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Technical Analysis of 6G Integrated Sensing, Communication, and Intelligence Wireless Network Technology

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Abstract: 6G Integrated Sensing, Communication, and Intelligence (ISCI) wireless network technology converges capabilities in communication, sensing, computation, and AI to construct a space-air-ground integrated, all-domain intelligent network. Its core lies in breaking down technical barriers to achieve deep fusion of multi-dimensional sensing, collaborative communication, and intelligent computing, thereby enhancing the network's multi-task processing efficiency. Through breakthroughs in key technologies such as Integrated Sensing and Communication (ISAC), intelligent computing power scheduling, and space-air-ground networking, this technology empowers scenarios like the low-altitude economy, intelligent manufacturing, and smart healthcare, driving digital transformation and innovative development to open a new chapter for the future intelligent society.

Keywords: 6G technology; integrated sensing, communication, and intelligence; wireless network technology

Introduction

With the acceleration of 5G commercialization, the global communication industry has set its sights on the next-generation technology—6G. 6G is no longer confined to the traditional scope of communication but is evolving deeply towards the integration of sensing, communication, and intelligence, aiming to build a wireless network where communication, sensing, and intelligent computing seamlessly converge. This integrated network will break through existing technological limitations, achieving all-domain coverage, ultra-low latency, ultra-high-precision sensing, and intelligent decision-making, providing critical support for the digital transformation and intelligent development of future society, and bringing unprecedented change and opportunities.

1. The Core Connotation and Architecture of 6G ISCI Wireless Networks

1.1 Definition and Characteristics

(1) Integrated Sensing and Communication: This breaks down the barriers between communication and sensing technologies, enabling communication signals to serve dual functions of data transmission and environmental detection. For example, base station signals can be used for target localization, speed measurement,

and environmental imaging. In vehicle networking scenarios, data exchange between vehicles and road obstacle perception can be performed synchronously. Dynamic resource allocation achieves cooperative optimization of communication rate and sensing accuracy, enhancing network multi-task processing efficiency.

(2) Intelligent Computing Power: This constructs a cloud-edge-device collaborative computing power network, dynamically scheduling computing resources according to service demands. For instance, in industrial IoT, edge nodes can perform real-time inference on device data, while the cloud undertakes large-scale AI model training tasks. Intelligent algorithms enable computing load balancing, reducing resource waste while enhancing network autonomous capabilities such as fault diagnosis and traffic prediction.

(3) Space-Air-Ground Integration: This integrates low-earth orbit (LEO) satellites, high-altitude UAVs, and terrestrial base stations to form a three-dimensional networking pattern. In remote areas or disaster scenarios, satellites can quickly fill coverage gaps, achieving ubiquitous signal coverage. Unified protocol standards and handover mechanisms ensure service continuity for users moving on the ground or in the air.

(4) Digital Twin: This establishes a digital model highly consistent with the physical network, collecting real-time data on network device status, user behavior, and environmental parameters. Simulation predicts network load changes, enabling proactive optimization of resource scheduling strategies. For example, in large-scale event scenarios, base station capacity can be adjusted in advance based on the digital twin to avoid network congestion.

1.2 Network Architecture Design

(1) Layered Architecture: The application domain focuses on industry-specific needs, providing customized services like smart transportation and telemedicine. The control domain uses an intelligent orchestration engine to achieve automated service process deployment and dynamic network parameter adjustment. The resource domain integrates communication, sensing, and computing resources into a shared pool for on-demand allocation. The terminal domain encompasses intelligent devices with integrated sensing-communication-computing access capabilities, enabling efficient interaction with the network.

