Vital Sign Monitoring Based on Wireless Sensing

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Abstract. With the acceleration of aging societies and the growing demand for health monitoring, wireless perception-based vital sign monitoring has become a research hotspot in various fields. Traditional contact devices have problems such as poor comfort and privacy leakage risks, while wireless sensing technology based on WiFi and millimeter-wave radar can achieve real-time monitoring of vital signs such as non-contact breathing and heart rate by analyzing the physical characteristics of wireless signals, such as channel state information CSI and the Doppler effect. CSI captures human micro-movements by using changes in subcarrier phase and amplitude. It has the characteristics of low cost and strong universality but is vulnerable to environmental interference; Millimeter-wave radar, on the other hand, detects micron-level body movements through high-resolution signals, with high precision but high hardware costs. This article reviews the technical principles, application scenarios and challenges of CSI and millimeter-wave radar, providing a reference for the promotion of wireless sensing vital sign monitoring. The research focuses on multimodal data fusion, privacy protection mechanisms, and hardware cost optimization to drive the technology from the laboratory to large-scale commercial scenarios, providing reliable non-contact monitoring solutions for areas such as smart healthcare, security monitoring, and smart home.

Keywords: Non-contact, Multimodal data fusion, Signal Processing.

1 Introduction

According to relevant research, one of the core aspects of actively addressing aging lies in promoting the development of the aging health industry, which is at the core of real-time, precise monitoring of the vital signs of the elderly [1]. However, traditional contact vital sign monitoring devices, such as heart rate bands and smartwatches, have many limitations. These devices often require users to wear them voluntarily, and they are not only less comfortable but also pose a risk of privacy leakage. In addition, traditional devices have limited applicability in specific scenarios, such as fall detection for elderly people living alone or apnea monitoring for patients with chronic diseases, and it is difficult to meet both real-time and privacy protection requirements. Therefore, it is particularly important to explore a new type of monitoring technology that can be seamlessly integrated into existing infrastructure and has both high precision and privacy protection capabilities.

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Wireless sensing technology, as an emerging non-contact monitoring method, provides a new solution for all-weather, unobtrusive vital sign monitoring by analyzing the physical properties of wireless signals. This technology takes advantage of the propagation characteristics of wireless signals such as WiFi and millimeter-wave radar to capture signal changes caused by human body movements, thereby extracting key physiological parameters such as breathing rate and heart rate [2, 3]. Compared with traditional methods, wireless sensing technology has significant advantages. It does not require direct contact with the human body, avoiding the inconvenience of users wearing devices. Based on existing wireless infrastructure, it is less costly to deploy and easier to promote. The technology performs well in terms of privacy protection, effectively reducing the risk of user behavior patterns being leaked. These features make wireless sensing technology have broad application prospects in areas such as healthcare, elderly care and smart home.

This article aims to systematically review vital sign monitoring methods based on WiFi channel state information and millimeter-wave radar technology, and explore their technical principles, application scenarios and challenges. This paper will analyze WiFi CSI technology and millimeter-wave radar technology in detail, and on this basis, compare the advantages and limitations of the two technologies, and explore the possibility of multimodal data fusion and its role in improving monitoring performance [4]. Ultimately, it is hoped that the research in this paper will provide a reference for the further promotion of wireless sensing technology in the field of vital sign monitoring and promote its practical application and development.

2 Typical technology analysis

2.1 WiFi CSI technology

Basic principles. Channel State Information (CSI) is an important parameter in wireless communication systems used to describe physical phenomena such as attenuation, scattering, and reflection that signals experience during transmission. CSI contains amplitude and phase information for each subcarrier, which can reflect the multipath propagation characteristics of the signal in complex environments [5]. Specifically, as the wireless signal travels from the transmitter to the receiver, multiple propagation paths are produced due to the presence of objects in the environment, and each path has different signal strength, phase, and delay [4]. Minor human movements, such as breathing or a heartbeat, causing a small displacement of the chest, can disturb these paths, resulting in detectable changes in the phase or amplitude of the signal. Reference [6], for example, presents a breathing sensing system based on subcarrier mutual information, which characterizes breathing by extracting dynamic component information from the subcarriers. This mechanism makes CSI an effective non-contact means of vital sign monitoring, especially in capturing millimeter-level body movements.

