Exploring Wireless Sensing Technologies and Their Applications in the Dawn of 6G

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Abstract. The recent advancements in communication technology have significantly fostered the development of wireless sensing technology. This burgeoning technology has found myriad applications in various fields like smart environments and indoor security, where the delivery of real-time and accurate data is pivotal. To comprehend the role of wireless sensing technology in the context of the forthcoming 6G revolution, it's essential to first understand its fundamental principles and key technologies. The basic concept of wireless sensing is to detect and interpret specific types of data (like temperature, motion, or sound) and transmit this information wirelessly to a device or system for analysis or action. Key technologies that underpin wireless sensing include sensor technology, wireless communication technology, and data interpretation algorithms. Reviewing the existing research, wireless sensing technology has evolved dramatically, with studies focusing on enhancing the quality and accuracy of sensed data, improving the reliability of wireless communication, and developing sophisticated algorithms for data interpretation. The utilization of machine learning and artificial intelligence has been a notable trend in recent studies, enabling more effective data interpretation and decision making.

Keywords: Wireless sensing technology, Feature extraction, 6G, CSI, Gesture recognition.

1. Introduction

As communication technology advances, we are increasingly surrounded by unseen wireless signals. Wireless perception typically involves leveraging these omnipresent signals to perceive and analyze our environment, extracting desired results about people or objects in our vicinity.

The ability to use communication signals for sensing stems from the properties of radio waves. Emitted by signal transmitters, these waves reflect, scatter, and refract as they traverse space. At the receivers, these waves form multipath superimposed signals carrying valuable information about environmental characteristics [1].

Numerous sophisticated wireless sensing techniques have been extensively studied and applied in diverse scenarios such as indoor localization, gesture and motion recognition, fall detection, and target imaging. In recent years, advancements have been made in Channel State Information (CSI)-based behavior recognition, becoming notably more sophisticated [2]. Concurrently, wireless sensing technology has achieved impressive strides with deep learning and other forms of artificial intelligence [3,4].

Current research reviews have examined human body and activity sensing based on WiFi signals, providing comprehensive processes and applications, such as indoor security technology predicated on wireless sensing [5,6]. However, as communication technologies continue to evolve, it becomes crucial to explore future prospects. This paper aims to analyze existing wireless sensing technologies concerning their principles and applications and ponder over the potential of wireless sensing technologies and related applications in the impending era of 6G [7].

2. Overview of wireless perception technology

The most common thing we see in our life is visual perception, such as cameras. The visual perception technology can accomplish the functions such as face recognition and vehicle violation detection. And wireless sensing technology can accomplish sensing by analyzing data such as channel

state information of wireless signal. The following paper will introduce the basic definition of wireless sensing technology and the technical process [8].

2.1. Basic Definition

Wireless sensing technology is a technique to obtain information highly relevant to human activity by analyzing changes in the characteristics of wireless signals. In wireless communication, CSI (Channel State Information) data describes the combined effects of a signal during propagation, such as scattering, fading, and energy attenuation with distance [9].

When people move around the home, they have an impact on the signal propagation, and these impacts are recorded by the CSI data. Using effective signal feature extraction techniques and artificial intelligence algorithms, the wireless signals at the receiving end can be processed to enable the sensing of the human activity state in the indoor environment.

For CSI, it is a very important and practical data describing the channel in wireless communication, which is the channel state information to measure the channel condition. It belongs to the physical layer and comes from the subcarriers decoded under the OFDM system. In wireless communication, the channel state information represents the propagation characteristics of the communication link, and its model can be expressed as the following equation:

$$Y = HX + N \tag{1}$$

Here Y,X,N are vectors, Y is the signal at the receiver, X is the signal at the transmitter, and N is the noise signal. H is the channel state matrix, which is described as:

$$H_i = |H_i|e_j \sin \angle H_i \tag{2}$$

Where each H_i represents the amplitude and phase of a subcarrier. The representative dimension of H is the information of multiple subcarriers of $N_t * N_r * S$.

where is the number of antennas at the receiver, is the number of antennas at the transmitter, and is the number of subcarriers.

People's activities within the range of wireless signals will interfere with the wireless signals, and the wireless signals emitted by the transmitter are affected by the physical space environment or human factors (action, posture, location) during transmission, forming multiple paths of direct, reflected and scattered propagation, generating multipath effects, and the signals received by the receiver reflect the multipath superposition characteristics of environmental characteristic information. When signal changes are detected at the receiving end, it can be inferred that there are certain factors that cause signal fluctuations. The reverse identification of human behavior in the environment using the obtained wireless signal changes is the main content of CSI applications.

