A Prospective Study of 6G Technology in Integrated Sensing and Communications for Human Action Recognition

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Abstract. With the continuous advancement of wireless technology, human activation recognition technology based on wireless signals has become a prominent area of research. It allows for real-time tracking of body movements and postures, enhancing applications in fitness, rehabilitation, and ergonomics. Simultaneously, the sixth-generation (6G) communication promises to revolutionize connectivity with unprecedented speed, lower latency, and massive device capacity. It aims to support advanced applications with enhanced security and Artificial Intelligence (AI) integration, thereby fostering innovation in information processing techniques as well as service technologies. This paper discusses the Integrated Sensing and Communication (ISAC) techniques based on 6G communication for human action recognition from three perspectives. Firstly, wireless sensing technology based on WiFi signal is introduced, where the concept and typical wireless sensing technology is highlighted. Secondly, 6G-based ISAC technology is elaborated focusing on representative signal and network design. Thirdly, key algorithms regarding 6G wireless perception is demonstrated. By deeply studying this emerging technology, this work expects to provide new ideas and directions for the development of future ISAC.

Keywords: Human Action Recognition, 6G Communication, WiFi Perception, Integrated Sensing and Communications.

1 Introduction

The human action recognition technology using Integrated Sensing and Communications (ISAC) in the context of sixth-generation (6G) communication is a technology that integrates communication functions into the behavior perception system, thus opening up new services, such as high-precision positioning, tracking, more accurate human body recognition, and non-contact biological monitoring function [1].

The new revolutionary technologies enabled by 6G networks offer endless possibilities for integrating communication functions into sensing hardware and

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software resources. Technologies such as very large-scale antennas provide higher bandwidth, lower latency and higher connection density, enabling behavior recognition technology to meet real-time data processing and multi-sensor fusion requirements. At the same time, the rapid rise of new services such as agents and virtual Spaces has not only increased the demand for 6G network information interaction capabilities, but also promoted the further development of information collection and expansion function technologies [2]. The highly coupled nature between these two requirements makes the core function of 6G network shift from transmission to perception extension

A human action recognition system can analyze and interpret human movements and gestures to identify specific actions or behaviors [3]. This system typically employs a combination of sensors, communication system, and machine learning algorithms. It is important and can significantly impact various domains, including healthcare, security, and entertainment. In healthcare, it can assist in rehabilitation and assistive technologies, enhancing patient care. In security, it can monitor and respond to potential threats more effectively. In entertainment, it can create immersive and interactive experiences [4]. By improving the accuracy and efficiency of human action recognition, these systems can lead to advancements in artificial intelligence, robotics, and the overall quality of life for individuals.

However, current transmission speed and bandwidth issues are a big barrier. Due to the characteristics of wireless signals, their transmission speed is often interfered by many factors, such as transmission media, distance and physical barriers, which lead to practical applications, especially large-scale sensor networks, the transmission rate is often difficult to reach the preset ideal state. At the same time, the lack of bandwidth capacity also affects the quality of data transmission and real-time data. Especially in the transmission of high-precision image video and data, the existing bandwidth capacity is often difficult to meet its needs. Therefore, incorporating 6G communication for ISAC is a promising field for improving the transmission speed and bandwidth of wireless sensing technology.

2 Activity Recognition Based on 6G Wireless Sensing

This chapter deeply discusses the ISAC technology based on 6G and the activity recognition technology based on wireless perception. Taking advantage of the integration of communication functions into perception software and hardware, the recognition technology can be used at a higher level.

Firstly, this chapter describes the activity recognition technology in detail. Two common wireless signals in the field of human activity recognition are WiFi and Frequency Modulated Continuous Wave (FMCW). The former has a wide deployment range in China, which means it has been installed in most indoor areas. It has caused significant advantages in cost, deployment and universality, which also makes it the focal point of this article.

Secondly, this work further discussed the 6G-based ISAC technology. Due to the technical support and market demand of the future 5G and 6G mobile communications, the concept of ISAC was proposed [5]. ISAC system is a unified system that provides wireless communication and radar sensing functions, which effectively improves the spectrum utilization and reduces the size and energy consumption of the device. This paper will focus on the signal and basic system of ISAC technology which directly affects the performance of communication and sensing.

2.1 Activity Recognition Based on WiFi Perception

Based on different physical layer characteristics, this work identified three common WiFi sensing techniques, including Received Signal Strength Indicator (RSSI), Channel State Information (CSI), and Doppler Shift [6,7].

