The Application of Wireless Sensing Technology in Smart Healthcare and Health Monitoring

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Abstract. The global ageing trend is increasing, and this is significantly affecting the already overstretched conventional health infrastructure. Wireless sensing technology is an innovative non-contact monitoring technique that identifies surroundings and human behaviors through the analysis of variations in wireless signals as they propagate. This technology therefore holds immense potential for alleviating the global burden on healthcare systems by enabling continuous, unobtrusive, and cost-effective health monitoring for the growing elderly population. In this manuscript, the authors will attempt to discuss the fundamental principles of wireless sensing technology, with special emphasis on channel state information, radar, and RFID-based sensing. In addition, this manuscript will attempt to highlight the latest research on advanced applications, including vital sign monitoring, activity recognition, chronic disease management, and safe care. The authors will also attempt to shed light on the different challenges faced by the latest health-related technologies in the various applications, and will look forward to the latest trends and innovative applications in multimodal fusion and artificial Intelligence-based personalized intervention systems.

Keywords: Wireless sensing, Physiological signal monitoring, CSI, RFID.

1. Introduction

Due to an ageing population and the growing burden of chronic diseases, the hospital-centred, centralized health system is under enormous pressure. With the gradual improvement in living standards, people are increasingly concerned about the efficiency of health management and the quality of elderly care. Consequently, "smart healthcare" and "smart healthcare" have gained significant attention. The key to 'smart healthcare' lies in the wireless monitoring of vital signs and behavioral activities. Compared with traditional healthcare, most of them use contact sensors, such as smart wristbands and heart rate chest patches [1]. Users need to charge the devices regularly, and some may feel uncomfortable while wearing them. There is also camera monitoring [2]. Although current computer vision technology is very mature, this method raises concerns about privacy leakage. Therefore, wireless sensing technology enables contactless, device-free, and privacy-preserving monitoring. The basic concept of wireless sensing monitoring technology is to utilise ubiquitous wireless signals in the environment as "virtual sensors", such as WiFi, Bluetooth, cellular signals, and radar waves. When these signals reach the human body, they undergo very characteristic modifications. These modifications are known as Channel State Information (CSI), Doppler shift, and signal strength variation, as they are produced by activities like respiration, heartbeats, and limb motion, among other body functions. By evaluating this variation, the bodily functions and activities can be interpreted without needing any assistance from the subject, as no wearable devices are required. This 'contactless', 'device-free', and 'privacy-preserving' sensing technique has vast potential applications in smart health monitoring and related applications. This paper concludes by describing the future research avenue on the utilization of wireless sensing techniques in innovative applications within the health sector.

2. Principles and Classification of Wireless Sensing Technology

The wireless sensing technology is based on the changes in physical information available in the surroundings of the earth, which are usually analysed by so-called 'virtual sensors' to monitor human vital signs and behavioral activities.

2.1. WiFi-Based Sensing Technology

Current research on wireless sensing through WiFi is now gaining attention in the field of health standards and progress. The main principle of this technique conceives the body as an 'obstacle' or 'reflector', which is capable of altering the wireless propagation channel. Anybody's motion will affect the channel along which the wireless signal is propagated, thus affecting the physical layer properties of the received signal. By tracking minute variations, it is now possible to infer body motion and functions [3]. Initially, this technique developed from crude systems to fine systems. The research work used the Received Signal Strength Indicator (RSSI), which is defined as the total value of received signal strength. However, this technique is confined by low resolution, low robustness, and high susceptibility to noise, and hence is ineffective in tracing minute body motion and functions. Hence, the current prevailing trend is the utilization of physical-layer Channel State Information (CSI) [3]. The technique conceives the channel as an 'effective complex-valued linear filter.' CSI is defined as the frequency response of this complex-valued linear filter, describing the attenuation (amplitude response) and delay (phase response) experienced by the signal on each of the subspace's orthogonal subcarriers. The technique improves both the resolution level (56 subspace measurements in a 20 MHz channel) and multipath [4]. The following is the signal processing flow chart.

