of the key development areas. The "14th Five-Year Plan for Civil Aviation Development" in 2022 proposed to vigorously guide the innovative development of UAVs, actively expand service areas, and improve regulations and standards. Provinces like Jiangsu, Zhejiang, and Guangdong, representing local governments, responded to national policies, promoting the application of UAVs in various industries. Entering 2024, the Ministry of Industry and Information Technology is also introducing a series of policies supporting the low-altitude economy's spectrum and industrial development.

3.4 Regulatory driver

As the low-altitude economy continues to evolve and scale, flight risks will inevitably increase. Risks associated with UAV operations include collisions with third parties on the ground, collisions with third parties in the air, and collisions with critical infrastructure[4]. Flying UAVs may also involves risks such as privacy violations, data theft, and cyber hijacking.Thus, the gradual intensification of UAV regulation has become one of the major trends in standardizing the development of the low-altitude economy.

International organizations and countries are adopting a regulatory approach that combines airworthiness management with operational risk. They are improving regulatory systems, developing supervision platforms, and taking various measures to promote the development of industry standards. The Joint Authorities for Rulemaking on Unmanned Systems (JARUS) categorizes UAV operations into open, specific, and certified categories. JARUS explicitly uses the Specific Operation Risk Assessment (SORA) methodology to evaluate and regulate UAV operations [4]. The European Union Aviation Safety Agency (EASA) classifies and registers UAVs based on their operational risks. EASA sets regulations for different levels of UAV weight, flight authorization, and pilot qualifications, and implements the U-space digital service and regulatory platform [20].

The United States FAA classifies UAVs based on their operational purpose. FAA issues regulations for controlled airspace, airworthiness certification, and other standards to manage UAV flights. Through legislation, it authorizes actions such as detecting, identifying, and monitoring UAVs to mitigate risks to specific facilities or assets [21].

China's State Council and Central Military Commission have issued the "Interim Regulations on the Flight Management of Unmanned Aircraft". It regulates UAV production and manufacturing, airspace control, pilot qualifications, regulatory information platforms, and flight plan applications [22]. Countries such as Japan and Australia have also enacted relevant regulations and guidelines for UAV regulation [23]. The regulatory approaches of international organizations and various countries are gradually evolving from conceptual frameworks to detailed standards driving the industry to a safer and standardized new stage.

04 Typical application scenarios

From the perspective of maturity and market space of civil UAV applications, the entertainment consumption market has passed its peak and market growth has slowed down. The agricultural plant protection and geographic mapping market has begun to take shape with relatively mature products, and the future market is expected to maintain stable growth. With the acceleration of China's smart city construction process, UAV security, monitoring, rescue, unattended and other applications in city management, transportation, energy and other fields will become important growth areas. The express logistics market is still in the small-scale commercial stage for specific scenarios. However, after breaking through the technology bottleneck , commercial mode and safety, the market potential of logistics scenarios is expected to grow the fastest in the future.

Industrial UAV can be mainly used in agriculture, geographic mapping, city management (including emergency), logistics, and other scenarios. Grand View Research and Technavio [5][6] predict that by 2030, the global UAV application market scale will be relatively large for geographic mapping, city management, and energy monitoring, respectively 37.5 billion USD, 33 billion USD and 30 billion USD. Agriculture will develop stably, with a scale of about 22.5 billion USD. Logistics applications has a scale of about 15 billion USD. According to data from Morgan Stanley [24] , passenger AAV is still in the incubation period in 2030, and the market scale is expected to reach 1 trillion USD by 2040.

4.1 Express delivery

The express logistics scenario is currently in its early exploratory stage, limited by public safety, airspace regulation, privacy concerns, and other aspects. The maturity level of applications is low, but it is expected to grow rapidly in the future and become a sizable market. Under the premise of breaking through the bottlenecks of logistics public safety and airspace authorization, UAV express logistics is expected to become one of the primary applications in the low-altitude economy. The main applications of express logistics UAVs are concentrated in the following two aspects.

The first example is the instant food delivery. Shenzhen, Shanghai, and other places have established 15 UAV food delivery routes, with a total of over 167,000 orders. As of June 2023, the number of online food delivery users in China has reached 535 million. In 2022, the size of the Chinese food delivery market reached 1.1 trillion RMB [25] (157 billion USD), with over 40 billion delivery orders. iResearch predict that the volume of the instant delivery industry will reach 95.78 billion orders by 2026 in China [26]. Once suitable airspace conditions are met, most of instant food delivery services can be realized by the UAV.

The second example is express logistics distribution, as shown in Figure 1. In 2022, China's express delivery orders exceeded 110.6 billion pieces [27]. Among these, small-batch, high-frequency, and lightweight delivery pieces for emergency delivery is suitable for UAV delivery [28]. In the long term, UAVs have enormous market potential in the express logistics scenario and are expected to create a trillion-RMB market in China [29].

Figure 1: Application of UAV in express logistics

4.2 Geographic surveying and mapping

Geographic surveying and mapping is one of the earliest scenarios for industrial UAV to achieve significant commercial value. Currently, this field has entered a mature stage with a sizable market. Considering the industry's cyclic variations in land survey applications, the future development space is expected to experience exponential growth. UAV applications in geographic mapping mainly concentrate on the following three aspects[30].

The first aspect is the stockpile measurement in the construction field, as shown in Figure 2. By collecting data from stockpiles, UAV can generate three-dimensional models to calculate the volume or weight. In 2022, the global market for construction UAV reached 5.335 billion USD [7].

The second aspect is the transportation and urban construction in the land planning. In 2023, the global market size of urban planning software and services reached 80.25 billion USD [8]. In the future, UAV with centimeter-level accuracy can assist construction professionals in creating city layouts and constructing three-dimensional road models from a global perspective.

The third aspect is the land ownership rights and real estate registration. Surveying UAV can perform data collection and image capture on collective rural land, obtaining high-precision three-dimensional surface data. This assists in land ownership rights and registration certification work. Compared with traditional surveying and mapping, the cost is reduced by 90%, and the efficiency is increased by 2 times [7]. Driven by the above advantages, it is expected that global geographic mapping UAV will potentially create a market space of over 10 billion dollars, with a CAGR of 24% [9]. UAV in China will grow with a CAGR of over 15% [6], creating an application market of over 10 billion RMB.

Figure 2: Application of UAV in building measurement

4.3 City management

In recent years, smart cities have been deeply under extensive development worldwide. According to the forecast by markets and markets, the global smart city market is expected to grow from 511.6 billion USD in 2022 to 1,024.4 billion USD by 2027, with a CAGR of 14.9% over the next five years [10]. With characteristics of no blind spots, flexibility, and rapid deployment, the UAV has become an important tool for smart city management. The application scenarios of UAV in city management are mainly concentrated in the following four aspects.

The first aspect is the security patrols for major city events and sports events. During major sporting events and exhibitions, UAVs can provide real-time monitoring of traffic, crowds, and vehicle flows. They can quickly manage traffic and help prevent stampede accidents. According to the Sullivan forecast, China's security UAV market will exceed 19.8 billion RMB (2.8 billion USD) by 2024 [31].

The second aspect is the monitoring in key urban areas, as shown in Figure 3. The UAV can automatically conduct real-time security patrols and warnings of abnormal events (such as illegal border crossings, crowd conflicts, traffic accidents, and other suspicious or illegal behaviors) in key areas, such as downtown areas, border areas, scenic spots, and highway entrances.

The third aspect is the monitoring of illegal construction and construction sites. By inspecting urban buildings, rooftops, and construction sites, UAVs can quickly and accurately identify unauthorized urban construction, dust pollution, and other illegal activities.

The fourth aspect is the criminal investigation. Using thermal imaging and infrared equipment to capture images in targeted areas, UAVs can obtain terrain information and track criminal suspects, thereby maintaining urban security. Demand for smart cities and security monitoring in China is strong, with a CAGR of around 50% [31][5], creating an application market of nearly a 100 billion.

Figure 3: UAV traffic monitoring in key urban areas

4.4 Emergency rescue

UAVs have been widely used in emergency rescue missions with advantages such as rapid response and flexibility. The application scenarios of UAVs in emergency rescue are mainly concentrated in the following three aspects.

The first aspect is the disaster reconnaissance, as shown in Figure 4. The UAV equipped with high-definition cameras can conduct a comprehensive inspection of the disaster area. It can transmit real-time disaster information, which is convenient for the command center to grasp the disaster situation in time.

The second aspect is the urgent rescue. When a disaster or accident occurs, the UAV can build a digital rescue sand table through 3D modeling tech nology to provide accurate information support for rescue decisions. In addition, the UAV can transport supplies rapidly to the rescue site, ensuring resource replenishment for disaster or accident zones.

The third aspect is the emergency communication. UAVs can be used as a temporary base station to quickly build an emergency communication network in the communication interruption area, providing temporary communication support. In 2022, the market share of emergency rescue UAVs in China was 15%, with a market inventory of 130,000 units and a market size of 8.7 billion RMB [29]. In the future, UAVs will be an important means of emergency rescue, with a CAGR exceeding 30% [31], creating an application market of over 10 billion RMB in China.

Figure 4: Application of UAV in emergency rescue

4.5 Energy monitoring

The energy monitoring scenario is experiencing the fastest growth among all scenarios, with a relatively high market potential. UAV applications in the field of energy monitoring primarily focus on three aspects.

The first aspect is the overheating monitoring of power transmission/distribution equipment. The UAV can conduct global thermal monitoring to detect abnormal heating issues in equipment, such as power lines, clamps, and switches. It is 7 times more efficient than manual monitoring.

The second aspect is the global modeling inspection of substation facilities, as shown in Figure 5. Transformers, circuit breakers, bus bars, and other equipment in substations are complex. They are subject to frequent modifications, and most of them have hollow structures, which require global modeling to inspect overall appearance and details of the facilities. The UAV inspection can reduce working costs significantly. The average annual cost of operating a lightweight substation inspection UAV is only 10,000 RMB per year (1,430 USD).

The third aspect is the management of clean energy generation facilities. Photovoltaic and wind power plants occupy a large area with sparsely distribution, which is not conducive to centralized management. UAVs are beneficial for the timely detection of subtle damages, providing strong support for the stable operation of wind power plants.

According to Drone Industry Insights, the most significant application scenario of UAVs in the world is energy monitoring [2]. In 2022, the share of inspection UAVs in China (including energy and transportation) was 12%, with a market inventory of 77,000 units and a market size of 7.8 billion RMB [29]. In the future, with the support of technologies such as flight control platforms and 5G network, the industry is expected to grow with a CAGR exceeding 30% [31], creating a market size of over 10 billion RMB in China.

Figure 5: UAV energy monitoring

4.6 Traffic monitoring

The traffic monitoring UAV market has entered a stage of rapid growth and holds significant market potential. Transportation infrastructure, particularly road construction, is crucial to industrial and economic development. UAVs have a broad market space in traffic monitoring due to their advantages of solid flexibility, high efficiency, wide monitoring coverage, and resilience to environmental and terrain factors. The application scenarios for UAV-based traffic monitoring UAVs are mainly concentrated in two aspects.

The first aspect is the abnormal monitoring of abnormalities in road facilities. UAVs can provide real-time warnings for various hazards that endanger road traffic safety, such as highway roadbed defects. They can also inspect the condition of traffic signs and monitor the status of railway tunnel entrances, curves, and bridges, effectively filling the blind spots in traditional video surveillance.

The second aspect is the traffic facilitation and command, as shown in Figure 6. UAVs can accurately locate and identify traffic accidents or congestion points, facilitate the rapid collection of evidence at traffic accident scenes. They can provide real-time information to assist traffic police in grasping the scene situation. They can also remotely broadcast commands in high-risk environments, presenting a multi-perspective view of traffic conditions. In China, for example, in 2022, the total length of roads exceeded 5.35 million kilometers, and the operational length of railways reached 155,000 kilometers [32]. With the extensive road and rail networks, there is a strong demand for traffic monitoring. The industry is expected to grow with a CAGR of exceeding 30% [31], potentially creating a market size of over 10 billion RMB.

Figure 6: UAV traffic monitoring application

4.7 Agriculture and plant protection

Agricultural plant protection is the earliest scenario where industrial UAVs achieve large-scale commercial value. It has now entered a mature stage with a large market size and will maintain stable growth in the future. Agricultural UAVs can be used in planting, spraying, plant protection, plant inspection, measurement, and other fields. With the characteristics of high efficiency, accuracy, and economy, they have been widely applied. The application scenarios of UAVs in agriculturel plant protection are mainly concentrated in the following four aspects[35].

First is the farmland irrigation. UAVs can precisely deliver seeds and pollen. They can also apply pesticides according to the growth of crops, diseases, and pests, which can improve efficiency by up to 100 times compared to traditional methods [31].

Second is the farmland monitoring, as shown in Figure 7. UAVs can monitor crop growth, soil conditions, and pest infestations in farmlands. Once anomalies are detected, UAV can immediately take action to protect crops. China has approximately 1.9 billion acres of arable land [33], but only 10% [34] of them have applied agricultural pest control UAVs, indicating significant market potential in the future.

