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Key Technology Analysis of Integrated Sensing System Towards 6G Communication

Jiale Zhang

School of information engineering, Heilongjiang University of Finance and Economic, Ha'erbin, 150000, China

Abstract: As emerging networks put forward higher demands for end-to-end information processing capability in 6G communication, integrated sensing and communication technology has become a prevailing trend for the future development of 6G. By adopting the integrated sensing and communication technology, the integrated sensing system in 6G communication could implement various functions, such as spectrum sharing, hardware sharing, and signal sharing, so as to further enable real-time monitoring, tracking, identification, and imaging of targets or objects, and to meet the needs of users in a better way. By separating communication and sensing, the integrated system could enhance both the performance of integration and collaboration. In this paper, with the purpose of discussing the application scenarios and performance metrics for integrated sensing and communication in depth, we also highlight the analysis of key technologies such as system architecture, air interface integration, and network integration. Our aim is to achieve an effective operation of the integrated system.

Keywords: 6G; Integrated sensing; Key technology; Communication.

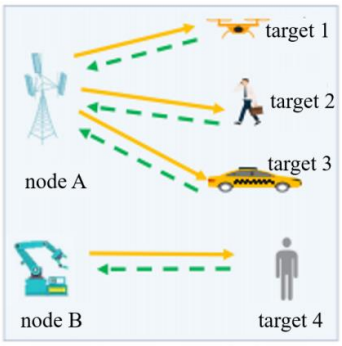
1. Introduction

As is figured out by the IMT-2030 (6G) Promotion Group in the white paper on "6G Vision and Candidate Technologies", 6G could utilize communication signals to achieve various sensing functions, such as target detection, localization, identification, imaging, which enables the technology of integrated sensing and communication as one of the core features of 6G.[1] In the period of 2030+, 6G technology will bring significant changes, making it easier to integrate virtual and physical scenarios. In this way, the goals of "digital twin" and "ubiquitous intelligence" will be achieved. The integration of sensing and communication is a new typical feature of 6G. On the one hand, the integration of sensing and communication will provide diversified capabilities such as high-precision positioning, environment reconstruction, imaging, etc., which will meet the needs of ultra-high resolution and precision applications. On the other hand, the integration of sensing and communication will also help to improve the performance and efficiency of the communication. For example, the utilization of wireless resources could be optimized by taking into account the user's moving trajectory and environmental changes [2]. In this paper, we survey and summarize the progress in the research on the integrated sensing and communication. Besides, the working modes, application scenarios, and key technologies in it are also discussed.

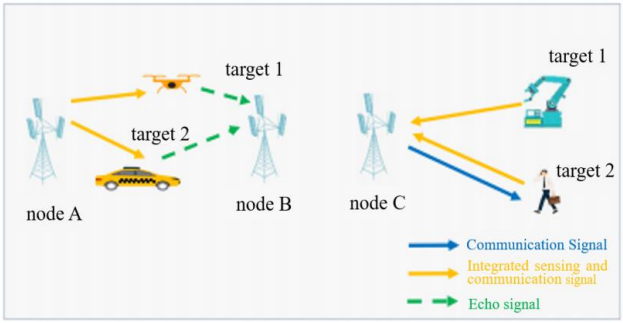
2. Working Modes of Integrated Sensing and Communication

2.1. Independent Sensing

The sensing agent is a node with the ability to actively send sensing information. The sensing target directly reflects echo information at its surface but does not need to actively feedback information. Since there is no need for terminal participation, such a working mode can effectively inhibit the synchronization accuracy deviation caused by changes in the sending and receiving time of the sensing target, which could significantly improve the sensing accuracy in return. As is shown in Fig. 1(a), node A is the base station of the sensing agent and could actively send integrated sensing and communication signals to detection targets in the environment. By using sensors such as UAVs (Unmanned Aerial Vehicles), pedestrians, and automobiles, it could capture the light reflected by the detection targets, and provide accurate localization data so as to support the simulations of communication and environment. Similarly, as is shown in Fig. 1(a), node B is able to use various smart devices such as UAVs, UAV based hospitals, UAV based agriculture, etc., and thus to monitor and analyze surroundings in real time so as to better implement effective decisions.



(a) Independent sensing



(b) Collaborative sensing

Figure 1. Working scenarios of integrated sensing and communication

2.2. Collaborative Sensing

Different from the independent sensing, collaborative sensing requires information interactions among multiple sensing agents to implement the sensing function. According to the different working patterns of collaborative sensing agents, it can be further divided into 2 kinds: collaborative sensing without terminal participation and collaborative sensing based on terminal participation. In the collaborative sensing without terminal participation, a part of the sensing agents (e.g., node A in Fig. 1(b)) sends integrated sensing and communication signals. After being reflected by the sensing target, these signals are received by another part of the sensing agents (e.g., node B in Fig. 1(b)). Meanwhile, in collaborative sensing based on terminal participation, by actively sending the integrated sensing and communication signals, terminals (e.g., target 1 in Fig. 1(b)) collaborates with sensing agents (e.g., node C in Fig. 1(b)) to achieve the sensing of the surrounding environment information. In this way, the sensing agent could decide whether it needs to feedback information according to the applications and scenarios requirements.

