Review of Sleep Monitoring Research Based on Wireless Sensor

Yuzhu Hu[1,2,3], Jian Chen[1,2,3], Shen Zhao[1(✉)], Kexin Tan[2], Kuai Yu[2], and Wei Wang[2,3,4]

[1] School of Intelligent Systems Engineering, Sun Yat-sen University, Shenzhen 518000, China
{huyzh27,chenj589}@mail2.sysu.edu.cn, z-s-06@163.com

[2] Artificial Intelligence Research Institute, Shenzhen MSU-BIT University, Shenzhen 518172, Guangdong, China
{1120200259,1120200296}@smbu.edu.cn, ehomewang@ieee.org

[3] Guangdong-Hong Kong-Macao Joint Laboratory for Emotion Intelligence and Pervasive Computing,
Shenzhen MSU-BITUniversity, Shenzhen 518172, Guangdong, China

[4] School of Medical Technology, Beijing Institute of Technology, Beijing 100081, China

Abstract. Since sleep quality is crucial to human health, sleep monitoring has become a hot spot in the field of smart healthcare. Previous methods depend on polysomnography and wearable devices need immediate contact with the subject, which brings discomfort. Contactless sensors can address this issue. The most common contactless sensors used in sleep monitoring are wireless sensors (including radar and WiFi). To clarify the research in this area, we summarized the existing sleep monitoring methods based on WiFi sensors and wireless radar and made a comparison. The conclusion shows that the two kinds of methods have advantages and disadvantages, so the development of complementary methods is very promising for sleep monitoring.

Keywords: Sleep monitoring · contactless sensors · wireless sensing

1 Introduction

Sleep is one of the most important basic life activities of human beings, and it is also an important basis for maintaining physical and mental health [1]. Chronic poor sleep has also been linked to cardiovascular disease, obesity, and even some mental health problems [2–4]. Therefore, sleep monitoring is important for health status monitoring and is now become a hot topic for research.

Polysomnography (PSG) is the most widely used tool to monitor sleep, and it is regarded as the gold standard to detect sleep-related breathing disorders [5]. PSG can provide comprehensive information on sleep stages on the basis of Electroencephalography (EEG) activity, eye movements, and muscular tension

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[6], However, the recording of PSG always needs expensive equipment and keep lots of contact with the subjects' body which bring discomfort. These drawbacks make it unsuitable for daily life sleep monitoring.

With the development of information techniques, more and more wireless sensors are used for sleep monitoring. There are already a lot of wearable devices used for sleep monitoring, but they also face resistance because of the discomfort brought to subjects and instability during sleep. Contactless sensors can effectively address the problem that invasive sensors bring natural sleep difficulties. There are various contactless sensors used in sleep monitoring now. The main of them are wireless sensors. Wifi sensor is also a kind of wireless sensor but since it has received more attention than other wireless sensors, it is put in a separate category.

Since wireless sensors are now widely used in sleep monitoring and have shown great potential, it is meaningful to review sleep monitoring research based on wifi sensors and wireless sensors. This can help develop contactless devices to achieve stable, safe, and non-contact sleep detection. In this work, we will first review the main sleep detection methods based on wifi sensors and wireless sensors respectively, and then a comparative analysis is made to summarize the difference between wifi sensors and wireless used in sleep monitoring. Finally, we provide a conclusion of our work.

2 Sleep Detection Based on Wifi Sensor

Wifi-based sleep monitoring activities are generally carried out through high precision indoor positioning, and the commonly used methods include Received Signal Strength (RSS) and Received Signal Strength (CSI) [7]. With the development of the technology, the CSI technique has demonstrated greater stability and accuracy and has become the more mainstream method nowadays. While using wifi sensors for sleep monitoring, CSI can be used to capture the effect of sleep activity contained by the Wifi signals [8].

Existing methods that use Wifi sensors to monitor sleep quality include heart rate monitoring and respiration monitoring [9]. A method is proposed to track the breathing rate and heart rate during sleep with Wifi [10]. They exploit to utilize the fine-grained channel information of existing Wifi networks to extract the minute movements that come with breathing and heartbeats. Wifi network activity is also used in a sleep-tracking approach called SleepMore which utilizes machine learning methods [11]. SleepMore constructs a semi-personalized random forest model to make a classification of the network activity behavior and the results are divided into sleep and awake states in minute dimensions. The experimental results show that SleepMore achieves an indistinguishable result with the Oura ring baseline within a 5% uncertainty rate.

Wifi sensors are also used for sleep stage classification and sleep-related disorders detection. An advanced signal processing and fusion method is proposed to extract accurate respiration and body movement for four-stage sleep classification, which achieves an accuracy of 81.1% [12]. In disorders monitoring, wifi sensors are used for obstructive sleep apnea (OSA) detection and rhythmic movement disorder (RMD) detection. An intelligent apnea monitoring system can utilizing linear fitting and wavelet transform eliminate the phase error of CSI. The system uses commodity wifi, which is better able to eliminate interference from changes in sleeping posture [13]. A sleep monitoring system named Wi-PSG is proposed to utilize CSI from Wifi infrastructures for RMD-related movement detection, which can achieve an accuracy of above 92% for different RMD movement classifications [14].