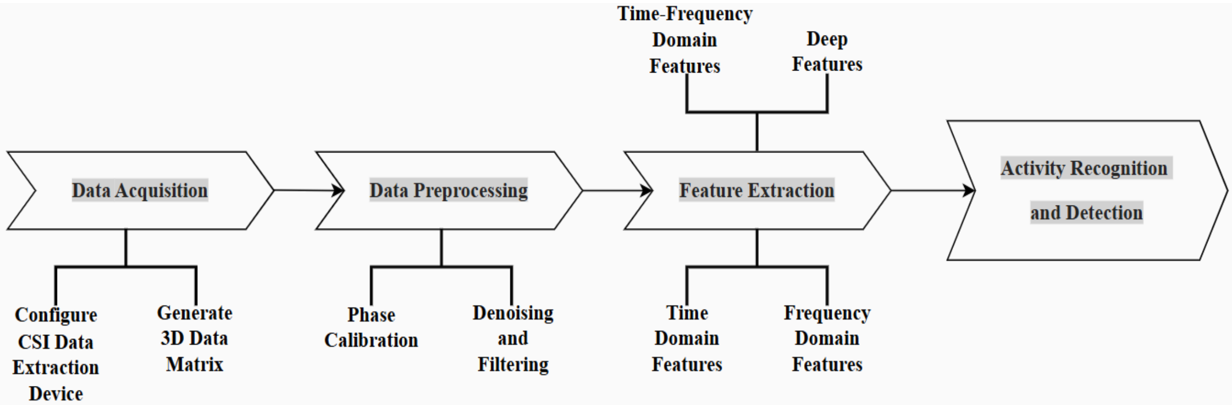

Figure 1. CSI Signal Processing Flowchart

Initially, data acquisition is undertaken, and it demands the use of CSI data extraction equipment to provide a three-dimensional time, carrier frequency, and space matrix based on the complex value of amplitude attenuation and phase shift in multipath WiFi channels.

After this, data processing takes place, which involves phase calibration and filtering to eliminate noise. The raw CSI phase, Φ, is affected by carrier frequency offset (CFO) and sampling frequency offset (SFO), making it complex and random, requiring phase calibration. The commonly used techniques are linear transformation and conjugate multiplication. Since human activity frequencies are low, with signal frequencies lower than 10Hz, and respiratory rates ranging from 0.1 to 0.5Hz, there is then need to design a low-pass filter with the capability to preserve the low-frequency part and suppress high-frequency noise. Additionally, a CSI cleaning algorithm has been proposed, reducing noise by 40% and 200% compared to the baseline, respectively, through gain and phase correction [5]. The CSI cleaning algorithm has been tested on real respiratory rate monitoring test benches, improving signal-to-noise ratio by 20% compared to the baseline techniques [5].

Next is feature extraction, where features are extracted from the pre-processed CSI, which are able to describe specific activities.

First, in the time domain, the mean, variance, standard deviation, amplitude range, kurtosis, and signal-to-noise ratio (SNR) of the signal need to be computed. When the human body starts to move, the value of variance or standard deviation increases, for example, during the process of moving from a seated position to a standing posture. The value reduces as the body is stationary. The amplitude range is high during large amplitude activities, for example, during stretching, compared to the range during breathing. Quick activities, like falling, result in high peaks.

In the frequency domain, the features of primary frequency, spectral energy, and spectral entropy are obtained by the Fourier transformation of the signal. The mentioned features are used to track periods and activities, wherein the primary frequency, indicating the peak value of the spectrum, is used as the primary feature for vital sign tracking. In respiratory activity tracking, for example, the primary frequency is directly related to respiratory rate, wherein 0.2 Hz is equal to 12 times per minute, and in heart beating activity, it is directly related to heart beating rates, wherein 1.2 Hz is equivalent to 72 times per minute. In the case of human activity, which does not possess strict periodicities and hence is non-stationary, handling both domains, namely the temporal and frequency domains, is required. In this case, both the Short Time Fourier Transform spectrum and the wavelet transform values are required. The Short Time Fourier Transform spectrum provides visual representations of signal frequency variation in the temporal domain and implies clear demarcations of the beginning, continuation, and ending of activities. In modelling techniques, wherein CNNs and LSTMs are used, automatic feature extraction is required. In sudden falls, the CSI temporal series will possess abrupt peaks in the temporal domain. In CNN models, distinguishing wave patterns signifying sudden falls from those for regular lying down is achievable. Hence, falls can be prevented.

Finally, activity recognition and detection are carried out by inputting the extracted features into the detection model, hence recognizing activities such as standing, walking, falling, and vital signs monitoring, as cited in [6].