3. Application Scenarios of Integrated Sensing and Communication

3.1. Intelligent Living

Relying on the future 6G mobile communication network and current communication network equipment, intelligent agents with sensing ability, cognitive ability, and even thinking ability can provide people with various services, such as more detailed gesture/motion recognition, all-round monitoring of vital signs, target localization and tracking, and environment reconstruction [3]. For example, using high-precision target localization and gesture/motion recognition, users can obtain immersive multi-sensory experiences in augmented/virtual reality and other application scenarios. Besides, by sensing human behaviors and positioning, intelligent control of home equipment could be realized, such as smart sensor lights, smart appliances, etc. Specifically, when an intruder is detected, an alarm could be triggered in a timely manner. Moreover, by using a wireless sensing network, users can achieve health monitoring of breathing, heart rate and other signs without any equipment.

3.2. Intelligent Manufacturing

In the future, with the development of technology, more and more UAVs, robots and environmental monitoring sensors will become an important part of the vertical industries. They could achieve strong connectivity between people and things, and among different things, which would enable intelligent devices to capture and analyze data more accurately, so as to enhance the intelligent operation and management of enterprises. With the development of intelligent manufacturing technology, the emergence of the 6G network makes it easier to monitor the status of intelligent terminal equipment on a large scale, achieve their security maintenance, and interact information among them. The 6G network could not only provide an efficient way to sense the environment, but also obtain environmental information in real time, thus ensuring the smooth implementation of production scheduling. In intelligent transportation application scenarios, the 6G network could use integrated sensing and communication signals to achieve the real-time detection, localization, identification, imaging and other sensing functions of vehicles, quickly and timely acquire the surrounding road environment information, and generate ultra-high-resolution images by using advanced processing algorithms and AI abilities, providing whole new services and experiences for people's safe travel in the future.

3.3. Social Governance

Climate and environmental monitoring and public security management are important parts of social governance. In the climate and environmental monitoring scenario, by utilizing the existing wireless network deployment and coverage capabilities, the base station could send integrated sensing and communication signals. By further combining with water molecules, dust and various types of chemical substances, it could analyze the characteristics of wireless signals attenuation and obtain signal strength and other changes in the integrated sensing and communication signals. In this way, the "fingerprint map" of the coverage area could be constructed. Besides, real-time monitoring of precipitation, atmospheric humidity, pollutant gas emissions and air quality could also be achieved [4]. From the perspective of public safety management, through the real-time detection of the sensing function, warnings on typhoons, floods, and sandstorms could be achieved so as to reserve time in advance for disaster prevention.



Figure 2. Application scenarios of integrated sensing and communication

4. Performance Metrics of Integrated Sensing and Communication

The performance metrics of wireless sensing mainly include sensing accuracy, sensing resolution, sensing range, sensing delay, sensing update frequency, etc. The meanings of performance metrics are summarized in Table 1. Among these metrics, the sensing accuracy is related to the performance of

hardware devices, specific resource allocation, and sensing signal to interference plus noise ratio (SINR), etc. The sensing resolution is related to the hardware capability and its resource allocation used for sensing. For example, the distance resolution is related to the bandwidth of the sensing signal while the angular resolution is related to the antenna aperture. Besides, the velocity resolution is related to the time domain width of the sensing signal. The specific meanings of the sensing performance metrics vary according to different sensing use cases or application scenarios. For example, in a road vehicle monitoring scenario, the corresponding sensing accuracy mainly refers to the distance accuracy, velocity accuracy, and angular accuracy. Meanwhile, the sensing resolution mainly refers to the distance resolution, velocity resolution, and angular resolution. Moreover, the sensing range refers to the distance range, velocity range, and angular range.