Third is the forestry patrol. UAVs can inspect various dynamic information in forest areas, such as identifying fire hazards, locating theft, and other security concerns[36].

Fourth is the crop transportation. UAVs can transport harvested agricultural products to collection stations. Since 2019, China's agricultural UAV industry chain is growing rapidly, with about 400 enterprises engaged in the research and development, production, and sales [34]. By 2022, China's agricultural plant protection UAV market will have 220,000 units, covering 17,000 hectares of sowing area [29]. Based on predictions from various institutions, we believe that the UAV market for agricultural plant protection will grow at a CAGR of 20% in China [5][6][9], potentially creating a market size in the hundreds of billions of RMB.

Figure 7: UAV agricultural inspection

4.8 Passenger autonomous aerial vehicle

Scenarios for passenger autonmous aerial vehicle (AAV) are currently in the testing and exploration phase. electric vertical take-off and landing (eVTOLs), in the context of practical operational scenarios, still face challenges in airspace management planning, infrastructure, regulations, and standards. The application scenarios of passenger AAV mainly include the following three aspects.

First is the urban air transportation. Urban air transportation provides rapid transit services within or between cities, substitutes ground transportation. It is the most crucial application scenario for passenger AAV [25][37]. In China, EHang's EH216-S became the first passenger AAV in the world to receive an airworthiness certificate.

Second is emergency rescue services. With their efficient personnel transport capabilities, passenger AAVs are the ideal solution for air rescue. They can quickly provide medical assistance and effectively carry out people from firefighting and disaster.

Third is the sightseeing and tourism. This provides tourists new ways to explore, allowing people to visit previously inaccessible areas. In July 2023, EHang Intelligent in China launched an aerial tourism and sightseeing service in Shenzhen using passenger AAV. It is expected that eVTOLs will first be commercialized in aerial tours and medical transport sectors. They will gradually expand to models like "air taxis" and "air buses," entering the public consumer market [38]. The global market value for passenger AAV is still very small, less than 1 billion USD [9]. However, it is anticipated that with the reduction in equipment costs, improvement in infrastructure, and technological advancement, a market worth over 4 trillion USD could be established globally [24].

05 Main technical challenges

Low-altitude network coverage needed to support the emerging commercial UAV industry is new and, as such, its development face many challenges.

5.1 Challenges for low-altitude flight aviation

To realize the large-scale, high-quality, safe, and controllable development of the low-altitude economy, it is necessary to monitor large-density, high-frequency, and multi-type low-altitude flight activities based on efficient, complete and scientific low-altitude flight supervision technology. Meanwhile, it is important to promptly identify and control unreasonable and unlawful flying conduct promptly. However, as for traditional radar technology, the monitoring capability of mono-static radar is limited. Specifically, it is difficult to detect and deal with “low-slow-small” targets flashing on the radar display. The multi-station networking is too expensive to meet the needs of large-scale low-altitude flight activity monitoring. As for camera monitoring technology, its monitoring range is limited and affected by brightness, which makes it difficult to meet long-distance and all-weather monitoring needs.

Currently, due to the lack of efficient technical monitoring methods, it is difficult for government regulatory agencies to discover unreasonable and illegal behaviors such as “random flying” and “unauthorized flying” in low-altitude airspace immediately. Meanwhile, it is also difficult for enterprises to ensure the security and reliability of their flight tasks. As a result, the development of the low-altitude economy can only adopt the trial-and-error method, which seriously hinders the scale of the low-altitude economy. Therefore, the high-precision, low-latency, and all-weather sensing technology, combined with aircraft-to-aircraft and aircraft-to-ground communications using cellular technology is the basis for effective and convenient monitoring and management of flight missions. Meanwhile, it is also a major technical challenge that urgently needs to be overcome.

In addition, due to the lack of unified technical standards for low-altitude flight monitoring, each region is exploring its own local low-altitude airspace opening regulatory plans. In this process, different low-altitude airspace technology monitoring systems are easily formed in various places, laying hidden dangers for the future interconnection of low-altitude flight monitoring technologies in various places. Therefore, there is an urgent need to study an efficient, complete, and scientific-technical monitoring system. Besides, the unified low-altitude monitoring platform and information service infrastructure need to be established to support collecting/analyzing low-altitude data and building a large-scale, high-quality, and safe low-altitude economy.

5.2 Challenges for low-altitude network coverage

Traditional wireless networks take ground coverage as the main goal, while low-altitude networks need to achieve three-dimensional air coverage. With the rapid development of the low-altitude economy, UAV applications have put forward higher requirements for wide-area continuous coverage of low-altitude networks. According to a large number of test results, although the beam side lobes of current ground coverage wireless networks have certain signal coverage in the air, the side lobes on the antenna are numerous and messy. The signal-to-noise ratio is generally poor and fluctuating, and there are even areas with no signal coverage. Due to these unfavorable factors, it will be impossible to guarantee continuous business services and uninterrupted flight control of UAVs throughout the entire journey. Therefore, it is the foundation for the high-quality development of the low-altitude economy to build a low-altitude three-dimensional continuous coverage wireless network, which is also a key technical challenge that needs to be overcome.

In the future, more and more low-altitude UAV services will generally require video or picture backhaul functions, and even high-definition video backhaul functions. The uplink speed generally requires tens to hundreds of megabits per second, while the downlink speed requirements are usually not high. Therefore, the uplink and downlink of UAV business are asymmetric. However, traditional mobile networks with ground coverage focus on downlink services and mainly mobile users. Specifically, the mobile communications field focused more on improving the downlink capacity of the network in the past. As a result, how to ensure the requirements of a low-latency uplink business of a large number of UAVs based on cellular mobile network technology is a major challenge that will be faced in the future.

In addition, unlike traditional air transportation services, low-altitude economic activities will show the characteristics of “digitization” and “informatization”. At this moment, the security issues of low-altitude networks are also one of the key challenges to be solved to ensure low-altitude economic activities. Due to the complexity of low-altitude economic activities, its security challenges are not only limited to hardware, software, communication links, and networks, but also to aircraft intrusion and destruction. Therefore, multiple parties need to jointly design a more flexible, intelligent, and secure information service system to meet the requirements of low-altitude economic activities.

06 Low-altitude network system

There are various options for low-altitude network coverage. At present, the civil aviation system is implemented in a centralized way. Based on the huge number and wide application of UAVs, as well as the expected capacity requirements of the network, the coverage provided by the cellular network technologies, augmented by ISAC, has been identified as one of the main solutions for low-altitude network systems. This chapter will focus on the network architecture and technology exploration based on cellular networks.

6.1 Overall architecture

The low-altitude network system is an intelligent and interconnected low-altitude digital service system integrated with sensing, communication, and computing functionalities which relies on the infrastructures such as the cellular mobile communication network, Internet of Things, and cloud computing. The low-altitude network aims to achieve the goals of "ubiquitous connectivity, global sensing, and intelligent computation", providing regulatory authorities with convenient, comprehensive, and intelligent solutions for low-altitude airspace management. It provides guidance to equipment manufacturers and service providers in the legal production and operational management of low-altitude UAV devices, offering intelligent and diverse low-altitude experiences for industry users, empowering new low-altitude applications.

The low-altitude network system comprises three major functionalities: communication, sensing, and intelligent computation. It provides diverse communication, sensing, and computation capabilities to the application layer based on different application fields and performance requirements. Communication capabilities aim to meet the diversified communication functions requirements of low-altitude UAVs, enhancing capabilities like identity authentication based on the basic communication functions. Sensing capabilities involve sensing and identifying targets such as UAVs, enabling the low-altitude network system with capabilities such as range measurement, angle measurement, speed measurement, positioning, and tracking. Different levels of confidence, accuracy, resolution, latency, refreshing rates, false detection rates, and false alarm rates could be provided for different low-altitude scenarios. Intelligent computation capabilities require the network to have comprehensive data processing and computing capabilities, facilitating intelligent functions of the low-altitude network system.

The functional architecture of the low-altitude network system primarily consists of the application layer and the functional layer. The application layer directly provides low-altitude services to third-party industry users, involved in emergency rescue, agriculture and plant protection, express logistics, city management, geographic surveying and mapping, and many other fields. The functional layer provides diverse communication, sensing, and intelligent computing capabilities for the application layer based on network resources, storage resources, and computing power resources. The functional architecture of the low-altitude network is depicted in Figure 8.

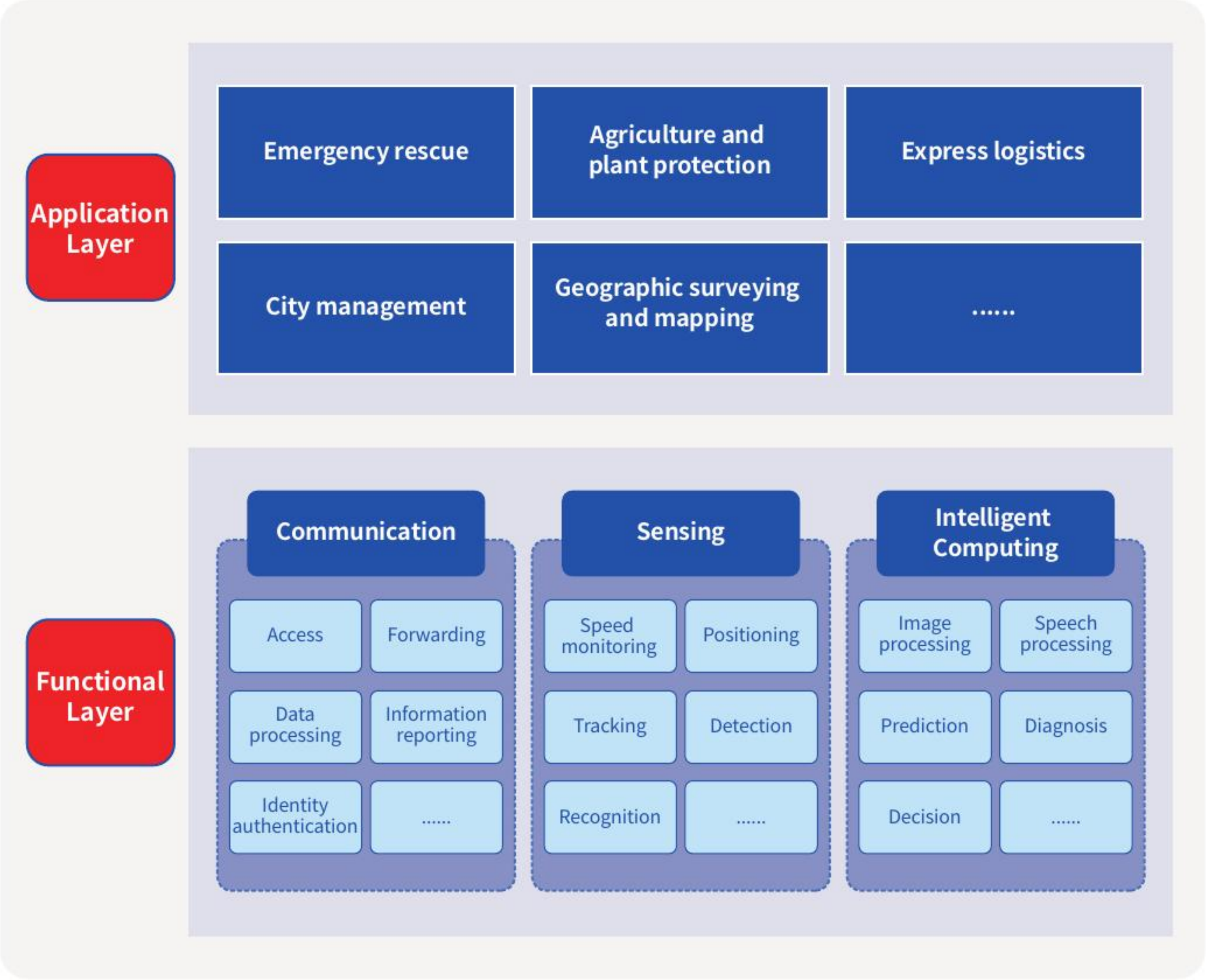

Figure 8: Functional architecture of the low-altitude network

The low-altitude network system based on cellular mobile networks consists of three logical systems: the flight control system, the data service system, and the sensing system. The flight control system manages UAV flight control, including reporting identity information and flight information of UAVs, and transmitting platform control instructions. The data service system primarily handles UAV-related data transmission. For example, video feedback. The sensing system is responsible for sensing UAV positions and status, enabling effective monitoring of unauthorized flight behavior. The flight control, data service, and sensing logical systems can be accommodated on the same or different base stations. They can also operate on different frequency bands within the same base station. The airspace coverage and networking modes for each logical system can be flexibly adjusted and configured according to actual environments and requirements. The system logic diagram is illustrated in Figure 9. In the integrated sensing and communication system, the three logical systems share the wireless physical resources.