(2) Key Modules: The integrated sensing-communication-computing air interface employs flexible waveform design to support co-frequency transmission of communication and sensing signals. The networked sensing system enhances sensing range and accuracy through multi-node data fusion. The intelligent computing power scheduling platform uses AI algorithms for real-time allocation and optimization of computing resources. Security and trust mechanisms, utilizing blockchain and zero-trust technologies, ensure the security of data transmission and resource sharing[1]

(3) Technology Integration Path: The initial phase achieves the fusion of communication and sensing technologies to enhance foundational network capabilities. The mid-term phase integrates computing resources to form a collaborative sensing-communication-computing architecture. The final phase constructs a "Capability-as-a-Service" platform, encapsulating sensing-communication-computing capabilities as standardized services for on-demand invocation by industry users, promoting the large-scale application of 6G technology across various fields.

2. Key Technological Breakthroughs and Innovations in 6G ISCI Wireless Networks

2.1 Integrated Sensing-Communication-Computing Air Interface Technology

(1) Waveform and Frame Structure Design: An OFDM integrated waveform is used, with the frame structure dynamically dividing communication subframes and sensing subframes to achieve flexible time-domain resource allocation. In the terahertz (THz) frequency band (0.3-3THz), waveform orthogonality is leveraged to reduce signal distortion and overcome high-precision imaging challenges. The core supporting formula is the THz signal propagation loss model:

$$LTHz = 20\lg(\frac{4\pi fd}{c}) + \alpha(f)d$$

Here, f is frequency (Hz), d is propagation distance (m), c is the speed of light (3×10^8 m/s), and $\alpha(f)$ is the specific attenuation coefficient for the THz band (dB/m). This model supports millimeter-level environmental reconstruction accuracy.

(2) Array Antennas and Beamforming: Based on

massive MIMO technology, an N×N array antenna (N ≥ 256) is employed, focusing signal energy through beamforming algorithms. The pattern gain formula is:

$$G(\theta,\phi) = \left| \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} e^{j2\pi \frac{d}{\lambda}(\sin\theta\cos\phi i + \sin\theta\sin\phi j)} \right|^2$$

Here, w_{ij} is the antenna weight coefficient, θ/ϕ are the azimuth/elevation angles, and λ is the signal wavelength. This technology improves sensing resolution to 0.1m, supporting sub-meter level positioning and high-speed moving target tracking[2].

(3) Interference Suppression and Resource Scheduling: A communication-sensing interference model is established (see **Figure 1**). A Dynamic Spectrum Allocation (DSA) algorithm allocates subcarriers, combined with a power control strategy $P_{opt} = \frac{\gamma_{req} N_0 B}{G_{ch}}$ (where γ_{req} is the target SNR, N_0 is the noise power spectral density, B is bandwidth, G_{ch} is channel gain), reducing mutual interference by over 30% and enabling multi-user collaborative sensing.

(4) Experimental Validation: Huawei's THz prototype system, operating at 0.6THz, simultaneously achieved imaging functionality with 0.5mm resolution and high-speed communication at 10Gbps with 64QAM modulation. China Mobile, building upon 5G-Advanced, completed vehicle target detection within a 500-meter distance, achieving a sensing accuracy of 0.8m, verifying technical feasibility.
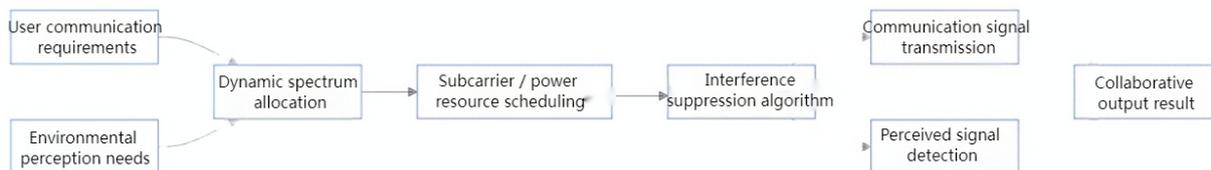

Figure 1. Communication-Sensing Signal Interference Suppression Logic Diagram

2.2 Networked Sensing Technologies

(1) Ubiquitous sensing capability: A distributed base-station sensing network is constructed to enable multi-node data fusion and achieve three-dimensional monitoring across air–ground–vehicle domains. In low-altitude economy scenarios, base stations receive reflected signals from unmanned aerial vehicles (UAVs) and, combined with Time of Arrival (TOA) and Time Difference of Arrival (TDOA) positioning algorithms, enable real-time UAV trajectory tracking. In intelligent transportation scenarios, roadside base stations perceive vehicle speed and inter-vehicle distance, supporting vehicle–infrastructure cooperative decision-making.