RSSI. RSSI, sometimes called Received Signal Strength (RSS), is an important indicator used by the wireless transport layer to determine the link quality. Most WiFi devices can receive a wireless signal from their transmitter to show the path loss of that signal over a certain distance. Its relatively simple mature application is to estimate the relative position of a WiFi-carrying target using this technique. In addition, in more advanced applications, RSSI is also used in the field of biological behavior detection and respiratory rate monitoring, which is because living organisms in the range of wireless sensing will cause signal attenuation, resulting in changes in RSSI measurements.

It should be noted that although RSSI can be obtained by most existing WiFi devices, its unreliable stability and coarse granularity lead to limited detection in limited application scenarios.

CSI. CSI is the channel state information that measures the channel condition, which is simply the road condition on the propagation path. It describes the joint influence of scattering, fading, power attenuation and so on in the channel, and represents the propagation characteristics of the communication link. The presence or movement of an organism can change the multiple reflected rays of the wireless signal in the room, so the measured CSI value can be used for behavior detection. Compared with RSSI, CSI can only obtain measurements from commercial WiFi devices without additional hardware equipment. Moreover, as a more fine-grained information, CSI uses Orthogonal Frequency Division Multiplexing (OFDM) modulation, which is the discrete sampling of Code of Federal Regulations (CFR) on different subcarriers. This makes it avoid the multipath effect of RSSI, and can achieve more accurate and reliable biological behavior detection, such as biological intrusion detection, and biological walking direction analysis and so on.

Doppler Shift. The Doppler shift was first discovered and proposed by the Austrian mathematician Doppler, which can also be called the Doppler effect. It refers to the change of phase and frequency caused by the difference in propagation distance when the mobile station moves along a certain direction at a constant rate. The Doppler shift reveals how the properties of the wave change in motion. Specifically, as an organism moves through the environment, the path length of its reflected signal changes accordingly, which introduces a Doppler shift in the carrier frequency. Using Doppler shift, WiFi sensing technology can measure the walking speed of an organism.

2.2 Representative 6G-based Integrated Sensing and Communication

ISAC technology is one of the key development directions for 6G mobile communication system. ISAC signal design focuses on detailed design and optimization of transmission signals from the micro level, while network and system design focus on planning and improvement from the macro level [8]. The two complement each other and jointly promote the development and application of ISAC technology.

ISAC Signal Design and Optimization. When considering the design and optimization of ISAC signals, three key aspects come into play: waveform, frame structure, and transmission mode. In terms of waveform design, scholars are actively exploring novel approaches based on 5G-Advanced and 6G technologies. Consequently, a pivotal challenge lies in evaluating and selecting the most suitable waveform based on its performance metrics. Regarding frame structure optimization, careful consideration of factors such as time-frequency allocation, synchronization methods, and signal processing algorithms can significantly enhance both communication and sensing efficiencies. Lastly, within the realm of transmission modes, duplex transmission remains an area of ongoing research due to challenges associated with achieving efficient duplex transmission while managing interference, spectrum sharing, and signal synchronization issues.

In waveform design and optimization, OFDM, being a prevalent modulation technique in mobile communication systems, has stimulated the development of numerous advanced technologies to enhance its performance. Concurrently, the emergence of alternative waveforms, such as Filter Bank Multi-Carrier Modulation (FBMC), Generalized Frequency Division Multiplexing (GFDM), and Orthogonal Time-Frequency Space (OTFS), is regarded as a promising direction for the evolution of modulation technology. Given the distinctive directionality and high sensing accuracy of Terahertz (THz) band signals, ISAC signals in this frequency range hold significant potential for enhancing both sensing and communication performance. Promising candidates include Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM) and single carrier frequency domain equalization (SC-FDE). As an integral part of the Internet of Things (IoT), ISAC technology finds applications not only at base stations for environmental sensing in areas like intelligent transportation but also at various IoT endpoints in scenarios such as smart homes. In these implementations, modulation technology must address specific requirements such as low sidelobe levels, high reliability, and multi-user interference mitigation while balancing the needs of communication and sensing.

In frame structure design and optimization, although current ISAC signals adhere to standardized frame structures, the rigidity of these fixed formats may limit their adaptability to diverse environmental requirements. Therefore, it is crucial to incorporate flexibility and reconfigurability in frame design for ISAC signals. Consequently, existing ISAC signals often rely on pilots to enable sensing without directly impeding communication; however, this approach can potentially degrade communication performance. Some alternative designs offer increased flexibility by optimizing pilot allocation, data subcarrier allocation, precoding matrix selection, and power allocation to enhance both sensing and communication capabilities. Moreover, flexible pilot allocation in ISAC signals has the potential to facilitate long-range sensing. Nevertheless, there is a scarcity of research focused on optimizing ISAC signals for cooperative sensing among multiple base stations. In summary, the joint optimization of parameters across space, time, and frequency domains represents a promising future direction towards achieving flexible and reconfigurable ISAC signals in various scenarios.