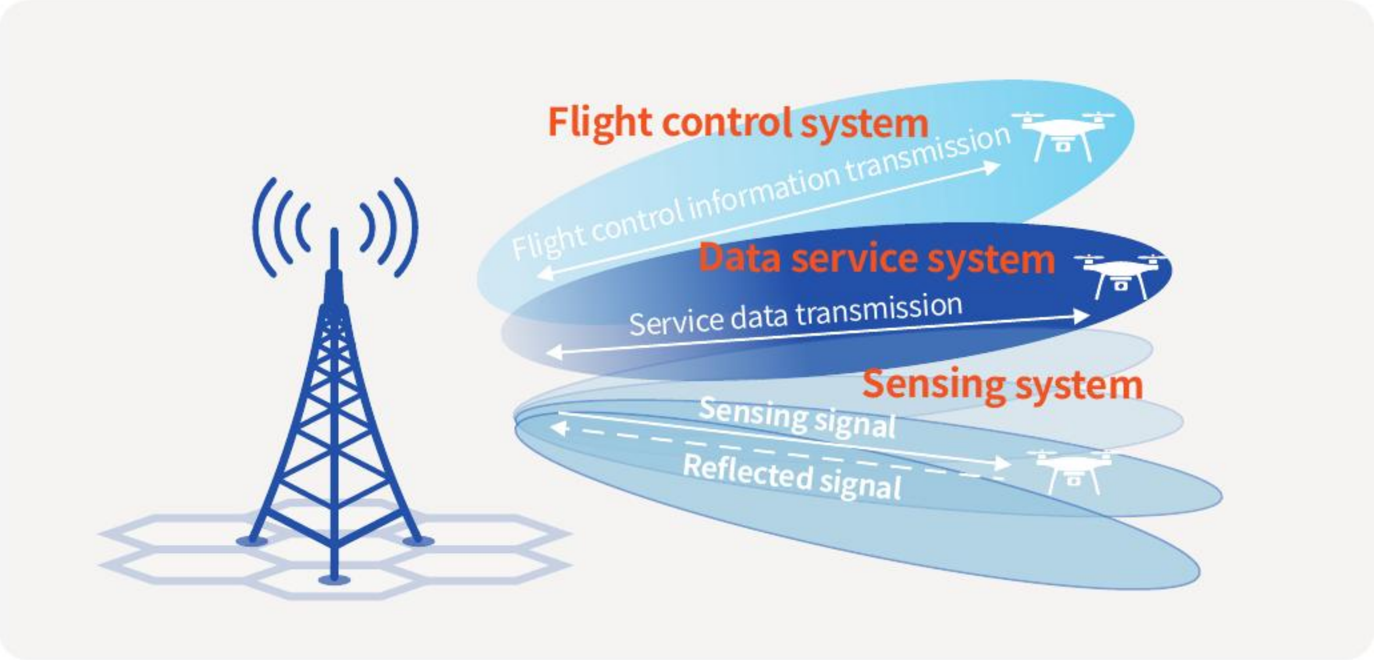

Figure 9: Logic diagram of low-altitude network system

6.2 Communication functionality

The communication capabilities aim to fulfill diverse communication functions for low-altitude cellular-connected UAVs including basic access, data/control signaling forwarding, information reporting, and identity authentication. Authentication of cellular-connected UAVs is particularly crucial and is the cornerstone of effective UAV regulation. For cellular-connected UAVs, it is necessary to provide basic communication capabilities such as data transmission and control command transmission. Image and video data collected by UAV, the position and attitude information obtained by UAV Global Positioning System (GPS) and sensor can be reported to various low-altitude business platforms and control platforms periodically or in real-time.

The flight control system can accurately transmit control commands to UAVs, guiding them to move as required or respond to emergency situations. UAV communication methods may include 5G/4G, and other wide and narrow-band wireless communication technology. Based on the specific requirements of service scenarios, UAVs can be configured with different communication methods. For instances, services demanding high reliability and low latency like emergency communication, navigation, as well as scenarios requiring substantial bandwidth like high-definition (HD) video transmission, inspection and monitoring, 5G has significant advantages in terms of data rate, latency, coverage, among others. It enables the efficient and reliable communication support for cellular-connected UAVs.

According to the performance requirements of 3GPP TS22.125 [11] for UAV applications, 8K video live broadcast demands an uplink data rate of 100Mbps with an end-to-end latency of 200ms, and a downlink data rate of 600Kbps with an end-to-end latency of 20ms. For 4×4K Artificial Intelligence (AI) surveillance, an uplink data rate of 120Mbps with an end-to-end latency of 20ms, and a downlink data rate of 50Mbps with an end-to-end latency of 20ms are required. For remote UAV controller through

HD video, an uplink data rate of 25Mbps with an end-to-end latency of 100ms, and a downlink data rate of 300Kbps with an end-to-end latency of 20ms are needed. For UAV command and control communication, the "Steer to waypoints" control mode necessitates an uplink data rate of approximately 0.672Kbps to 1.12Kbps and a downlink rate of about 0.8Kbps. For the "Automatic flight on UTM" control mode, an uplink data rate of around 2.4Kbps and a downlink rate of approximately 16kbps are required.

6.3 Sensing functionality

The sensing capabilities aim to leverage wireless signals to achieve passive sensing of target UAVs or the environment. The impact of dynamic targets such as UAVs and static targets like the environment on wireless signal characteristics can be effectively extracted, enabling the low-altitude network to possess capabilities such as distance measurement, angle measurement, speed measurement, positioning, tracking, etc., for low-altitude flying targets. The information can assist in achieving intrusion detection and collision avoidance for UAVs, tracking the trajectory of UAVs, thereby achieving remote monitoring and control.

For legal UAVs with flight qualifications, cellular-connected UAVs will periodically report flight information such as position and status through the communication network in accordance with monitoring requirements, while the information for non-cellular-connected UAVs, including the flight route and UAV model parameters information, can be obtained from the flight route declaration information system. The sensing functionality of the low-altitude network will utilize wireless sensing technology to determine the position and trajectory data of each identifiable UAV, comparing and jointly analyzing it with the aforementioned UAV information. This enables effective detection of illegal UAVs without flight qualifications, facilitating their efficient expulsion and ensuring the safety of the low-altitude airspace.

According to the performance requirements in 3GPP TR22.837 [12], for UAV intrusion detection, a positioning accuracy of 5-10m, a maximum sensing service latency of 1000ms, and a 5% missed detection and false alarm rate are required. For UAV collision avoidance, a horizontal positioning accuracy of 1m and a maximum sensing service latency of 500ms are required. For UAV flight trajectory tracing, a range resolution of 1-10m and a velocity resolution of 1-10m/s are required. The implementation of sensing functionality is based on the physical resources of the network. In the integrated sensing and communication system, the sensing functionality will share physical resources with communication functionality, allowing dynamic management and multi-dimensional reuse of resources in the time domain, frequency domain, and spatial domain based on the requirements of business scenarios. The low-altitude network needs to possess flexible resource allocation capabilities and allocate communication and sensing resources considering the business metrics of different application scenarios to achieve collaborative optimization of sensing and communication resources, so as to improve the utilization efficiency of spectrum resources and maximize the sensing performance while ensuring the communication performance.

6.4 Intelligent computing functionality

The intelligent computing capabilities aim to provide reliable intelligent computing functions for the low-altitude network. This system aims to realize intelligent processing of information based on image, voice, and relevant data. The goal is to realize functions such as service prediction, fault diagnosis, and flight decisions within the low-altitude system. Intelligent calculation and analysis of sensor data and video data obtained by UAVs are carried out to provide diversified low-altitude services support capabilities such as abnormal detection and illegal intrusion monitoring. Through feature extraction and analysis of UAVs and other targets, the types of targets are identified. By tracking the locations of the UAVs and analyzing their historical trajectories, the computing functionality can predict future trajectories and potential residence cells.

The low-altitude network integrates the basic data of UAVs and users, data collected and reported by UAVs, third-party service data, and other information. It requires a network with comprehensive, efficient, and intelligent data processing and computing capabilities. The realization of intelligent computing functions is based on computing resources, which significantly influences the performance and efficiency of low-altitude network services. The distribution and collaboration of computing power resources are also crucial in determining the delay of low-altitude network systems. Therefore, it is necessary to flexibly schedule computing resources, storage resources, and network resources to achieve a low-altitude network with cloud, edge, and end collaboration.

07 Key technologies

The network covering low-altitudes can take advantage of ground coverage and develop into low-altitudes based on ISAC technology. Therefore, its key technology is developed based on terrestrial cellular mobile technology.

7.1 Channel model for ISAC

ISAC serves as a new channel for communication networks to connect the physical world and the digital world, prompting communication networks to further penetrate vertical industries such as low-altitude economy, smart transportation, and smart factories. The 3rd Generation Partnership Project (3GPP) approved the sensing channel model and network architecture study items (RP-234069, SP-231754) in December 2023. 3GPP RAN1 will start the Study Item at February 2024. The sensing targets include the UAV, vehicle, automated guided vehicles (AGV) and road hazard.

The channel model is the basis for research on ISAC. Existing channel models are mainly oriented to communication system design such that cannot meet the research requirements of sensing technology. For example, the 0.5-100GHz communication channel model defined in 3GPP TR 38.901 and channel models of low-altitude scenarios defined in 3GPP TR 36.777 only consider the communication channel models without the characteristics of sensing, such as mono-static channel modeling, target characteristic modeling, ISAC channel correlation, etc. Therefore, it is necessary to design a channel model for ISAC to meet the requirement of sensing propagation channels.

The ISAC channel model can be enhanced based on the 3GPP statistical channel model to maintain better continuity with the 5G channel model. Meanwhile, a hybrid ISAC channel modeling method is proposed by introducing deterministic multipath channel components. This model divides the sensing channel into two parts: the target channel and the background channel. The target channel is the multipath channel associated with the target in the propagation environment, which can be modeled by a deterministic method. The background channel is the multipath channel unassociated with the target in the propagation environment, which can be modeled by statistical methods.

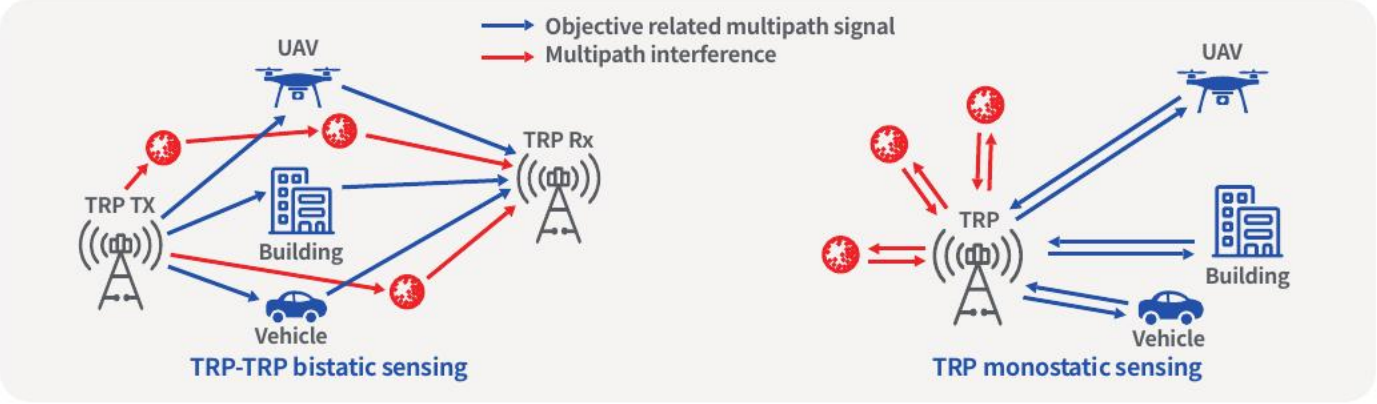

Figure 10: Hybrid channel architecture of ISAC

In the process of ISAC channel modeling, modeling the scattering characteristics of the sensing target is one of the key steps. Based on the radar scattering theory, the total scattering response of the target can be regarded as the coherent superposition of the responses of several local equivalent scattering sources. These equivalent scattering sources are called the scattering centers of the target. However, the types of sensing targets are different for different ISAC application scenarios. Therefore, before modeling the scattering characteristics of ISAC targets, it is necessary to classify the characteristics of the sensing targets first. Considering the complexity of the channel model, it is recommended that sensing targets can be classified based on application scenarios. At the same time, taking into account the requirements and simulation complexity of the actual scenario, the multi-scattering center modeling parameters of different targets can be determined according to the application scenario. As for the low-altitude UAV detection scenario, when the UAV is small and far away from the base station, the multi-scattering center model can be degenerated into an equivalent single-point model. When the UAV is larger and closer to the base station, the number of scattering points of the multi-scattering center needs to be modeled separately according to the size of the UAV.