2.2. Technical Process

The wireless sensing technology process is basically similar to the visual sensing system (as shown in Figure 1), including the perception and data set phase, data pre-processing phase, feature extraction phase, algorithm recognition phase, and result determination phase. In the sensing and data set phase, the wireless access point (AP) acquires RF signal data by sending and receiving data, similar to using a camera to take pictures to acquire images in the vision field.

This data will constitute a data set for subsequent processing and analysis. In the data pre-processing stage, operations such as filtering of the data are required to reduce signal noise and improve the quality of the signal. This is similar to operations such as denoising images in the field of vision. In the feature extraction phase, some features related to the environment need to be extracted using a deep learning algorithm framework. RF signals have some variation patterns in the spectrum and can be used to build neural network models for feature extraction for wireless signals.

In the algorithm recognition phase, models such as convolutional neural networks (CNN) can be used for recognition. These models can be applied to different applications and domains and can also be used in the field of wireless sensing. For example, identity recognition using RF signals can be

performed by analyzing the perturbation characteristics of human actions (e.g., gait, gestures, and other actions) on the signal to sense the identity. In the result determination phase, both wireless perception and visual perception output discrete or continuous values from the classification or regression point of view for the determination of the corresponding result. Identity recognition using RF signals can be performed using trained classifiers [10].

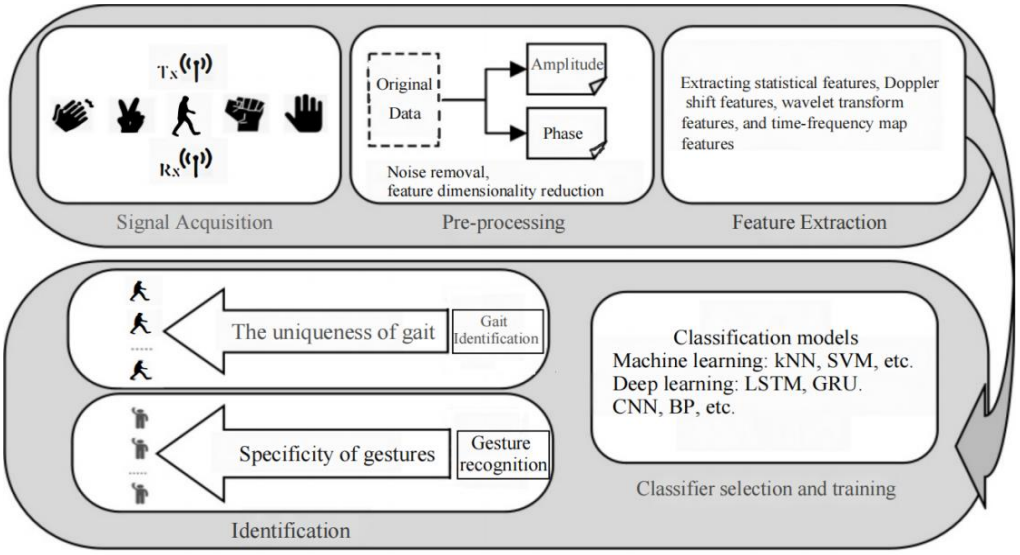


Fig. 1 The basic process of wireless sensing

3. Key Technologies

The most critical technology in wireless sensing technology is feature extraction technology. The following paper will introduce the principle and application of feature extraction technique and elaborate the method of wireless sensing technology in doing gesture recognition.

3.1. Feature Extraction Technique

Feature extraction is a crucial process that involves siphoning relevant information from original data for subsequent analysis and processing. In fields such as wireless perception, facial recognition, and fingerprint identification, feature extraction serves as an integral step towards achieving identity recognition.

The underlying principle of feature extraction is the transformation of raw data into representative feature vectors, effectively removing redundant or noisy information. Methods commonly employed for this purpose encompass time domain, frequency domain, wavelet transform, and deep learning techniques.

Time domain methodologies involve operations such as sampling and differentiation on data to procure information like signal amplitude, slope, and curvature. Conversely, frequency domain techniques convert signals from the time domain to the frequency domain through mechanisms like the Fourier transform and short-time Fourier transform to isolate frequency information. The wavelet transform has the ability to analyze signals across multiple frequency scales, offering superior extraction capacity for local fine features. Lastly, deep learning methods primarily process data through neural networks, employing backpropagation algorithms to optimize model parameters and garner discriminative features.

Feature extraction has widespread applications across various domains, including identity authentication, object detection, and image segmentation. For instance, facial recognition is achieved by extracting key facial feature points such as eyes, nose, mouth, etc. In fingerprint recognition, the details of fingerprint images, including unique line patterns, are extracted. Within the realm of wireless perception, pre-processed signals can provide effective information that reflects the signal perturbation characteristics of human actions, such as breathing cycles and gesture activities.