Table 1. Sensing performance metrics and corresponding meanings

Sensing performance metrics	Meanings
Sensing accuracy	Sensing accuracy refers to the deviation between the true result and the actual sensing result under a specific confidence level. It can be described by the sensing error (e.g., root-mean-square error). The smaller the sensing error is, the higher the sensing accuracy is. Sensing accuracy includes distance accuracy, velocity accuracy, angular accuracy, and other sensing accuracies. Other sensing accuracies include detection probability, false alarm probability, etc. Detection probability is defined as the ability to judge the presence or absence of a sensing target or the occurrence or non-occurrence of a sensing event. It is usually calculated as the probability of a sensing target judged as presence under the assumption that it really exists. False alarm probability is defined as the ability to judge the presence or absence of a sensing target or the occurrence or non-occurrence of a sensing event. It is usually calculated as the probability of a sensing target judged as presence under the assumption of absence.
Sensing resolution	Sensing resolution refers to the ability to distinguish multiple sensing targets from different dimensions, such as distance resolution (including lateral distance and longitudinal distance), velocity resolution, angular resolution (including azimuthal and pitch direction), humidity resolution, imaging resolution, etc.
Sensing range	Sensing range refers to the range of sensing under the premise of satisfying certain sensing performance metrics, including sensing distance range, sensing velocity range, sensing angular range, etc. For example, the sensing distance range could be the distance range from the sensing target to the node which receives sensing signals.
Sensing delay	Sensing delay is used to quantitatively describe the real-time requirements of the sensing services, such as the delay from the generation of the sensing service request to the feedback of the sensing result.
Sensing update frequency	The sensing update frequency is the multiplicative inverse of the time interval between two neighboring sensing results.

5. Key Technologies of Integrated Sensing and Communication

5.1. Air Interface Integration

5.1.1. Waveform Design

1) Single-carrier waveforms. It is often used in the design of integrated sensing and communication with the combination of spread spectrum technology, such as single-carrier integrated sensing and communication waveforms based on direct sequence spread spectrum (DSSS), time hop spread spectrum (THSS), and chirp spread spectrum (CSS). Spread spectrum technology has been widely used in communication systems to obtain higher security and robustness. In order to ensure the sensing performance, it is necessary to use the spread spectrum sequences and spread spectrum factors with good autocorrelation and inter-correlation characteristics so as to adapt to different sensing accuracy and dynamic range. In addition, training sequences such as the pilot in single-carrier communication systems can also be utilized for sensing. For example, for the IEEE 802.11ad system which adopts single carrier frequency domain equalization (SC-FDE) waveforms, the short training field (STF) and the channel estimation field (CEF) in the wireless frames consist of complementary Gray sequences. They are used for frame synchronization, frequency offset estimation, and channel estimation in communication systems. Besides, they are also used for target detection and range and velocity measurement in radar systems [5].

2) Multi-carrier waveforms. Orthogonal frequency division multiplexing (OFDM) waveforms are widely used in 4G/5G mobile communication systems due to their high spectral efficiency and flexible bandwidth resource allocation. OFDM waveforms have also been introduced into radar systems, which do not have the range-Doppler coupling effect in parameter estimation. Besides, the detection algorithm based on the Fourier transform used in the receiver is simple and efficient. Moreover, the transmission mechanisms used in radar and communication systems based on OFDM waveforms are highly similar to each other. All these features facilitate the design of integrated sensing and communication. However, OFDM waveforms also have drawbacks such as high peak-to-average power ratio, and sensitivity to Doppler and phase noise, which need to be optimized. For example, the design of constant envelope-orthogonal frequency division multiplexing (CE-OFDM) could be used to mitigate the problem of nonlinear distortion in high power amplifiers resulting from high peak-to-average power ratios of conventional OFDM [5]. In addition, filter-bank multicarrier

(FBMC) has been considered in [6] as a waveform with integrated sensing and communication. Orthogonal time frequency space (OTFS), a potential 6G waveform, has been shown to have comparable performance to OFDM waveforms in terms of radar estimation characteristics. Furthermore, due to its smaller cyclic prefix overhead than OFDM, it could achieve higher spectral efficiency at the cost of higher complexity [7].

3) Commonly used radar waveforms. Simple pulse waveforms and frequency modulated continuous waves (FMCW) could be taken as typical examples. Simple pulse waveform radar transmits a simple pulse signal in a time range determined by the duty cycle within each pulse cycle, and receives an echo signal during the rest of the pulse cycle, which is processed for sensing. This kind of waveform does not require the system to own a full-duplex capability and is relatively simple to implement. However, it suffers from blind range and inefficient resource utilization due to the discontinuity of its signals in time. Simple pulse waveforms are typically used in long-range sensing applications, such as monitoring of intruding flying objects in the military. FMCW radars, by transmitting chirp signals with linearly varying frequencies and sensing the echo signals, have the advantages of large time-bandwidth product, constant envelope, good autocorrelation characteristics, straightforward transceiver architectures and simple signal processing workflows. Furthermore, the communication modulation data can be loaded into the FMCW waveform so that it could carry the communication information and could achieve integrated sensing and communication. Nevertheless, such kind of waveform requires the radar system to have full-duplex capability, and has high requirements for transceiver signal isolation, which is suitable for the close-range sensing with low power to transmit signals, such as the automobile radar. In addition, ultra-wide band (UWB) waveform refers to the signal waveform with an absolute bandwidth greater than 500 MHz or a relative bandwidth greater than 0.2, which is usually a nanosecond or sub-nanosecond extremely narrow pulse waveform. The distance information of the target could be obtained by measuring the flight time of the extremely narrow pulse. This waveform system is simple in architecture and implementation with low cost and power consumption. It is usually suitable for close-range detection, such as vital signs detection and gesture recognition applications.