7.2 Waveform and frame structure design for ISAC

The design of the ISAC waveform needs to consider both communication performance and sensing performance. Appropriate waveform design can improve the accuracy of sensing and the efficiency of communication. A simple ISAC waveform transmission method for achieving diversity transmission of communication and sensing is based on time division, frequency division, space division, or other methods. However, this method causes low resource utilization efficiency. To improve resource utilization, we can also integrate communication and sensing functions into the same waveform to achieve integrated design. There are two specific ways to achieve this goal, namely modifying the existing waveform and designing a new ISAC waveform.

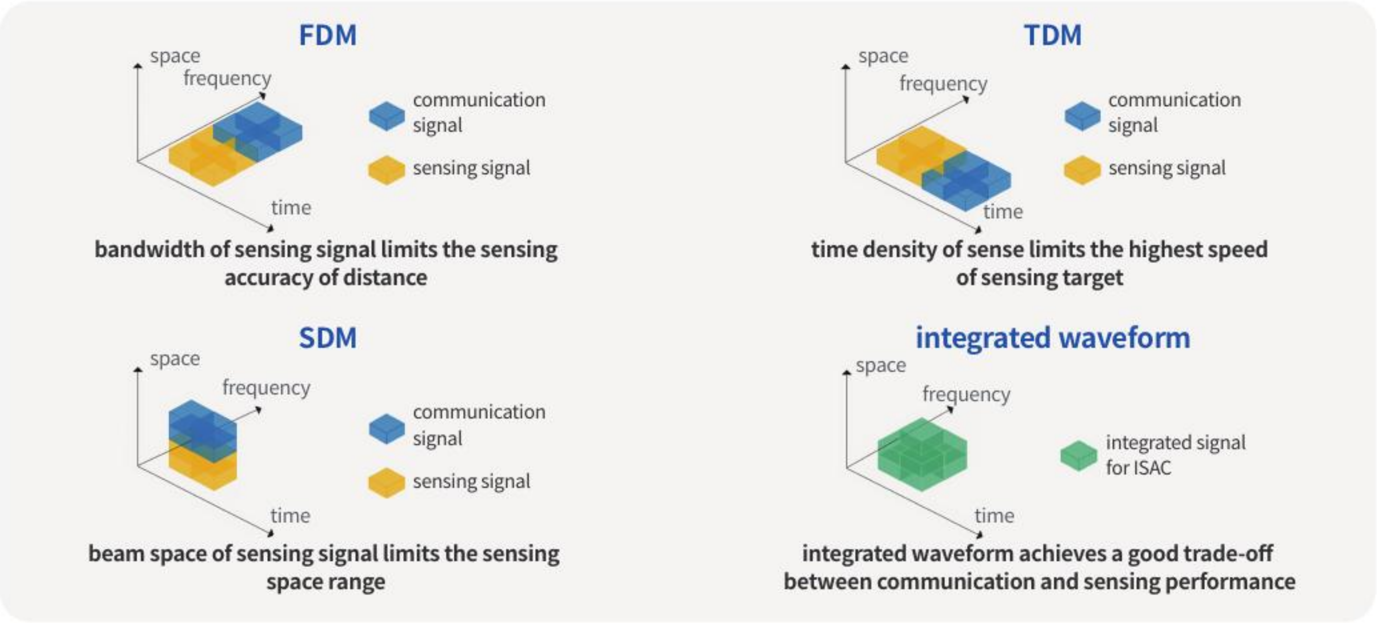

Figure 11: Waveform for ISAC

The idea of ISAC waveform design based on the existing waveform is to form a single/composite waveform by analyzing the performance of existing communication and sensing waveform. The design can be further subdivided into two types of waveform designs: communication-oriented waveform design and sensing-oriented waveform design. The communication-oriented waveform is usually designed based on orthogonal frequency division multiplexing (OFDM) waveform. As a 4G/5G communication waveform, the OFDM waveform has the advantages of strong anti-fading capability, high spectrum utilization, and strong resistance to inter-symbol interference. As such, a high communication transmission rate can be guaranteed. At the same time, as a sensing waveform, the OFDM waveform is sufficient to realize the basic sensing capabilities, e.g., ranging, speed measurement, and angle measurement, can be realized. The sensing-oriented waveform is generally designed based on linear frequency modulation (LFM) waveform. LFM waveform is one of the typical pulse compression waveforms used in radar. Communication capabilities are achieved by embedding communication information in the LFM waveform. The tradeoffs between the data rates achievable by such schemes and resulting impacts to sensing capabilities needs further study.

The new ISAC waveform design needs to comprehensively consider both communication and sensing performance. That is to say, the new waveform can be designed according to integrated design criteria with the consideration of the corresponding basic theories. In this way, new waveforms can achieve a good trade-off between communication and sensing performance. However, waveform designing optimization is highly complex and difficult to adapt to existing hardware, which means it still faces great challenges in practical implementations.

In addition, the existing communication frame structure needs to be redesigned for ISAC. Currently, NR frame structure configuration mainly considers information transmission requirements, including uplink transmission mode, downlink transmission mode, and flexible transmission mode. However, with the development of ISAC technology and the continuous emergence of new services, sensing capabilities will gradually become endogenous capabilities of mobile communication systems. Therefore, the new ISAC frame structure design needs to comprehensively consider the requirements of communication and sensing performance, especially the characteristics of sensing frequency band, sensing scenario, sensing accuracy, timeliness, interference, and equipment capabilities. For example, for sensing scenarios with high-precision requirements such as low-altitude detection, the pilot symbol configuration in the existing frame structure may not be able to meet the performance requirements. It is necessary to consider introducing new sensing symbols that can be flexibly configured when designing the frame structure. At the same time, it is also necessary to combine business requirements and performance requirements to further explore differentiated requirements such as power, waveform, and uplink/downlink switching [39].

7.3 Low-altitude sensing mode

Low-altitude sensing mode can be divided into monostatic sensing mode, bistatic sensing mode and terminal based sensing mode.

01 Monostatic sensing:

The low-altitude sensing system can adopt the monostatic sensing mode, that is, the single-station self-transmitting and self-receiving full-duplex sensing mode. In this self-transmitting and self-receiving mode, the transmitted signal will leak directly to the sensing receiver, forming self-interference, causing the RF front-end to be saturated and unable to detect weak signals at long distances. Therefore, in the single-station sensing mode, the base station needs to overcome the issue of self-interference. Since the self-interference signals are usually highly correlated with the target echo signals, it is difficult to completely eliminate them through coherent signal processing techniques. It requires the use of transceiver antenna isolation, radio frequency interference elimination and other technologies in the analog domain. This method is combined with self-interference cancellation technology in the digital domain to eliminate base station self-interference, thereby achieving single-station low-altitude sensing functions.

02 Bistatic sensing:

The low-altitude sensing system can also adopt a bistatic sensing mode, where base station A transmits, and base station B receives. The advantage of this sensing mode lies in the elimination of the need for full-duplex functionality in the base stations, thereby avoiding the complexity of base station self-interference processing. However, strict time and frequency synchronization must be achieved between base station A and base station B. Time synchronization errors between base stations can impact high-precision ranging performance. According to the existing 3GPP NR protocol TS 38.133, a synchronization accuracy error of ±1.5 microseconds between base stations can result in a distance measurement deviation of approximately 450 meters, which may not meet the requirements of high-precision applications. To achieve time synchronization, the impact of synchronization errors can be mitigated by averaging the propagation delays of the two links: one between base station A transmitting and base station B receiving, and the other between base station B transmitting and base station A receiving. Additionally, the effect of synchronization errors can also be mitigated by measuring the multipath time difference. For frequency synchronization, the frequency deviation mainly originates from the frequency offset of the crystal oscillator of the base station transmitter and base station receiver, as well as the relative motion caused by the moving sensing target between the transmitter and the receiver, and the signal Doppler shift caused by object motion. Therefore, the classic Schmidl&Cox (S&C) algorithm can be used for frequency synchronization. Both monostatic sensing and bistatic sensing belong to network sensing and do not require terminals to participate in the sensing process. There is no need to upgrade the terminal, and it has better compatibility with the terminal, reducing the complexity of the sensing system deployment and improving the system's scalability.

03 Terminal network sensing with User Equipment(UE):

Base station sensing usually requires both base stations and sensed objects, such as UAV, to have a Line of Sight (LOS) for optimal sensing performance. However, when planning communication networks, it is often necessary to minimize overlapping coverage between cells. Additionally, the complexity of dense urban areas and factors like interference can pose significant challenges to receiving sensing signals in LOS environments. At this point, deploying UE as a sensing node in the network through terminal based or terminal network collaborative sensing can effectively alleviate issues such as Non-Line of Sight (NLOS) and interference. It can enhance sensing performance with little cost on communication performance. UE as a sensing node, where either the base station exchanges sensing signals with the terminal or the terminal sending and receiving sensing signals and reporting results to the network, can reuse existing frame structures and signals. By selecting suitable sensing UE (e.g., those closer to the perceived target, or some strategically deployed UEs, e.g. a special box mounted on the outside wall of a high-rise building) to participate in sensing, coverage performance can be improved. When UE serves as a sensing node to transmit/receive sensing signals, it may not necessary to be in LOS connection with the sensing base station, as long as a LOS with the sensing object exist, thus the sensing range and coverage area could be extended, without incurring high cost of deploying additional new ISAC capable base stations. However, the challenge lies in the need for carefully selecting UEs close to the sensed object or designing new types of UEs with a focus on sensing performance such as enhanced synchronization capability with sensing base station. Moreover, the relative position and channel variations between the sensing UE and the sensed object may introduce additional sensing errors into terminal network sensing.

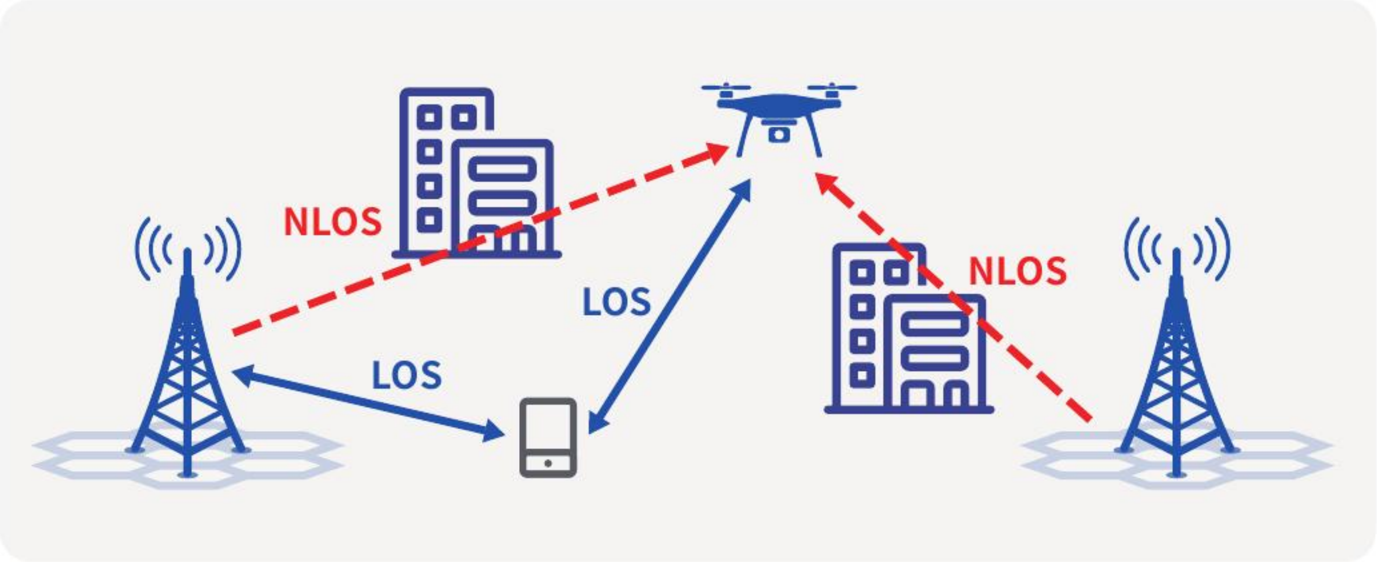

Figure 12: UE as sensing node for auxiliary sensing

Therefore, terminal network sensing with UE requires careful planning for the deployment of sensing UE and optimization of sensing algorithms to mitigate error impacts. Firstly, ensuring LOS between sensing UE and targeted sensing area is crucial to minimize the impact of sensing errors. Secondly, considering the uncertainty of sensing UE and the differential impact of the relative positions of sensing UE, sensed objects, and base stations on sensing errors, algorithms need to be optimized for compensation and correction. To maximize the enhancement of sensing accuracy, specific sensing anchor UE can be designed. Through meticulous planning in deploying anchor UE and positioning them relative to base stations, the improvement in sensing performance can be maximized.