In a broader perspective, feature extraction techniques play a crucial role in facilitating machine learning and artificial intelligence (AI) algorithms. They help in condensing high-dimensional data while preserving the relevant information. This data condensation accelerates the learning process, making it possible to use complex algorithms on large datasets. Furthermore, a robust feature extraction process contributes to improved model performance by reducing the chance of model overfitting and improving generalizability.

In conclusion, feature extraction is a vital step in the process of extracting valuable information from raw data. It serves as the foundation for subsequent data analysis and processing and plays a pivotal role in a multitude of fields. The continuous advancement in feature extraction techniques is key to unleashing more potential in areas like AI, image processing, biometrics, and wireless sensing technology.

3.2. Analysis of Classical Methods

There are many methods of wireless sensing technology in doing gesture recognition, which will be discussed specifically in this paper below.

3.2.1 Gesture recognition based on CSI information of WiFi signal

CSI is the change of WiFi signal in the transmission process, which can reflect the subtle change of human movement. The method requires pre-processing and feature extraction of CSI data, and then uses machine learning algorithms for classification. There are also studies on gesture recognition based on beam assignment techniques of WiFi signals.

3.2.2 Gesture Recognition Based on RSSI (Received Signal Strength Indicator) Information of WiFi Signal

RSSI is the received signal strength indicator of WiFi signal, which can reflect the effect of human motion on the signal. The method requires pre-processing and feature extraction of RSSI data, and then uses machine learning algorithms for classification.

3.2.3 Multi-modal Sensor-based Gesture Recognition

This method uses multiple sensors (e.g., WiFi, accelerometer, gyroscope, etc.) to obtain multiple information to improve the accuracy and robustness of gesture recognition. The method requires fusion and feature extraction of data from multiple sensors and then uses machine learning algorithms for classification.

3.2.4 Deep Learning-based Gesture Recognition

This method uses deep learning algorithms (e.g., convolutional neural networks, recurrent neural networks, etc.) to automatically extract features and perform classification. This method requires a large amount of data and computational resources to train deep learning models, but higher accuracy and robustness can be obtained.

3.2.5 Time-frequency Analysis-based Gesture Recognition

This method uses time-frequency analysis techniques (such as wavelet transform, short-time Fourier transform, etc.) to extract the time-frequency domain features of the signal. These features can reflect the dynamic changes of the gesture, thus realizing the gesture recognition. The time-frequency analysis method can be applied to different types of wireless signals, such as WiFi, Bluetooth, millimeter wave, etc. The time-frequency analysis method requires pre-processing and feature extraction of the signal.

3.2.6 Machine Learning Based Gesture Recognition

This approach employs conventional machine learning algorithms, such as Support Vector Machine (SVM), Random Forest (RF), and decision tree, for the classification and recognition of gestures. The method involves several steps, including data pre-processing, feature extraction, and utilizing machine learning algorithms for classification. To begin with, the data undergoes pre-

processing, which involves cleaning, filtering, and normalizing the raw input. This step ensures that the data is in a suitable format for subsequent analysis.

Following pre-processing, feature extraction techniques are applied to extract relevant information from the input data. These techniques involve identifying key characteristics or patterns that can differentiate between different gestures. Examples of common feature extraction methods include time-domain analysis, frequency-domain analysis, and statistical measures. Once the features are extracted, the machine learning algorithms are employed for the classification of gestures. Algorithms like SVM, RF, and decision tree are trained on a labeled dataset, where each gesture is associated with a specific label or class.

3.2.7 Other Methods

In addition to the above methods, there are some emerging methods that deserve attention, such as joint learning methods based on artificial intelligence, gesture recognition methods based on metamaterials, and gesture recognition methods based on human eye vision. All these emerging methods have their own unique advantages and application scenarios, which are worthy of further research and exploration.

4. Related Application Analysis

Wireless sensing technology can be applied in a wide range of fields, such as intelligent fields and indoor security fields. The following paper analyzes the application of wireless sensing technology in these two fields.

4.1. Intelligent Field

Intelligent fields encompass various domains, including intelligent transportation, smart homes, intelligent healthcare, and intelligent manufacturing, among others. Wireless sensing technology plays a pivotal role in these fields, enabling applications such as traffic flow monitoring, vehicle positioning, home environment monitoring, medical equipment monitoring, and production process monitoring.

In the realm of intelligent transportation, wireless sensing technology is employed for diverse purposes such as traffic flow monitoring, vehicle positioning, and traffic accident warning. By capturing essential information such as vehicle location, speed, and direction, real-time monitoring and prediction of traffic flow can be achieved, enhancing transportation efficiency and safety.

Smart homes leverage wireless sensing technology for home environment monitoring, intelligent control of household appliances, and enhanced security. By sensing parameters like temperature, humidity, and light, wireless sensors enable automatic control and energy conservation for intelligent home appliances, augmenting the comfort and convenience of home life.