Technical implementation features. One of the most notable features of WiFi CSI technology is its non-contact monitoring capability, which significantly reduces hardware costs and enhances the universality of the technology. The existing WiFi routers and terminal devices can meet the monitoring needs, making it widely applicable in scenarios such as homes and hospitals [4]. Espressif's ESP32 series chips, for example, can collect CSI data by modifying the driver, providing developers with a convenient hardware platform. CSI provides much richer information, including amplitude and phase changes for each subcarrier, compared to traditional reception signal strength indications. Taking the IEEE 802.11n standard as an example, the number of subcarriers can reach 306, which is much higher than the resolution of RSSI and can capture signal fluctuations caused by tiny movements such as breathing [4]. Reference [6] successfully characterized the fluctuation form of breathing characteristics by extracting dynamic component information from subcarriers through mutual information theory, verifying its potential for high-precision perception. In addition, support from open-source tools has also provided an important boost to the promotion of WiFi CSI technology. Frameworks such as the Intel 5300 CSI Tool and ESP32-CSI-Tool provide standardized interfaces for data acquisition and processing, lowering the threshold for development. These tools not only speed up the algorithm optimization process but also facilitate collaboration between academia and industry and drive further technological advancements.

Limitations. Although WiFi CSI technology shows many advantages in vital sign monitoring, its high sensitivity to environmental interference remains an urgent problem to be solved. Multipath effects, electromagnetic noise and interference from other wireless devices may mask weak physiological signals, thereby affecting the accuracy of monitoring [4]. Commercialized WiFi devices are designed with data transmission performance in mind rather than the need for high-precision vital sign monitoring, and thus there are some hardware-level limitations. For example, phase linearity errors and insufficient precision of analog-to-digital converters can cause signal distortion, which in turn affects the accuracy of monitoring results [4]. Processing large amounts of CSI data in real time requires a lot of computing resources, which is another major challenge for WiFi CSI technology. Since CSI data contains amplitude and phase information of multiple subcarriers, its data volume is much larger than that of traditional RSSI data, which poses higher demands on computing power and storage capacity [4]. WiFi CSI data contains a wealth of user behavior information, which could lead to serious privacy issues if leaked. For example, by analyzing CSI data, it is possible to infer a user's daily activity patterns, physical condition and even specific location, which gives malicious attackers an opportunity [4].

Typical applications. In the field of medical monitoring, WiFi CSI technology enables non-contact vital sign monitoring by analyzing periodic fluctuations in CSI data, with an accuracy rate of up to 99.54%[4]. Combined with multi-link data fusion and support vector machine classification models, this technology can efficiently identify abnormal activities such as falls. For example, researchers constructed multi-dimensional feature

Spaces using multi-link CSI data and classified different types of behaviors through SVM models, significantly improving the reliability of anomaly detection [4].

In the field of smart homes, WiFi CSI technology enables the automation control of smart devices by differentiating user behavior patterns. For example, by analyzing the variance changes in CSI data, it can be determined whether a user is in motion and trigger the on/off of devices such as light strips or air conditioners [4].

In the field of security monitoring, WiFi CSI technology can identify illegal intrusions by detecting abnormal CSI changes and is suitable for security management in public places or warehouses [4]. For example, when someone enters the monitored area, their body movements can cause significant disturbances to the CSI signal, and the system can determine whether there is an intrusion by analyzing these disturbances.

2.2 Millimeter-wave radar technology

Basic principles. Millimeter waves are electromagnetic waves with frequencies ranging from 30GHz to 300GHz and wavelengths ranging from 1 mm to 10 mm. They detect and track target objects by transmitting and receiving electromagnetic waves in the millimeter band. The radar system first emits a frequency-modulated continuous wave signal, which is reflected upon encountering the target object. The echo signal is captured by the radar receiver [1-7]. In vital sign monitoring, millimeter waves can detect micrometer-level displacement changes in the human chest due to breathing or heartbeats [8]. The wide frequency band of millimeter waves provides them with higher data transmission rates and stronger anti-interference capabilities, which are particularly important for signal processing in complex environments. The strong penetration of non-metallic materials by millimeter waves enables them to maintain good performance in complex environments such as rain, fog, and dust, further expanding their application scenarios [3].

Technical implementation features. Millimeter-wave radar stands out in the field of vital sign monitoring with its outstanding high-precision detection capability. Thanks to its short wavelength and high frequency band characteristics, millimeter-wave radar can sense micrometer-level movement changes of target objects, which is crucial for capturing weak physiological signals such as human breathing and heartbeats [8]. Studies have shown that millimeter-wave radar can detect breathing rate as accurately as 95.76 percent, and heart rate as accurately as 98.76 percent [8]. Millimeter-wave radar's ability to resist interference in complex environments is another prominent advantage. Compared with traditional optical or infrared sensors, millimeter-wave radars are less affected by ambient light, color changes, and adverse weather conditions, and can maintain stable performance in a variety of scenarios [3]. Millimeter-wave radar has strong penetration through non-metallic materials and can effectively detect the motion information of the target object even when it is partially occluded [8]. This strong anti-jamming capability makes millimeter-wave radar an ideal choice for a variety of environments.