7.4 Networked sensing interference analysis

In a networked low-altitude environment, sensing receiving nodes are susceptible to various types of inter-cell interferences, as illustrated in the diagram below. Specifically, signals transmitted by neighboring base stations may interfere with the sensing echo signals. In the non-monostatic network modes, sensing receiving nodes may also encounter interference along the LOS path from sensing transmitting nodes. The bistatic mode significantly impacts the uplink/downlink allocation and dynamic switching mode of existing communication networks, introducing additional inter-cell cross-link interferences. To effectively mitigate inter-cell interferences in a networked environment, strategies combining both hardware and software, such as time-frequency domain resource partitioning, intelligent antenna beamforming, power control, coherent processing and uplink UE scheduling, are typically employed.

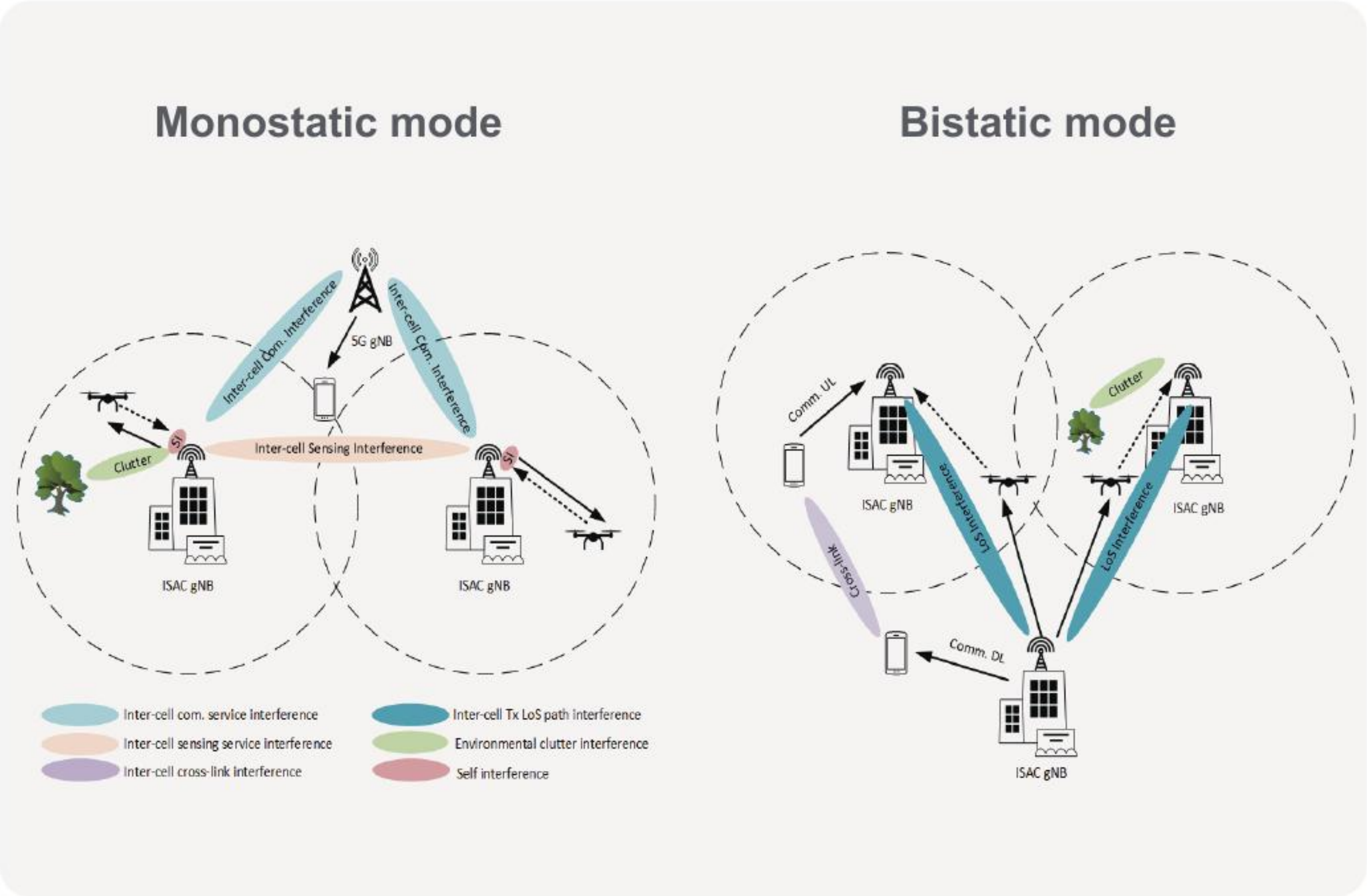

Figure 13: Interference illustration of networked integrated sensing and communication system

Due to the deployment of low-altitude networks, typically in densely populated environments, both sensing and communication signals are vulnerable to significant environmental clutter interference. To address this interference, batch processing elimination and sequential algorithms can be employed to suppress interference and extract echo signals from static objects in the environment. Subspace mapping and least squares algorithms can then be applied to eliminate clutter [13]. Under the condition of stationary sensing targets, removing environmental clutter can suppress or reduce interference from LOS paths and environmental reflection paths, thereby improving the signal-to-clutter ratio by approximately 20dB. This enhancement contributes to the overall improvement of target detection performance, as illustrated in the diagram below.

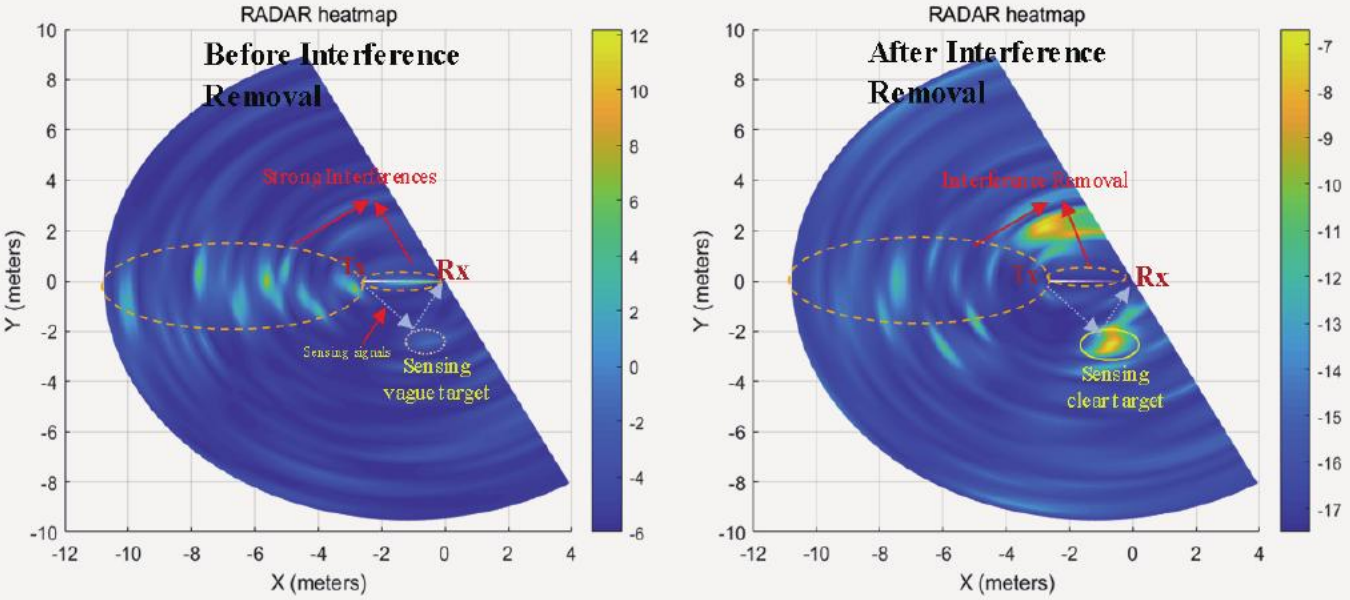

Figure 14: Experimental results of clutter removal in bistatic mode

In summary, achieving interference elimination in networked integrated sensing and communication systems necessitates a comprehensive analysis of the impact of various types of inter-cell interferences and environmental clutter on system performance. Currently, employing the mentioned technological approaches can significantly reduce interference levels and mitigate the adverse effects on the accurate detection of sensing targets.

7.5 Highly-reliable target detection in ISAC network

One of the major advantages of the ISAC systems is the massive networking capability of cellular networks, achieving extensive coverage and high detection rates. The diagram below illustrates a simple ISAC network. In a multi-static ISAC system, it is essential to employ efficient information processing methods to maximize the sensing capabilities and performance. Such technologies including associating and merging the sensing results from multiple base stations can overcome the limitations on detection range, sensing accuracy, and response speed of monostatic ISAC systems. Coverage blind spots of the monostatic system will be mended, thus achieving highly-reliable target detection.

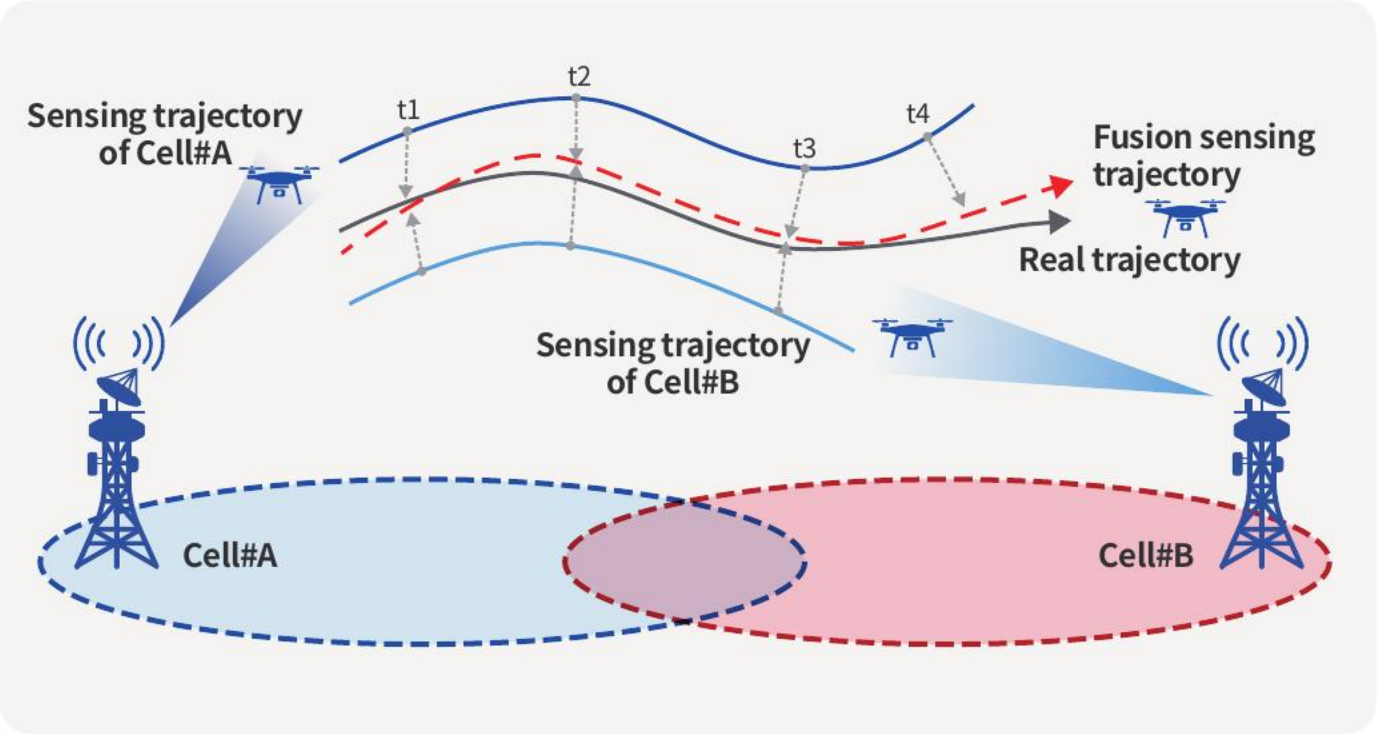

Figure 15: Highly-reliable target detection in ISAC network

Highly-reliable target detection in ISAC network can be realized through the following technologies:

01 Association and fusion of multi-cell trajectories:

By methods of coordinates transformation, space-time aligning, and trajectory association and fusion of single-station target tracking results, a fused track with information from multiple base stations is obtained. This approach yields a diversity gain in target detection rate, anticipating a detection rate improvement to 90-95% [40].

02 Multi-cell joint coordinate calculation:

By jointly processing sensing information from multiple base stations, the equivalent SINR of the sensing targets is enhanced. Utilizing information from multiple sensing nodes for joint coordinate calculation improves the performance of detecting and tracking certain targets.

03 Inter-cell target mobility management:

With the capability of continuous networking, ISAC systems can achieve continuous coverage for target sensing, which enhances the continuity and completeness of moving target detection. Each sensing cell is essentially considered as a large-scale distributed network. Effective distributed information exchange enables the association and matching of trajectories of moving targets among different cells. This achieves seamless trajectory continuation and inter-cell soft handover for moving targets. Issues such as target losses, false alarms, and flickers caused by limited coverage in monostatic systems will be mitigated, therefore improves the completeness of target trajectories during inter-cell switching to over 90-95% [40].