In the field of intelligent healthcare, wireless sensing technology finds application in medical equipment monitoring, patient health monitoring, and medical resource management. Through the monitoring of medical equipment operation and patient vital signs, wireless sensors enable optimal allocation of medical resources and real-time health monitoring, thereby improving the quality and efficiency of medical services. Intelligent manufacturing benefits from wireless sensing technology in areas such as production process monitoring, equipment status monitoring, and logistics management. By capturing information such as temperature, humidity, and pressure during the production process, wireless sensors enable real-time monitoring and optimal control, leading to improved production efficiency and product quality.

The adoption of wireless sensing technology in intelligent fields has garnered significant attention due to its transformative potential. As wireless sensors continue to evolve and become more advanced, their applications within intelligent systems are expanding rapidly. This technology enables the seamless integration of various devices, enabling them to collect and transmit data wirelessly, which is crucial for real-time decision-making and system optimization.

Moreover, wireless sensing technology offers advantages such as scalability, flexibility, and cost-effectiveness. These sensors can be deployed in diverse environments, enabling widespread data collection and analysis. Furthermore, wireless communication protocols facilitate seamless connectivity between sensors and the central intelligence system, enabling efficient data transmission and processing.

As the demand for intelligent solutions grows across different domains, wireless sensing technology is poised to play an increasingly critical role. Ongoing research and development efforts are focused on enhancing the capabilities of wireless sensors, improving their power efficiency, range, and data processing capabilities. These advancements will further drive the adoption of wireless sensing technology, propelling the growth of intelligent fields and fostering innovative applications. In conclusion, wireless sensing technology is an integral component of intelligent fields, facilitating advancements in intelligent transportation, smart homes, intelligent healthcare, and intelligent manufacturing. With its ability to capture and transmit essential data, wireless sensing technology enables real-time monitoring, control, and optimization, leading to improved efficiency, safety, and quality in various domains. As technology continues to advance, wireless sensing is expected to revolutionize the way we interact with and benefit from intelligent systems.

4.2. Indoor Security Field

Wireless sensing technology can use indoor wireless signals and other physical quantities to sense the state of the indoor environment, so as to achieve such functions as personnel detection, location and identity authentication. This is the basis for the application of wireless sensing technology in the field of indoor security.

In the wireless sensing-based indoor security technology, the emergence of detection is the most basic technology. The technology monitors the wireless signal in the space to determine whether someone enters or leaves the room. Location positioning, on the other hand, refers to the use of wireless signals to track individuals and determine their location. In large public places and smart buildings, accurate location information is important to help users better manage space and resources. In addition, identification is a key part of wireless sensing-based indoor security technology. This technology can protect confidential information and valuables, prevent illegal intrusion, etc. by authenticating the user's identity. Wireless sensing-based indoor security technology is widely used, such as in shopping malls can use the technology for crowd analysis and behavior recognition, so as to optimize sales strategies; in hospitals, the technology can be used to monitor the trajectory of personnel activities and equipment status to improve the efficiency of medical resources; in enterprises, this technology can be used to control the leakage of confidential information by employee identification and location tracking. In addition, wireless sensing technology can be used in combination with other sensors, such as temperature, humidity, light intensity, sound and other sensors together to further enhance the accuracy and reliability of indoor environmental sensing. Compared with traditional indoor security, wireless sensing technology in the field of indoor security applications with high accuracy, equipment for environmental adaptability, high pervasiveness, and so on, and therefore receive more and more attention.

5. Conclusion

This paper delves into the key technologies underpinning wireless sensing and explores a range of applications that these technologies enable. The wireless sensing technology field has received significant emphasis over time, leading to notable accomplishments, such as fingerprint recognition. However, while substantial research has been undertaken on wireless perception systems, the technology has encountered bottlenecks.

These challenges arise primarily from the high interference of wireless signals and a dearth of robustly trained models that can accurately interpret these signals. Despite these hurdles, we can derive insights from the multitude of wireless sensing technology applications. Such insights can help

us more accurately identify the information transmitted by wireless signals and develop comprehensive, well-trained models to interpret these signals.

Looking ahead, the emergence of 6G will usher in an era of superior spectral and energy efficiency in communication technology. Such advancements will expand the horizons for wireless sensing technology, opening up a realm of unlimited possibilities. Whether it's the perception of human bodies, enabling the Internet of Everything, or a myriad of other applications, wireless perception technology will have a significant role to play in our future. Moreover, this technology can be designed and used in ways that effectively safeguard user privacy, a consideration of increasing importance in our data-driven world.

In conclusion, by continuing to push the boundaries of research and development in wireless sensing technologies, we can expect a future where these technologies provide substantial value in various applications while ensuring the preservation of user privacy. To realize this future, however, it is essential to overcome current challenges, particularly around signal interference and model training.rs.

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