(2) Intelligent data processing: A lightweight CNN–LSTM hybrid model is employed to process sensing data, which can be expressed as:

$$y_t = LSTM(CNN(x_t), y_{t-1})$$

where x_t denotes the sensing data at time ttt. The CNN extracts spatial features, while the LSTM captures temporal correlations. This hybrid architecture improves target recognition accuracy to 98% and reduces decision latency to within 10 ms.

(3) Typical cases: Shandong Mobile deployed an ultra-dense 5G-A base station cluster in Qingdao. Through multi-base-station cooperative sensing, UAV trajectory tracking with an accuracy of 0.5 m was achieved, covering a sensing radius of up to 3 km. Meanwhile, ZTE implemented networked sensing technology in a vehicle–road cooperative demonstration zone in Suzhou, achieving vehicle positioning errors of no more than 0.3 m and supporting safety warnings at vehicle speeds of up to 100 km/h [3].

2.3 Intelligent Computing Power Network Technology

(1) Unified Scheduling of Computing Resources: Based on base station computing virtualization technologies (e.g., NFV), idle base station computing power is encapsulated into "computing slices". A scheduling algorithm, Maximize $k = \sum_{k=1}^{N} R_k P_k$ (where R_k is the rate for user k, and P_k is the computing power allocation ratio), enables on-demand resource allocation. AsiaInfo deployed a lightweight large model (parameter size < 100M) on base stations, reducing edge inference latency to 5ms.

(2) Cloud-Edge-Device Collaboration: A "cloud training, edge inference" architecture is established. The cloud leverages GPU clusters to train complex

models (e.g., Transformer), while edge nodes deploy quantized versions of these models for real-time computation. In industrial applications, the edge analyzes equipment vibration data in real-time through the computing power network. By integrating this with cloud-based fault diagnosis models, a device health monitoring accuracy rate of 95% is achieved.

(3) Experimental Platform: China Mobile's 6G Integrated Sensing, Communication, Computing, and Intelligence Trial Platform integrates 50 edge computing nodes and one cloud computing center. Its intelligent orchestration system enables a computing power scheduling response time of < 200ms and improves resource utilization by 40%.

2.4 Space–Air–Ground Integrated Technologies

(1) Satellite–terrestrial integrated networking: Low Earth orbit (LEO) satellites (e.g., Starlink) are coordinated with terrestrial base stations to form an integrated network through a satellite–ground handover protocol, denoted as Handover(S,B), where S represents a satellite node and B denotes a terrestrial base station. This mechanism enables seamless coverage and continuous connectivity. In marine monitoring scenarios, satellites provide wide-area signal coverage, while terrestrial base stations compensate for coverage gaps in nearshore regions, extending communication coverage to approximately 98% of the Earth's surface [4].

(2) Reconfigurable Intelligent Surfaces (RIS): By dynamically adjusting the reflection coefficient θmn (where m,n denote the element coordinates), RIS optimizes signal propagation paths. The channel gain can be expressed as:

$$G_{RIS} = \left| m = \sum_{m=1}^{m}\sum_{n=1}^{n} \alpha_{mn} e^{j\theta_{mn}} \right|^2 G_{Tx-RIS} G_{RIS-Rx}$$

where α_{mn} represents the amplitude coefficient of the RIS element, and G_{Tx-RIS} and G_{RIS-Rx} denote the channel gains between the transmitter and RIS, and between RIS and the receiver, respectively. Through adaptive phase control, RIS technology can more than double overall network capacity.