The core mission of an ISAC system is accurate target detection. However, in practical applications, challenges arise due to limitations in shortage of time-frequency resources, restricted coverage, and complex random clutter and interference, which affect the precision and reliability of bistatic systems. To achieve high-precision and high-reliability target detection, it is essential to fully utilize the networking coverage capabilities of base stations and adopt collaborative methods among base stations in ISAC systems. As the smallest units and foundational nodes of an ISAC system, base stations need to possess collaborative capabilities as in cellular mobile communication systems. Through technologies such as the association and fusion of multi-view detection results, multi-cell joint coordinate calculation, and management of target mobility across regions, the capabilities of signal processing and data processing, as well as corresponding results of multiple ISAC stations are combined. This dramatically enhances the detection rate, reliability, and accuracy of target detection of the ISAC systems, while significantly reduces the impact of environmental clutter and interference. As a result, the detection capabilities of the ISAC systems in scenarios with low visibility targets, complex motion paths, and multiple environmental clutter and interference will be effectively improved, and the commercial value of ISAC systems will be therefore greatly broadened.

7.6 Accurate target recognition

Target recognition, building upon functions such as target detection and tracking, further enables base stations to differentiate between different categories of targets. This provides important references for the implementation of countermeasures in response to specific targets. As the scope of sensing expands to low-altitude, road, maritime, and other scenarios, the demand for target recognition in scenarios such as national security, route support, urban security, and others is increasing. The diversity of target types and the complexity of deployment environments pose increasing challenges to target recognition. The diagram below illustrates the technical approach to target recognition in the sensing system.

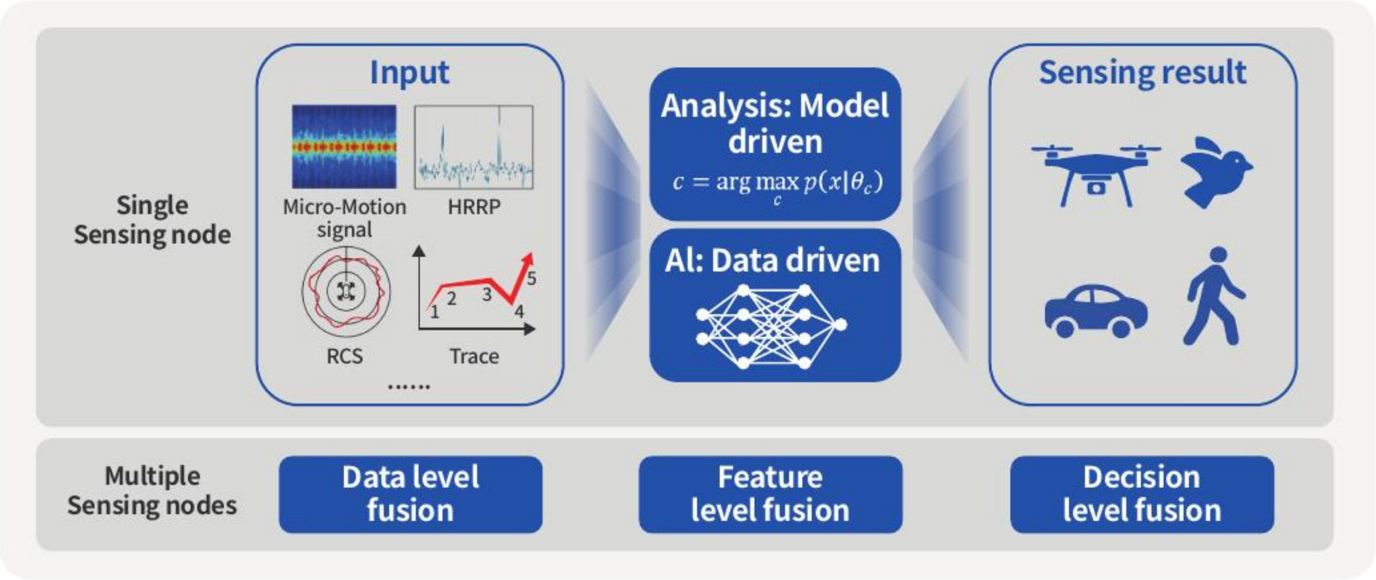

Figure 16: Schematic diagram of the technical approach to target recognition in sensing systems

To achieve accurate target recognition, potential technical approaches include:

01 Extracting effective target features:

Different types of targets exhibit variations in material, structure, and motion patterns. These differences impact radar echoes differently, providing possibilities for accurate target recognition. Based on radar resolution, target features can be classified into low-resolution features and high-resolution features. Low-resolution radar features include radar cross-section (RCS) and motion trajectories, while high-resolution features include micro-Doppler spectrum, high-resolution range profiles (HRRP), etc. By comprehensively integrating low-resolution and high-resolution radar information, unique target features can be thoroughly extracted, providing high-quality data inputs for recognition algorithms.

02 Combining model-driven and data-driven approaches:

Mainstream target recognition algorithms can be classified into model-driven analytic methods and data-driven AI methods. Analytic methods rely on modeling based on domain-knowledge for feature extraction, requiring low or even no demands for training data. They are well-suited for scenarios where collecting and labeling training data is challenging. However, their performance is limited by the accuracy of feature modeling. On the other hand, AI methods, based on data-driven algorithms, do not require modeling based on domain-knowledge and show significant performance advantages when the dataset is sufficient. To adapt to different levels of dataset completeness in different scenarios, an adaptive fusion of analytic and AI methods can be employed. This approach may achieve a balance between robustness and performance, improving the accuracy of single-station target recognition.

03 Multi-cell fusion target recognition:

Leveraging the inherent networking advantages of base stations, sensing of targets is conducted from different geographic locations to maximize the quality of target feature sensing. Based on different stages of multi-cell fusion in target recognition, various fusion strategies can be employed, including data-level fusion, feature-level fusion, decision-level fusion, and others [14]. Furthermore, adaptive selection of the optimal fusion strategy can be adopted based on deployment environments, echo quality, and other parameters. This improves target recognition accuracy in scenarios with collaborative sensing from multiple stations.

Compared to regular radar systems, target recognition in ISAC system faces challenges from limited sensing resources and complex clutter interference. On the other hand, opportunities arise from the intelligent algorithms and multi-cell networking. Intelligent algorithms, in particular deep neural networks, can fully exploit multi-dimensional features from different data sources, expecting to achieve better performance than conventional model-driven analytic methods. However, considering the high demands of deep learning on data and the difficulty of radar data collection and annotation, the integration of model-driven analytic methods is required in practical applications to ensure foundational performance. Multi-cell networking, building upon single-cell capabilities, further diversifies the sources of target feature information, reducing the probability of recognition failures caused by blockage and transient interferences. In summary, target recognition in ISAC systems should leverage the advantages of intelligent algorithms and collaborative multi-station sensing, achieving or even surpassing the performance of regular radar systems.

7.7 Air-and-ground coordinated network

The low-altitude network and the ground communication network are expected to be deployed at the same base station. The ground communication network is blocked by ground buildings and the base stations are relatively densely deployed to ensure continuous coverage. The low-altitude information network covers the airspace and has fewer building blocks. Aerial base stations sparsely deployed can ensure continuous coverage. However, owing to the overlapping regions between the ground communication network and low-altitude information network, coordination between the two networks is required to reduce mutual interference.

In low-altitude network, air-and-ground inter-frequency deployment solution or air-and-ground co-frequency deployment solution can be used for airspace and ground coverage. If the airspace and ground are deployed on the same frequency, the network will mainly cover the ground, while the airspace mainly covered by side lobes, with limited height, mixed signals, serious cross-area coverage as well as uplink and downlink interference, which negatively impact the ground user experience. Additionally, complexities arise in terms of neighboring cell relationships and interoperability strategies configurations, making network optimization relatively challenging. If the airspace and ground are deployed on the different frequency, the airspace coverage can adapt the antenna tilt angle flexibly, covering a broader aerial domain range with controlled interference. This approach simplifies neighboring cell relationships and interoperability strategies.

The air-and-ground coordinated network should be able to identify UAV terminals. It can provide appropriate mobility strategies and multi-frequency collaboration migration or residency strategies to ensure the service experience of each UAV terminal. This will impove the overall network's resource utilization efficiency. Identification methods for UAV terminals can consider using radio access technology (RAT)/frequency selection priority (RFSP)/service profile identifier (SPID), 5G quality of service identifier (5QI)/quality of service class identifier (QCI), slice, International mobile station equipment identity and software version number (IMEISV), etc.

In low-altitude scenes, due to side lobe coverage and signal clutter, frequent switching and ping-pong switching may occur. Therefore, it is necessary to configure appropriate mobility strategies for UAV terminals on the basis of identifying them, such as handover events, thresholds, hysteresis and other parameters, as shown in Figure 17.

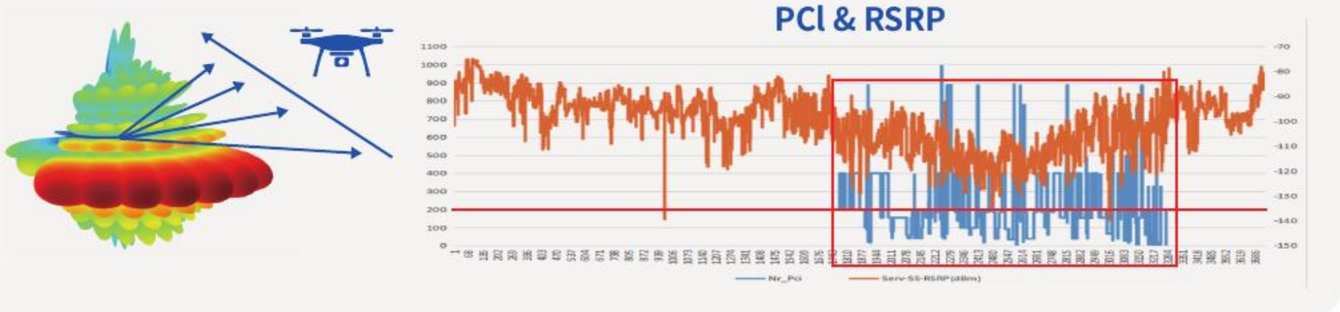

Figure 17: Frequent switching in low-altitude network

If a low-altitude private network is deployed, appropriate migration and residency strategies between public and private networks are required. For ordinary terminals in the public network, migration to low-altitude private network cells is prohibited. For UAV terminals, directional switching needs to be used during the take-off phase to quickly migrate UAV terminals to low-altitude private network cells. During the flight phase, same-frequency switching should be prioritized to keep UAV terminals in private network cells. And during the landing phase, coverage-based switching should be employed, migrating UAV to the public ground network when the private network coverage deteriorates, as shown in Figure 18.

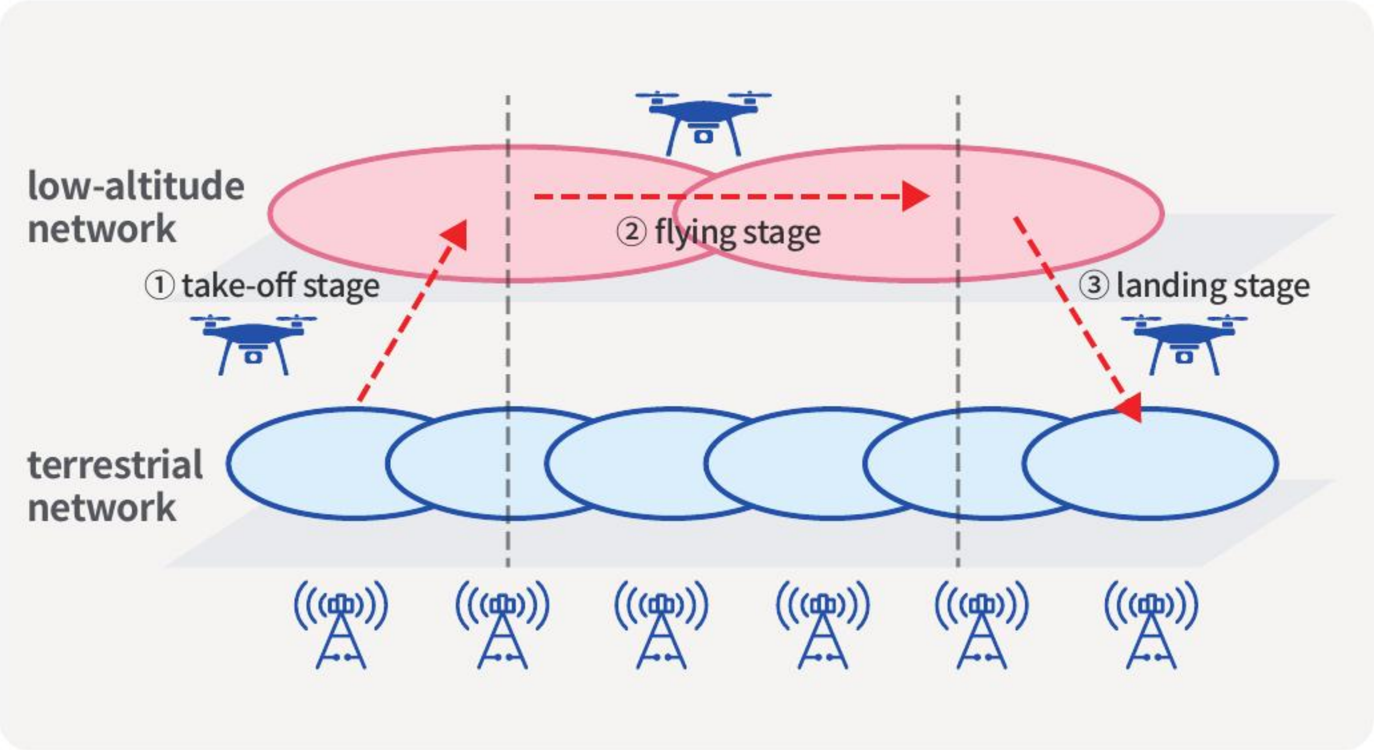

Figure 18: Moving strategy in low-altitude private network

7.8 Low-altitude network communication assurance

The low-altitude information network consists of communication management and sensing management. Communication management involves sending control command to UAVs through the low-altitude information network, receiving information reported by UAVs, etc. It is an essential component of the low-altitude information network. Therefore, the performance and reliability of the wireless communication network are crucial for the safety and efficiency of UAV services. Additionally, different low-altitude communication services have varying requirements for data rate, latency, jitter, and reliability. To further enhance the performance and reliability of wireless communication networks, it is necessary to accurately identify low-altitude communication services and provide precise and differentiated service assurance capabilities.