2.2. Radar-Based Perception Technology

In contrast to WiFi-based sensing systems, radar-based sensing systems have received considerable attention in the healthcare sector mainly due to their high accuracy, sustainability, and privacy assurance. The fundamental theories are based on two phenomena, namely the Doppler effect and the properties of propagation in electromagnetic waves. Also, radar systems are divided into various types, namely continuous wave radar, FMCW radar, ultra-wideband radar, and millimetre-wave radar systems.

The Doppler effect is the basis for all types of CW and coherent wave radars. On hitting the human body, minute oscillations in the range of micrometres to millimetres, due to respiratory action, cardiac activity, or arm oscillations, reflect as echoes, causing minute variation in the frequency, known as the Doppler effect. The demodulation of this minute variation yields periodic phase modulation, which is linked to vital functions. Hence, minute contraction of the heart is sensitively detected, which is the prime basis for monitoring heartbeat and respiratory patterns [7]. In general, FMCW radar ranging and millimetre-wave radars are used for accurate positioning and imaging of the human body. The FMCW radar uses a continuous wave with variations in linear frequency. The echo received is used to calculate the frequency variation and accurately measure the range of the transmitter and receiver. Even minute variation in the body is identified by this method, and it distinguishes various parts—the chest, abdomen, and limbs. The millimetre-wave radar uses wavelengths in the range of micrometres, causing wavelengths to be very narrow and focused. Hence, minute physiological oscillations, ranging from millimetres to micrometres, are detected, and accurate monitoring of heartbeat and respiratory patterns is achieved. Additionally, this can accurately traverse non-metallic objects like cloth, blankets, and so on, and is used for special applications like monitoring respiratory activities during nocturnal sleep and burn cases [8]. The radar can accurately trace minute details like finger motion, human posture, and walking patterns [8]. For example, Zhicheng Yang et al. proposed the development of the 60 GHz millimetre-wave radar system, which showed an average error of 0.43 per minute for respiratory activity and 2.15 per minute for cardiac activity. In addition, it accurately locates the human torso with only 98.4% accuracy within a reflecting duration of 100 milliseconds [9].

2.3. RFID-Based Perception Technology

The Radio Frequency Identification (RFID) sensing technique uses passive ultra-high frequency tags as sensors and captures changes in the surroundings through monitoring the variations of backscattered waves. The technology is mainly deployed for recognizing behaviour related to objects, including tracking medication and the usage of objects [10]. The working mechanism of this technology is centred on the principle of recognizing minute variations within the surroundings of the tag antenna. Variations, including human presence and motion, thereby affecting the phase and amplitude of the backscattered wave, are predominant in altering the phase and amplitude of the backscattered wave [11]. In this manner, by monitoring the perpetual phase and amplitude variations within the backscattered wave, the dynamic surroundings of the tag can be sensed. Importantly, the RFID sensor is battery-free and sustains itself only through radio frequencies received from the reader. Another significant scenario where RFID is used is in recognizing human activities. HAR-SAnet, as quoted by Z. Chen et al., is an emerging innovative platform for recognizing human activities through radio frequencies. The platform utilizes an exclusive signal-adaptive CNN architecture and aims to merge both frequency and time information by creating an end-to-end artificial neural network model for recognizing human activities [12].

3. Typical Application Scenarios in Smart Healthcare and Nursing

3.1. Vital Signs Monitoring

In vital signs measurement, wireless sensing technology has progressed from contact-type to non-invasive techniques. By understanding the finite variation of wireless signals due to the fluctuation and contraction of the chest and the minute motion generated by the beating of the heart, it is now possible to non-invasively and continuously measure a person's respiratory and heart rates without any wearable devices on the body. This non-invasive technique is highly appropriate for special cases, including burn victims, neonates, or overall sleep studies. There are no risks of discomfort and irritation on the body as required by the invasive technique, and all the required physiological information is provided to doctors in closer-to-natural conditions. In millimetre-wave radar systems, the early stages of cardiac arrhythmias, including atrial fibrillation, are quantifiable, ultimately proving their utility in preliminary research and diagnosis for cardiovascular ailments [9].