Limitations. Although millimeter-wave radar has many technical advantages, the problem of its high hardware cost limits its promotion in large-scale applications. The core components of a millimeter-wave radar system, including antennas, transceivers, and signal processing units, are complex in manufacturing processes and costly in materials, resulting in high overall equipment prices [3]. For example, the design and production of high-performance millimeter-wave radar antennas require the use of advanced micro-nano processing technology, which not only increases the difficulty of research and development but also raises production costs. To meet the demand for high-precision detection, millimeter-wave radar systems typically need to be equipped with highly sensitive receivers and high-speed signal processors, which further adds to the burden of hardware costs [8].

Typical applications. The application of millimeter-wave radar in medical monitoring is mainly reflected in real-time monitoring of vital signs, especially for contactless monitoring of critically ill patients or the elderly. For example, with millimeter-wave radar technology, doctors can remotely obtain critical physiological parameters such as a patient's respiratory rate and heart rate, thereby promptly detect abnormalities and take intervention measures [2]. By analyzing the harmonic components of the respiratory signal, it can be determined whether a patient has respiratory disease, while abnormal fluctuations in the heart rate signal may indicate the risk of cardiovascular problems [8].

In intelligent transportation systems, millimeter-wave radar is widely used in driver vital sign monitoring and autonomous driving assistance functions. For example, by detecting changes in a driver's breathing and heart rate, fatigue can be evaluated, and alerts can be issued, when necessary, thereby reducing the incidence of traffic accidents [9]. Millimeter-wave radar can also be used for pedestrian detection and obstacle avoidance functions, enabling autonomous vehicles to perceive their surroundings in real time and make corresponding decisions through high-precision distance measurement and speed estimation.

Applications of millimeter-wave radar in the industrial sector are mainly focused on monitoring the operational status of equipment and ensuring personnel safety. For example, by detecting machine vibration and noise, potential mechanical failures can be detected in time, thus preventing production accidents [9]. It can also be used to monitor the safety of personnel in the factory, such as detecting whether workers have fallen or had other accidents and notifying relevant personnel to handle them in the first instance.

2.3 Comparative analysis of WiFi CSI and Millimeter-wave radar

WiFi CSI technology has shown significant advantages in vital sign monitoring due to its low cost and universality. Combined with the analysis in Table 1, as a technology based on existing wireless communication infrastructure, WiFi CSI can sense human micro-movements without additional sensors, thereby significantly reducing the cost of hardware deployment [4]. Because it relies on widely available WiFi devices, the technology is highly applicable in scenarios such as homes and hospitals and is particularly suitable for large-scale promotion. Millimeter-wave radar technology has become an important tool for vital sign monitoring thanks to its high precision and anti-interference capabilities, and its high frequency characteristics enable it to detect micrometer-level body movement changes, which are crucial for capturing subtle physiological signals such as breathing and heartbeats [8]. Studies have shown that millimeter-wave radar can maintain stable performance in complex environments and is not easily affected by ambient light, color, or electromagnetic noise, which provides a guarantee for its high-precision application in medical monitoring [3].

Table 1. Comparison of the two technical features.

Dimensions	**WiFi CSI**	**Millimeter-wave radar**
Signal band	2.4/5 GHz	60/77 GHz
Detection accuracy	Lower (breathing error ±5%)	High (breathing error <1%)
Deployment cost	Low	High
Applicable scenarios	Home, smart home, multi-objective activity monitoring	Healthcare, elderly care, industrial high-precision monitoring
Anti-interference capability	Vulnerable to environmental occlusion and network interference	Strong resistance to multipath effects and good penetration
Privacy	Better	Less

3 Challenges and future outlook

Although WiFi CSI technology and millimeter-wave radar technology each have their advantages, both also have obvious limitations. WiFi CSI is highly sensitive to environmental interference, especially in scenarios where multipath effects are significant or electromagnetic noise is strong, and its monitoring accuracy may be severely affected [4]. Problems such as phase linearity error and insufficient ADC accuracy, which are common in commercial WiFi devices, further limit its monitoring capabilities [6]. In contrast, the main drawback of millimeter-wave radar technology lies in its high hardware cost. The core components of millimeter-wave radar systems, such as antennas and transceivers, are complex to manufacture and expensive, which to some extent hinders their promotion in large-scale application scenarios [8].