In transmission mode, communication transmission modes primarily consist of full-duplex and half-duplex, with the latter currently dominating. However, a novel full-duplex mode has emerged, which not only enhances data transmission rate but also addresses blind detection issues. The search for additional transmission modes tailored for ISAC remains an active area of research.

ISAC Network and System Design. In the realm of integrated communication and perception systems, two fundamental forms exist: single-base perception and bi-base perception.

In single-base sensing, it involves collocating the sensing transmitter and receiver, enabling data static loading within the sensing signal to eliminate the need for communication resource consumption. Moreover, the shared source of the transmitter and receiver eliminates synchronization issues and other non-ideal factors, leading to improved complexity of sensing algorithms and estimation accuracy. However, due to its self-collection nature, the detectable signal angle range heavily relies on incident angles influenced by material properties and target object placement angles. Most echo signal components correspond to primary reflection paths that satisfy radar assumptions, resulting in minimal issues when solving ill-conditioned equations and high accuracy in sensing results.

In Bi-base perception, bistatic sensing involves the placement of the receiver and transmitter at separate locations, necessitating the utilization of dedicated pilot or known signals for the sensing signal. This results in the consumption of communication resources for the sensing function. Furthermore, due to disparities between the transmitter and receiver, non-ideal factors such as synchronization issues and phase noise are introduced, leading to increased algorithm complexity and reduced estimation accuracy. Addressing these challenges requires a more intricate calibration algorithm. Despite these complexities, bistatic sensing offers an expanded range of detectable environmental angles, with enhanced coverage of perception angles through terminal movement. However, in urban environments characterized by abundant scattering, multiple high-power reflection paths contribute to an echo signal comprising ill-conditioned equations that can potentially lead to shadowing and incorrect solutions during virtual environment simulations.

Mobile communication networks significantly enhance cooperative sensing, facilitating the sharing of sensing results among network nodes. A diverse range of nodes, including Base Stations and User Equipment (UE), can collectively function as a comprehensive sensing system, encompassing single-base, dual-base, and multi-base configurations. This collaborative approach effectively reduces measurement uncertainty, expands coverage area, and enhances sensing accuracy and resolution through the fusion of sensory data.

3 Representative Algorithms in 6G Wireless Perception

This chapter further discusses the algorithms for activity recognition. Among them, as the algorithms of WiFi-based behavior detection technology tend to be perfect and mature, this paper will focus on several key algorithms of ISAC [9,10].

Unsupervised Clustering Algorithms. Sensory data segmentation typically falls into two main categories: supervised and unsupervised methods. While supervised techniques, often leveraging deep learning, are widely used, the scarcity of electromagnetic sensing datasets and the requirement for detailed point or pixel annotations present challenges. The complexity in interpreting electromagnetic sensing data further complicates annotation difficulties. Moreover, the sparsity of most electromagnetic sensing data can result in the loss of crucial spatial features necessary for deep learning segmentation algorithms. Consequently, supervised methods are currently suboptimal for segmenting electromagnetic sensing data. Among unsupervised algorithms, the Gaussian Mixture Model (GMM) stands out as a notable approach that aims to model the probability distribution of multi-dimensional Gaussian models capable of fitting data distributions with varying shapes. As a soft decision algorithm, GMM assigns each data sample to a cluster group while also providing probabilities indicating its membership likelihood in that group or other potential groups. This probability-based approach grounded in data distribution significantly enhances environmental reconstruction accuracy. Therefore, employing the Gaussian mixture model algorithm presents a viable solution for achieving precise segmentation of electromagnetic sensing data.

ISAC Signal Processing. The signal processing of ISAC incorporates both single base station sensing and multi-base station cooperative sensing algorithms. Achieving optimal ISAC signal processing entails striking a balance between high sensing accuracy and low computational complexity. Presently, the key to enabling large-scale, high-precision sensing for applications such as intelligent transportation and smart cities lies in multi-base station cooperative sensing. However, the algorithmic design for this technology presents certain challenges.

When designing ISAC signal processing algorithms, striking a balance between complexity and precision is crucial. Although previous studies have explored the sensing performance using various reference signals within existing frame structures, effectively harnessing these multiple signals still poses a challenge. Looking ahead, with ISAC systems predominantly operating in the mm Wave and terahertz bands, future research will focus on developing high-precision signal processing algorithms tailored to these frequencies.