01 Accurate identification of low-altitude communication services

Wireless communication networks need to have intelligent recognition capabilities for UAV services. Based on the analysis of service flow characteristics and the inference of service profile models, precise recognition of UAV services is achieved, such as real-time control, emergency commands, and high-definition video. At the same time, differentiated wireless air interface scheduling strategies need to be implemented for identified different service flows to meet the experience requirements of different services, achieving dual optimization of service experience and network resource efficiency.

In wireless communication networks, it is necessary to establish an end-to-end quality evaluation system for UAV services, including factors such as UAV command delay, video playback buffering duration and stuttering, etc. Through real-time service quality evaluation and feedback, it guides the fine-tuned closed-loop adjustment of wireless air interface scheduling strategies to ensure deterministic assurance performance during the movement of UAVs.

02 Assurance of low-altitude communication services

Low-altitude coverage mobility and interference coordination are key challenges. Traditional ground station antennas are usually tilted downward, with the main lobe of the antenna pointing towards ground users to provide communication services, while low-altitude UAVs are primarily served by the side lobes of base station antennas, leading to two challenges: (1) The upper side lobe coverage of antenna beams can easily result in serious cross-area coverage. Mis-switching will be caused if side lobe fragmentation leads to significant cross-region coverage. (2) For aerial signal propagation, LOS propagation is predominant, and it is easy to receive signals from multiple cells, causing serious interference, as shown in Figure 19.

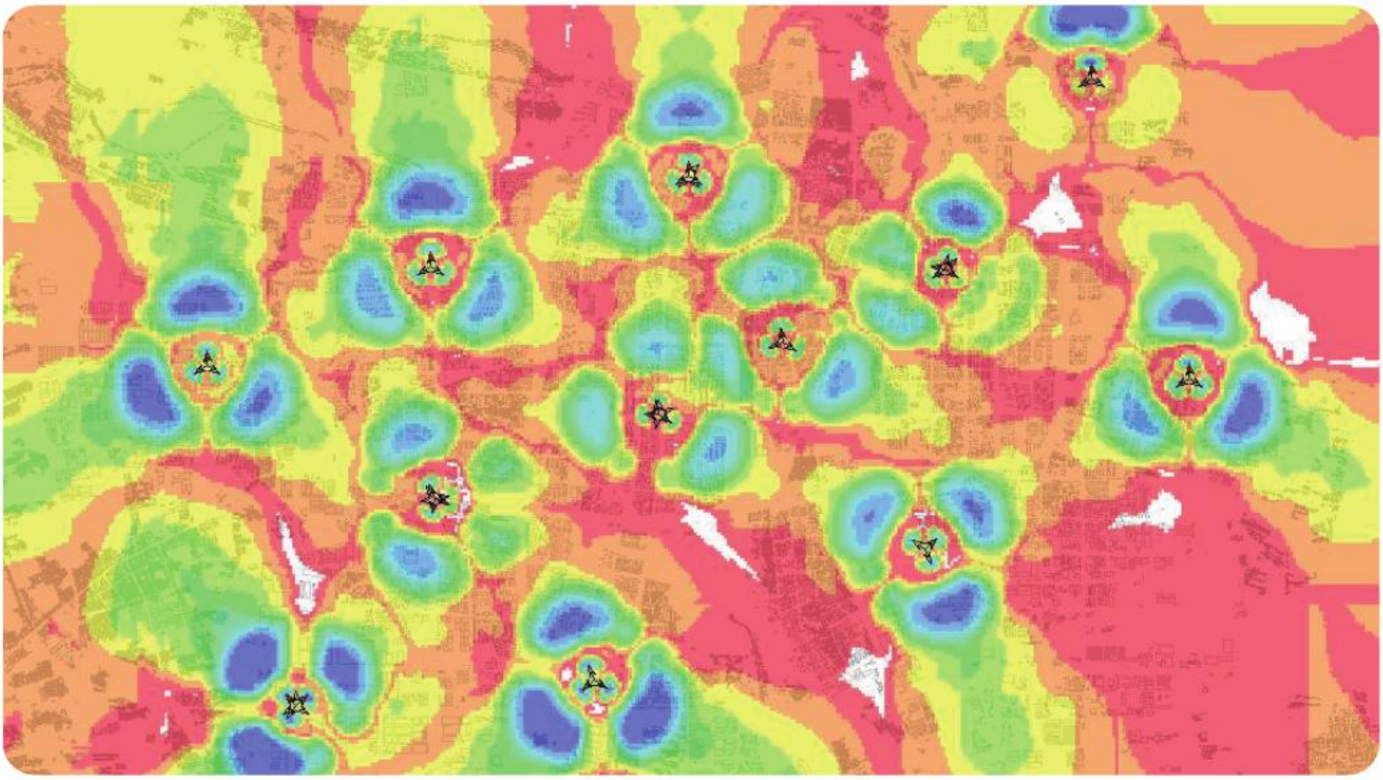

Figure 19: Severe interference in low-altitude network

Based on the above considerations, to ensure the reliability and high data rates of low-altitude communication services, it is recommended to use air-and-ground inter-frequency coverage. At the same time, the frequency points for airspace can also cover ground hotspots. In the case of using air-and-ground co-frequency coverage, the issue of low-altitude network interference affecting user communication can be addressed by introducing the concept of clusters in the spatial domain. Within a cluster, resources can be jointly scheduled, and base stations antennas can be synchronized for multi-antenna transmission and reception, thereby reducing low-altitude interference and enhancing the benefits of joint transmission and reception, as illustrated in the diagram below.

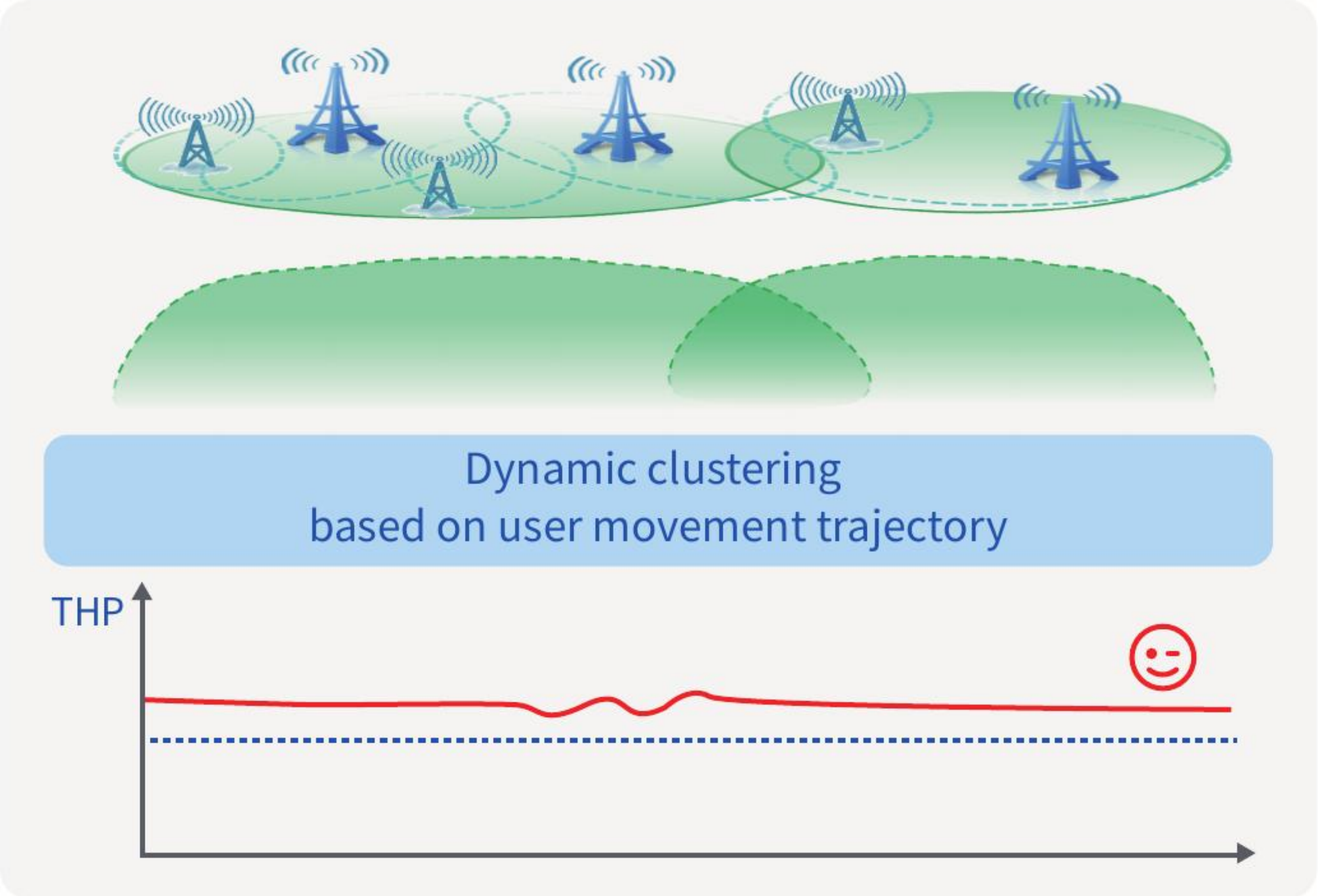

Figure 20: Cluster based user service architecture

03 Site density of low-altitude networks

In the low-altitude three-dimensional coverage environment, the signal transmission loss from base stations to UAVs is primarily through the direct path, resulting in smaller transmission losses compared to ground transmission at the same distance [15]. Therefore, the cell radius of low-altitude coverage is larger than that of ground coverage. The cell radius ratio of low-altitude networks and ground networks is denoted as 1:N, where the value of N depends on factors such as ground environment, carrier frequency, coverage requirements, etc. When there are more buildings in the ground environment and higher carrier frequencies, leading to increased penetration loss and diffraction/refraction loss, and larger ground coverage path loss, the value of N tends to be larger. Conversely, when the coverage altitude is higher, resulting in a larger beam height angle and a smaller horizontal projection radius of the low-altitude network cell, the value of N tends to be smaller. Combining link budget analysis and practical evaluation, in rural scenarios, the cell radius ratio N is within the range of 2-3. In most urban areas, the cell radius ratio N is within the range of 5-6, and in dense urban areas, the cell radius ratio N is within the range of 6-8. Additionally, considering factors such as high building causing obstruction and coverage holes, urban scenarios may require denser deployment of low-altitude stations to ensure the communication quality in low-altitude network.

7.9 Aircraft-to-anything(A2X) communication

Solutions for tactical deconfliction of UAVs are of high importance in low-altitude network, especially in dense air spaces like in urban operations. A global concept of aircraft-to-anything (A2X) is being developed in various regulatory standards and is being supported by completed and ongoing 3GPP standardization efforts in order to provide tools for efficient tactical deconfliction that supplement solutions like sensing.

A2X relies on communication technology that allows devices to communicate directly with each other without cellular connectivity. This direct communications capability provides for low latency communications to support collision avoidance anywhere that UAVs may fly, and in the conditions where communications with cellular base stations are degraded or non-existent. A2X is an independent capability that persists even as the command and control link may come and go. It is a redundant and complimentary function to network-enabled command and control, and it is appropriate for safety-sensitive and safety-critical operations.