To overcome the limitations of a single technology, multimodal data fusion of WiFi CSI and millimeter-wave radar technology is a potential solution. Multimodal data fusion can significantly improve the accuracy and robustness of vital sign monitoring by integrating the advantages of different sensors [10]. For example, the high universality and low cost of WiFi CSI technology can make up for the high hardware cost of millimeter-wave radar, while the high precision and anti-interference ability of millimeter-wave radar can effectively improve the performance of WiFi CSI in complex environments [9]. Research shows that the method based on sparse representation and modal joint airspace estimation has made significant progress in multi-target vital sign monitoring, further confirming the feasibility of multimodal fusion [8-10]. In the future, with the advancement of algorithm optimization and standardization processes, multimodal data fusion is expected to become a mainstream direction in the development of wireless sensing technology, providing a more comprehensive and reliable solution for vital sign monitoring.

4 Conclusions

Wireless sensing vital sign monitoring technologies have shown great potential for application in healthcare, elderly care, and smart homes in recent years. WiFi CSI and millimeter-wave radar, as two typical examples, each have their own unique application principles, technical features, and limitations. WiFi CSI enables non-contact monitoring of breathing and heart rate by analyzing the channel state information of wireless signals during propagation and capturing the modulation effect of human micro-movements on signal phase and amplitude. The high resolution of CSI enables it to sense subtle changes in physiological signals, but it also faces problems such as sensitivity to environmental interference, hardware limitations, and high algorithmic complexity. For example, multipath effects and electromagnetic noise may mask the target signal, and the phase linearity error and insufficient ADC accuracy of commercial WiFi devices need to be compensated by calibration algorithms. Millimeter-wave radar technology takes advantage of the characteristics of electromagnetic waves in the 30-300 GHz band to detect micrometer-level body movements by transmitting and receiving reflected signals, thereby obtaining high-precision vital sign data. The technology has strong anti-interference ability and is less affected by ambient light and color and can maintain good performance in complex environments. However, the high hardware cost of millimeter-wave radar limits its promotion in large-scale application scenarios. Since the high-frequency harmonic components of the breathing signal are close in frequency to the low-frequency parts of the heartbeat signal, how to effectively separate these two signals is also one of the main challenges facing millimeter-wave radar technology.

From the perspective of technology comparison, WiFi CSI technology has an advantage in terms of cost and popularity, while millimeter-wave radar technology is more prominent in terms of accuracy and anti-interference ability. The combination of the two, namely multimodal data fusion, is expected to further enhance the accuracy and robustness of the monitoring system, providing a new direction for the future development of wireless sensing technology. In future research directions, algorithm optimization will be the key to improving the performance of wireless sensing technology. By improving signal processing algorithms and machine learning models, the accuracy and real-time performance of vital sign monitoring can be effectively enhanced.

References

1. J. Li, Y. Huang, L. C. Petropulu, Millimeter-wave radar for non-contact vital sign monitoring: A review. IEEE Signal Process. Mag. 36, 100-115 (2019)
2. H. Chao, J. Chen, X. Chen, Design of non-contact vital sign detection device. J. Sens. Technol. 37, 45-52 (2024)

3. N. Zhang, H. Li, J. Yu, S. Wang, S. Zhang, Research progress on radar technology for non-contact vital sign detection. Semicond. Technol. 48, 1-10 (2023)
4. Y. Zhu, Z. Bai, S. Xiong, Research progress on the application of non-contact respiratory rate monitoring methods in the medical field. Chin. J. Rehabil. Med. 39, 230-238 (2024)
5. A. Alsheikh, S. Lin, H. Nazeri, T. S. Rappaport, Vital signs monitoring using WiFi channel state information: A survey. IEEE Commun. Surv. Tutor. 20, 2560-2589 (2018)
6. Y. Liu, M. Hu, Z. Qian, Human breathing sensing system based on Wi-Fi subcarrier mutual information. J. Commun. 45, 1-12 (2024)
7. L. Pan, K. Liu, Y. Zhang, Multi-target vital sign signal detection based on FMCW radar. Acta Metrol. Sin. 45, 78-85 (2024)
8. T. Liao, X. Wan, W. Gong, M. Wu, B. Wang, Millimeter-wave radar breathing heart rate detection based on modal joint airspace estimation. J. Shaanxi Univ. Sci. Technol. 42, 112-120 (2024)
9. H. Zhang, R. Zhou, Y. Cheng, C. Liu, Cross-scene gesture recognition based on point cloud trajectories and compressed Doppler. Comput. Sci. 51, 1-15 (2024)
10. H. Wang, J. Ma, Z. Huang, Multi-objective vital sign estimation based on sparse representation in complex scenarios. J. Commun. 45, 23-35 (2024)