5.1.2. Frame Architecture Design

The frame structure design is crucial for the implementation of the integrated sensing and communication. At present, the new radio (NR) frame structure configuration technique focuses on the information transmission requirements. The frame structure is configured in symbols and is accomplished through high-level signaling and physical layer signaling. Among them, the symbol types include uplink transmission, downlink transmission and flexible transmission. However, with the development of integrated sensing and communication technology and the abundance of emerging services, the sensing ability will become the endogenous ability of mobile communication systems. In order to make communication and sensing become the basic functions of future communication networks and promote the development of intelligent networks, its design needs to comprehensively consider the needs of communication and sensing performance.

5.1.3. Beam Management

An integrated communication and sensing system could achieve communication and sensing by transmitting omnidirectional beams. In this mode, the coverage angle of a single beam in the system is large and the link budget is more comprehensive. Thus, it is favorable for the system to detect and sense the presence of targets from more angles. However, due to the dispersion of omnidirectional wave emission energy, the distance covered by the emission beam in this mode is small, so it is not suitable for long-distance communication and sensing. In addition, in the independent sensing mode, the sensing signal emitted by the omnidirectional beam is reflected after irradiating the object, forming an echo that is received by the sensing receiver. In complex environments such as dense urban areas, there is much interference within the echo signal received by the receiver, which would reduce the sensing accuracy of the system.

5.2. Network Integration

5.2.1. Multi-band Collaboration

6G will be a full-spectrum communication system with multi-band collaboration covering low, medium, and high. The coverage will still be dominated by frequencies below 10 GHz. Sub-6G band is the main band of the current commercial communication network with the advantages of low frequency, strong diffraction ability, low transmission loss, and large coverage. Meanwhile, it also suffers from scarce spectrum resources, low transmission rate, and low sensing accuracy, etc. Millimeter wave [8] has the advantages of rich bandwidth, higher data transmission rate, and higher sensing resolution (velocity, distance, angle, etc.), which is suitable for mobile scenarios such as automated driving. Terahertz band (0.1~10 THz) [9] means a higher transmission rate and wider bandwidth, which has brought extremely high data transmission rate and low transmission delay, etc. It can be used in scenarios where high precision, high transmission rate, and low latency are required, such as intelligent medical applications. However, its short wavelength may lead to serious signal attenuation. Visible light band (380~790 THz) [10] features extremely rich spectrum resources, no radiation, high security, and theoretically could obtain a higher communication rate and more accurate sensing. Meanwhile, it's unable to penetrate objects and the signal is easy to be blocked, and thus could be used for indoor micro-environment monitoring.

5.2.2. Network Interference Coordination Technology

In both independent sensing and collaborative sensing, the impact of upstream and downstream interferences on the system should be taken into account. The core idea of interference coordination is to coordinate resource allocation, scheduling, transmitting power, and waveform according to the rules determined by the implementation, which requires that the rules and methods of coordination be determined in advance with the aim of reducing upstream and downstream interference, transceiver interference, and inter-cell co-frequency interference in a small cell. In the collaborative sensing scenario, it can keep the orthogonality as much as possible among the behaviors of communication and communication, communication and sensing, and sensing and sensing by coordinating the resources from the perspective of time domain, frequency domain, space domain, code domain, and power domain. Besides, according to the service requirements, the interference coordination can take three categories of static, semi-static, and dynamic interference coordination. Furthermore, noted that the interference

presence and process techniques are different in collaborative sensing networks and traditional communication networks. Especially for the sensing network, in addition to considering inter-cell interference, it is also necessary to consider the interference between sensing and communication, as well as the interference between different sensing tasks.

6. Conclusion

As a potential key technology of 6G, integrated sensing and communication technology is expected to implement a high integration of communication and sensing in terms of resources, data, and capabilities, so as to meet the development needs of 6G new services. In this paper, we started with the necessity of communication and sensing integration, and analyzed its application scenarios. In particular, the system architecture and key technologies of communication and sensing integration were highlighted. Moreover, technical research suggestions on air interface integration and network integration are also outlined. Communication and sensing integration is a brand-new field with both opportunities and challenges, and more in-depth researches on integration performance metrics, network architecture, signaling design, and other aspects are needed.

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