The use of A2X in addition to cellular connectivity by UAV enables Aircraft-to-Aircraft (A2A) communication for UAV detection using broadcasting of information from the UAVs, and UAV deconfliction using unicast communications between UAVs that have detected a conflict. Additionally, sensors and computing technology onboard can leverage such communications to detect potential conflicts and perform deconfliction when the UAV is equipped with DAA (Detect and Avoid) autonomous deconfliction logic. A2X also provides Aircraft-to-Ground (A2G) communications to transmit DAA information to authorized ground receivers and for UAVs to receive information from authorized ground transmitters (e.g., for obstacle avoidance). Leveraging A2X enables UAV-Remotely Piloted System (RPS) communications using cellular connectivity via a mobile network to report detected conflicts and communicate/receive deconfliction information with the RPS.

With A2X technology in UAS, it is possible to share information between UAVs to prevent collisions between UAVs and obstacles, and also to prevent collisions with ground movement obstacles enabled with A2X. The communication distance of this standard is about two to three kilometers, allowing UAVs and other aircraft (e.g., helicopters) to be mutually recognized, thereby securing flight safety of crewed and uncrewed aircraft at the same time. For example, A2X can recognize flying drones from different manufacturers to spray pesticides on large farmland simultaneously, or for several drones to fly over a targeted fire area at the same time. Compared to heavy and expensive radar solutions for drone recognition, A2X can be manufactured relatively inexpensively (as demonstrated by the C-V2X market), making it suitable for DAA solutions for UAVs.

The deployment of A2X solutions using dedicated spectrum allocated for UAV A2X applications will support devices without cellular connectivity or those using different carrier spectrum. Spectrum is being made available worldwide for such scenarios, and a dedicated spectrum should be allocated for A2X. Unlicensed spectrum is not an appropriate alternative to ensure safer and more efficient UAS flights and collision avoidance via DAA communications because it lacks interference protection and may experience high levels of unwanted and uncontrollable noise in populated areas of the country where UAS operations will be prevalent. Simulations have shown that a dedicated 20 MHz channel is sufficient to support safety-critical, authenticated communications at distances to support reliable, safe, and high-speed UAS flights, ensuring UASs can reliably implement DAA communications across expected UAV densities in urban areas and other dense operating environments.

7.10 UAV collision avoidance system

UAV collision avoidance system is a comprehensive system designed for the broad low-altitude airspace. It is based on spatial resources gridding and integrated flight information, constituting a collision avoidance system for UAV. This system integreates functions such as flight safety sensing, collision warning, flight alert, and intelligent route planning. The deployment of this system is built upon spatial gridding and refined operation. It makes use of technologies such as ADS-B, UAV flight data reporting, low-altitude detection radar, etc., and combines them with deep learning technology and powerful computing capabilities, to achieve collision avoidance for UAV in the general low-altitude airspace.

The main functions of the UAV collision avoidance system include:

01 **Airspace Griding [41]:** Airspace griding is the foundation of the UAV collision avoidance system. It involves pre-cutting airspace resources into specific rectangular grids based on three-dimensional geographic coordinate information. Subsequently, each grid is individually marked.

02 **Flight safety sensing:** Flight safety sensing is based on spatial griding, where meteorological (micro-meteorological)[42] conditions are marked in the spatial grid, providing continuous protection for flight safety.

03 **Active communications via A2X:** A2X enable situational awareness of UAV thanks to direct communications between UAVs, and network awareness of UAVs by using aircraft-to-gound cellular communications from the UAVs;

04 **Collision Warning [16]:** Collision warning involves pre-evaluating collision risks for planned flight activities. Considering factors such as the UAV's flight speed, personnel/equipment reaction time, the impact of weather conditions on flight, and safety-related elements, a virtual buffer zone is reserved around the physical edges of the UAV. The UAV is then modeled as a specific cubic shape and gridized, assessing collision risks based on this setup.

05 **Flight Alert:** Flight alert involves the conversion of real-time comprehensive flight information into airspace grids. Through deep learning, it judges and predicts the four-dimensional flight trajectory as well as the associated flight safety assessment.

06 **Intelligent Route Planning [17]:** Intelligent route planning involves determining a three-dimensional flight route based on real-time airspace traffic, weather conditions, service assurance conditions, along with factors such as the cost of path length, safety, feasibility, altitude, and path smoothness, given the takeoff point and landing point.

Figure 21: Collision buffer zone effect of UAV

7.11 Low-altitude supervision service platform

The low-altitude supervision service platform is designed for the management and control of low-altitude UAV flights. It aims to achieve the management goals of UAVs being visualized, schedulable, and monitorable. This platform includes modules such as meteorological processing services, airspace processing services, intelligence processing services, flight plan processing services, surveillance information processing services, and integrated computing services, with the following features:

01 **Meteorological processing services:** Provides pre-flight and in-flight meteorological information and weather conditionfor UAVs to ensure flight safety, by integrating professional third-party meteorological forecast data and real-time meteorological data.

02 **Airspace processing services:** Provides precise management services for low-altitude airspace resource utilizing Beidou grid location codes, City

Information Models (CIM), and geographic elevation data. This involves constructing a manageable airspace digital foundation to enhance the efficiency of airspace resource utilization.

03 **Intelligence processing services:** Provides detailed pre-flight intelligence information for UAV users, including suitable flying zones, controlled zones, no-fly zones, as well as other user-declared temporary isolation zones and notices, to ensure flights take place within legally defined ranges.

04 **Flight plan processing services:** Manages UAV user registration and their flight plans, establishes models for expressing and describing flight plans, provides declaration services through a human-machine interface, validates plans before flight, and monitors execution in real-time during flight to ensure the compliance and safety of flight plans.

05 **Surveillance Information plan processing services:** Integrates trajectory information from active and passive surveillance systems, providing flight status monitoring services. It accurately supervises UAV operations based on information such as flight plans, meteorology, electronic fences, and geographic elevation, offering various alert services.

06 **Integrated computing services:** Establishes fine operational capabilities for a four-dimensional trajectory based on the digital foundation. This includes services such as airspace traffic control, refined airspace organization and management, UAV collision avoidance testing, intelligent route planning, and optimization of air routes and networks. It achieves computing and management of UAV operations.

Through the combination of the above technical modules, the platform provides efficient, safe, and controllable flight management. It also provides control solutions for low-altitude UAVs, and reliable technical support for future applications in the low-altitude field.

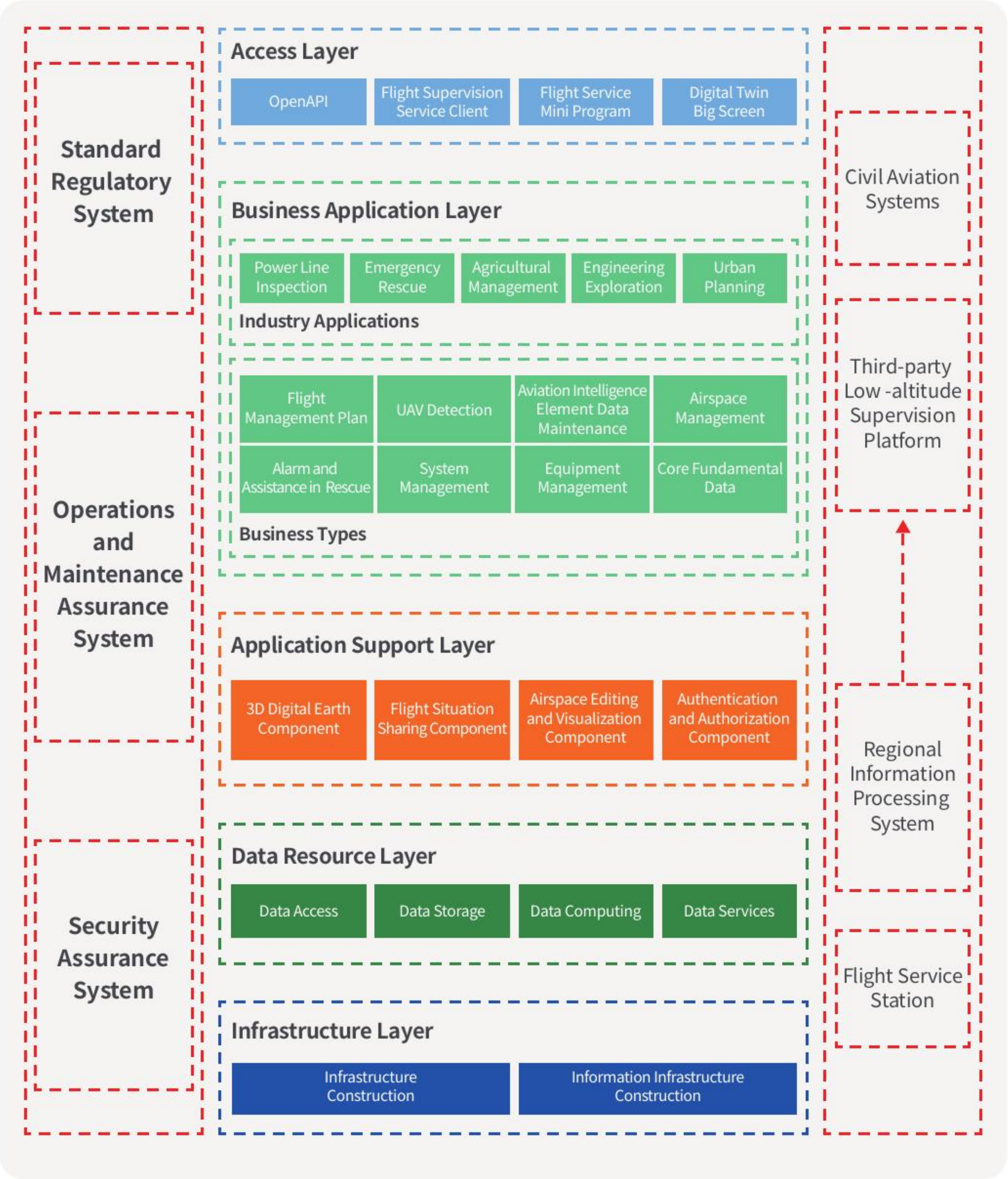

Figure 22: Low-altitude UAV supervision and service platform architecture

08 Outlook

The low-altitude economy, as a strategic emerging industry, has been included in the national development plan. An unstoppable development trend for the low-altitude economy has formed by the market driven and local government participation. Compared to the mature management and commercial operation of aviation flight, the low-altitude economy, as a pioneering business form, may have some uncertainties in its development and requires more effective techniques to support the UAV flight with high-capacity, multi-layers, high-density, , high reliability and safety, and high-frequency in low-altitude airspace.

According to local government policies, vertical industrial and business progress, China Telecom will collaborate with industry partners, and take low-altitude connectivity via cellular networks as a starting point to carry out the integrated sensing and communication network trial to achieve the identification, management, and controllability capability for low-altitude aircraft to promote the maturity of low-altitude management network. China Telecom is willing to create a cooperative, innovative, and win-win low-altitude network ecosystem assist the low-altitude economy from being poised to taking off.

Acronyms and Abbreviations

Acronym	Full Name
3GPP	Third Generation Partnership Project
4G	4th-Generation
5G	5th-Generation
5QI	5G Quality of Service Identifier
6G	6th-Generation
A2A	Aircraft-to-Aircraft
A2G	Aircraft-to-Ground
A2X	Aircraft-to-Anything
AAM	Advanced Air Mobility
AAV	Autonomous Aerial Vehicle
ADS-B	Automatic Dependent Surveillance-Broadcast
AI	Artificial Intelligence
CAGR	Compound Annual Growth Rate
CIM	City Information Modeling
C-V2X	Cellular-Vehicle-to-Everything
DAA	Detect and Avoid

Acronym	Full Name
EASA	European Union Aviation Safety Agency
eVTOL	electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
GPS	Global Positioning System
HD	High-Definition
HRRP	High Resolution Range Profile
IMEISV	International Mobile Station Equipment Identity and Software Version Number
IPP	Integration Pilot Program
ISAC	Integrated Sensing and Communication
JARUS	Joint Authorities For Rulemaking on Unmanned Systems
LFM	Linear Frequency Modulation
LOS	Line of Sight
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NLOS	Non-Line of Sight
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
QCI	QoS Class Identifier

Acronym	Full Name
QoS	Quality of Service
RAT	Radio Access Technology
RCS	Radar Cross-Section
RFSP	RAT/Frequency Selection Priority
RPS	Remotely Piloted System
S&C	Schmidl&Cox
SINR	Signal-to-Interference Plus Noise Ratio
SORA	Specific Operation Risk Assessment
SPID	Service Profile Identifier
UAM	Urban Air Mobility
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UTM	Unmanned Aerial System Traffic Management
Wi-Fi	Wireless Fidelity

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