Networked mobile communication systems facilitate cooperative sensing among multiple base stations, thereby enhancing the accuracy and range of sensing. Consequently, it is imperative to investigate signal processing techniques for cooperative sensing. Presently, many existing methods for cooperative sensing focus on impulse or coherent radar. Coherent radar involves frequency and phase synchronization of signals upon target reception, which improves the SNR of echo signals. However, the stringent requirements for time and phase synchronization in coherent radar make its signal processing methods incompatible with ISAC mobile communication systems. Limited research has been conducted on cooperative awareness methods specifically tailored for ISAC systems, indicating this as a potential avenue for future development.

Reconstruction of the Scatterer Environment with Double Confidence Propagation. The accuracy of position determination in electromagnetic sensing data significantly differs from that of lidar point clouds, as it is heavily influenced by factors such as beam width, distance, and the incidence angle with respect to the environment plane. Therefore, it is essential to consider the accuracy of each sensor's data within the communication network. Gaussian mixture models commonly assign a probability of class membership to individual points, thereby providing an initial confidence measure based on data distribution. Furthermore, a second level of confidence can be derived from the understanding that the accuracy of electromagnetic sensing data is governed by physical propagation characteristics.

The double confidence propagation algorithm incorporates prior research findings. Initially, the Gaussian mixture model facilitates environment reconstruction by simultaneously initializing the first confidence level through parameter estimation of the model. Building upon this initial reconstruction, the second confidence is derived from electromagnetic propagation characteristics. By combining these two confidences, the accuracy of perceptual environment reconstruction is enhanced, which further refines the second confidence. Iterative updates within this loop contribute to an overall improvement in the accuracy of environment reconstruction.

4 Discussion

Integrating 6G with ISAC for human action recognition could benefits several fields. In terms of medical monitoring, behavior recognition technology combined with the ultra-high speed and low latency characteristics of 6G networks can achieve more accurate and real-time monitoring of patients' vital signs. Through sensors worn on the patient's body, the system can capture critical data such as the patient's breathing and heartbeat, and transmit it in real time to the medical center's servers for analysis and processing. For severe patients, this uninterrupted monitoring method can provide timely and effective medical intervention, greatly improving treatment efficiency and patients' quality of life.

In the smart home, 6G network will bring a wider range of application scenarios for behavior recognition technology. By arranging various sensors and cameras in the home, the smart home system can monitor the daily behavior of family members in real time, and adjust the operation mode and parameters of home equipment accordingly, improving the comfort and convenience of living. At the same time, combined with the low latency characteristics of the 6G network, the smart home system can also achieve instant response and intelligent reminders for family members, bringing more convenience to family life.

In summary, the application of 6G networks in behavior recognition technology will greatly improve security and efficiency in various fields. With the continuous development and popularization of 6G technology, it could be believed that behavior recognition technology will play an important role in more fields in the future, bringing more convenience and security to people's lives and work. In terms of medical monitoring, behavior recognition technology combined with the ultra-high speed and low latency characteristics of 6G networks can achieve more accurate and real-time monitoring of patients' vital signs. Through sensors worn on the patient's body, the system can capture critical data such as the patient's breathing and heartbeat, and transmit it in real time to the medical center's servers for analysis and processing. For severe patients, this uninterrupted monitoring method can provide timely and effective medical intervention, greatly improving treatment efficiency and patients' quality of life.

5 Conclusion

This work summarizes the application of 6G communication in ISAC for human action recognition. It highlights the WiFi-based wireless sensing, 6G-based signal and network optimization, and key algorithms for 6G-based ISAC. This technology has a vast potential for application. In the medical and health field, behavior recognition combined with wireless perception technology helps to monitor patients' daily living habits and physical status changes, and provide more accurate and personalized medical services. In the field of smart home, the use of wireless sensing technology can realize the intelligent recognition of user behavior, so as to achieve more personalized and intelligent home environment control. However, the application of wireless sensing technology for behavior recognition also faces some challenges, such as data privacy protection, algorithm accuracy improvement and other problems need to be overcome. In the future, in the 6G era, this technology is expected to play an important role in many fields such as medical care, education, and transportation, and will gradually become an essential part of people's lives. Therefore, in the future research direction, it is necessary to further explore how to improve algorithm accuracy, strengthen data security protection, and promote the formulation of relevant standards and policies. Health care, education, transportation and other areas have played an important role in bringing more convenience to people's lives.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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