(3) Huawei validation results: In experimental LEO satellite communication trials conducted by Huawei, stable 64QAM modulation transmission was achieved at vehicular speeds of up to 120 km/h, with a peak data rate of 500 Mbps and an end-to-end latency of less than 20 ms. These results demonstrate the feasibility

of integrated space–air–ground communication technologies in high-mobility application scenarios.

3. Typical Application Scenarios and Industrial Value

3.1 Low-Altitude Economy

(1) Coordinated UAV management: Relying on 6G integrated sensing–communication base stations, real-time information such as the position and velocity of unmanned aerial vehicles (UAVs) in low-altitude airspace can be accurately captured, enabling intrusion detection and dynamic path planning. When multiple UAVs operate in close proximity, sensing data are used to rapidly predict collision risks and trigger early warnings, thereby ensuring operational safety in scenarios such as logistics delivery, power line inspection, and agricultural plant protection. For example, in logistics applications, UAVs can leverage precise network-based positioning to identify delivery targets and avoid obstacles; in agricultural spraying, base stations perceive farmland terrain and crop distribution, optimizing spraying routes and improving operational efficiency.

(2) Case study: China Mobile Chongqing, in collaboration with industry partners, completed a validation of 5G-A low-altitude sensing technology by deploying an integrated sensing–communication base station network in urban areas. The network is capable of simultaneously monitoring more than 50 UAVs and supports UAV logistics delivery within a 30-kilometer range. This solution effectively addresses safety and efficiency challenges associated with the "last mile" of low-altitude logistics, promoting the large-scale development of the low-altitude economy.

3.2 Intelligent Manufacturing

(1) Intelligent coordination of industrial equipment: With microsecond-level communication latency and sub-millimeter sensing accuracy, 6G integrated sensing–communication–computing networks enable highly coordinated operations among factory equipment. In precision manufacturing processes, machines exchange data in real time and synchronize actions to ensure production accuracy. In applications such as remote surgical robots, the network supports sub-millimeter operational precision, ensuring surgical accuracy, while computing resources process surgical data in real time to assist medical decision-making [5].

(2) Case study: The Beijing Economic–Technological Development Area has deployed a prototype 6G cloud-based base station, connecting more than 200 industrial devices within a smart factory. Through coordinated sensing, communication, and computing, real-time monitoring of equipment operating status is achieved. When abnormalities occur, the system rapidly diagnoses fault types and pushes corresponding solutions, reducing equipment downtime by approximately 30% and significantly improving production efficiency.

3.3 Smart Healthcare

(1) Contactless health monitoring: Using 6G optical wireless integrated sensing–communication technology, physiological indicators such as heart rate and respiratory rate can be collected in real time without physical contact. Intelligent algorithms analyze data characteristics and provide timely warnings for risks such as myocardial infarction or cerebral infarction when abnormalities (e.g., irregular heart rate or rapid breathing) are detected. This approach is particularly suitable for elderly individuals, postoperative patients, and other populations for whom wearing monitoring devices is inconvenient.

(2) Case study: An optical wireless sensing prototype developed by Huawei has been tested in hospital environments. By transmitting optical signals at specific frequency bands and receiving reflected signals, the system calculates human respiratory rates with a monitoring error of no more than ±1 breath per minute, comparable to smart wearable devices. This provides a low-cost, contactless monitoring solution for smart healthcare applications.

Conclusion

As a frontier innovation in the field of wireless communications, 6G integrated sensing–communication–intelligence–computing network technology combines multiple advanced concepts and technologies, demonstrating tremendous potential and broad prospects. Beyond achieving significant technical breakthroughs, it has also generated new applications and value across diverse fields such as the low-altitude economy, intelligent manufacturing, and smart healthcare. Although some technologies remain under development, continued research and practical deployment will inevitably reshape the future network landscape, injecting powerful momentum into the advancement of intelligent and digital societies and ushering in a new era of communications.

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