3.2. Daily Activities and Behaviours Recognition

In terms of activity and behaviour recognition, this technology exhibits superior situational awareness. The technology is indeed very accurate in recognizing regular human activities, and fall detection is essential here. The moment it detects any inverse pattern of sudden collapse, it immediately generates an automatic alarm, which is indeed very essential for elderly people dwelling alone. In addition, wireless sensing is indeed capable of analysing more complex behaviour patterns, as evidenced by the ability to control smart home devices without any contact through gesture recognition. Not only is this very useful for those with mobility issues, but it also offers distinct benefits in sterile operating rooms. Additionally, by monitoring regular arm motion frequencies and durations during meals, this technology is indeed essential for evaluating dietary patterns and nutrition among elderly citizens. It also enables the evaluation of sleeping behaviour patterns and body turning frequencies by monitoring regular breathing rhythms.

3.3. Identity Verification and Health Status

Apart from the monitoring of the physiological and behavioral activities, the potential applications of wireless sensing technology are emerging in the areas of identity verification and health status inference. Every person has his/her distinct walking posture, known as gait. The gait recognition system, based on wireless signal, verifies identity by examining the patterns of limb swinging and the Doppler patterns all over the human body. Moreover, research is in progress to develop applications of wireless signals for health status inference, namely, deriving the status of human emotions and overall health. Human emotions change periodically, and anxiety, as well as pain, affect the acceleration and breathing patterns, causing them to become deviated from the normal ones. On the other hand, lack of activity patterns and reduced walking speeds may help detect depression as well as loss of cognitive functions.

4. Challenges and Future Research Directions

4.1. Challenges Facing Smart Healthcare

Regarding privacy, although this technology is non-video-related, the details it extracts may still reveal sensitive information about consumers' daily behavioral patterns and physiological status. Privacy-protection mechanisms should be put in place in the future. At the same time, today's generalization capability is still inadequate, and monitoring capability may possibly degrade dramatically in different environments and different individuals, which should be improved to achieve greater robustness. In consideration of the cost entailed in this deployment, high expenses involving semiconductor fabrication and setup are generated, and this becomes an obstacle. In fact, critical research is still limited to lab tests and lacks substantial long-term data to evaluate the accuracy and effectiveness of this monitoring technology.

4.2. Future Research Directions

The overall emphasis is on improving multimodal fusion by integrating and calibrating wireless sensing, wearable sensing, and environmental sensing, and significantly improving the monitoring outcome reliability and completeness. The secondary emphasis is on the exploration of more advanced deep learning models, namely generative learning models or meta-learning models customized for few-shot learning, which will have the potential to provide more robust feature extraction from smaller datasets, thereby improving the generalization abilities of models. Notwithstanding progress in the communication sector, actively pursuing the inherently integrated sensing capabilities of upcoming communication standards, namely 5G-A or 6G and Wi-Fi 7, will unlock innovative applications for high-precision, low-latency medical sensing. The final aim of this system is to evolve from passive real-time monitoring to active and intelligent intervention, thereby creating an entirely closed-loop system from 'sensing-analysis-decision-intervention.' This will require systems being capable of predicting health-risk anomalies, as well as integrating innovative intervention methodologies into the health domain, thereby achieving the ultimate aim of innovative healthcare itself.

5. Conclusion

The great potential of wireless sensing technology in competent healthcare is evident in its non-contact, continuous monitoring capabilities. In this context, this article systematically introduces the essential principles and characteristics of core technologies like Wi-Fi, RF radar, and RFID. It explores their applications in vital sign monitoring, behaviour recognition, and health status evaluation. The wireless sensing technique is of great significance to early disease warning and health management, and will play an important role in solving the problem of resource shortages within the healthcare sector and improving the quality of life of citizens.

Although there are still obstacles in the realms of privacy, robustness, and clinical validation, persisting in the exploration of other areas, like multimodal fusion, innovative algorithms, as well as communication and sensing systems, will increasingly improve the accuracy and applicability of wireless sensing technology. With the development of emerging technologies such as 5G and 6G, as well as the continuous accumulation of clinical datasets, wireless sensing is poised to deliver greater value in home health management, chronic disease prevention and control, and elderly nursing. The future will see the dawn of a closed-loop system with the capability of real-time monitoring and customized health management. Inevitably, this will pave the way for shifting health paradigms from the treatment of existing diseases to the prevention of potential ones and will play a critical role in the construction of an all-inclusive, efficient, and innovative healthcare system.

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