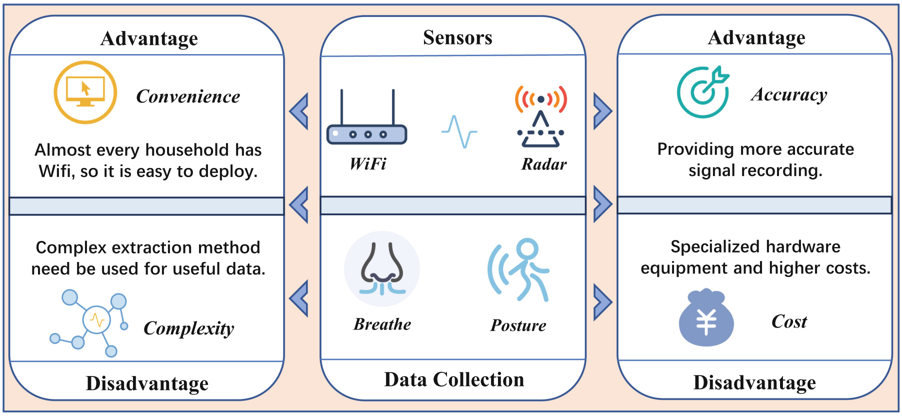

Fig. 1. Comparison between WiFi sensors and radars.

3 Sleep Detection Based on Wireless Sensor

Wireless radars are the most widely used sensors in sleep detection based on wireless sensors. Systems with wireless sensors are usually used for vital signs detection during sleep and sleep quality detection. The main sensors used in these systems are Ultrawideband (UWB) radar, Doppler radar, and Radio Frequency (RF) sensors.

UWB radar is commonly utilized for precise localization, employing low energy levels for short-range and high-bandwidth communications across the radio spectrum [15]. The required sleep information can be extracted by the UWB radar sensor penetrating the clothes and quilt. A fine-grained prototype for overnight respiration monitoring is proposed by exploiting the complementarity between the amplitude and phase of the radar signal [16]. Four respiration patterns are recognized during overnight sleep in this method. Another image processing method converts the raw signals collected by the UWB radar into a 2-D heatmap image and then an image-processing algorithm is used to capture respiratory information for respiratory motion measure [17]. An attention-based LSTM model is proposed to use the vital signs detected remotely by an impulse-radio UWB radar for sleep stage classification [18].

Doppler radar is widely used in the field of sleep detection due to its excellent ability to measure target displacement remotely. Doppler radar can capture the information of chest displacement due to respiration or heartbeat through the transmitted microwave signals and analyze it through the Doppler effect [19]. A contactless system named PRMS using quadrature microwave doppler radar to monitor sleep apnea events in real time. The system contains a real-time actigraphy and sleep apnea detection algorithm [20]. A novel sleep posture recognition technique is proposed, which employs classifiers that are amenable to optimization through Bayesian hyperparameter tuning. These classifiers operate on data from a dual-frequency monostatic continuous-wave radar system [21]. DopplerSleep, a contact sleep sensing system, uses a single Doppler sensor to track sleep quality. DopplerSleep can monitor both body movements and tiny chest and heart movements, and the system has been experimentally validated to perform well on sleep stage classification tasks [22].

RF signals are widely used for contactless motion and vital signs monitoring in the field of sleep monitoring. Radio Frequency Identification (RFID) is a contactless communication technology that enables two-way data exchange for identification and data transfer using RF signals with flexibility and low cost. A respiration monitoring system with RFID sensors called LungTrack is proposed to achieve dual objective monitoring with an accuracy of above 93% for two targets at a distance of 10 cm at least [23]. TagSleep is a sleep posture recognition system using the concept of two-layer sensing with RFID sensors [24]. A model combining a convolutional network and recurrent neural network is trained on the RF-measured sleep dataset with an adversarial training regime [25].

4 Comparative Analysis

WiFi sensors and other wireless sensors, as non-interference devices, offer both advantages and disadvantages in sleep monitoring. Figure 1 shows a comparison between these two methods. WiFi sensors typically utilize wireless signals and receivers to track variables such as breathing, body movement, and sleeping positions. These sensors analyze movement patterns and breathing rates by observing changes in WiFi signals. They are cost-effective and easy to deploy, but privacy concerns may arise.

On the other hand, radar technology emits high-frequency pulse signals and measures the time it takes for the signals to bounce back. This enables accurate positioning and tracking of objects, including monitoring human movements and breathing patterns during sleep. Radar provides precise distance and position measurements, boasting high accuracy and reliability. However, radar requires specialized hardware and incurs higher costs. Both UWB and doppler radars described previously are capable of real-time sleep monitoring with a high degree of accuracy, but there is the problem of higher equipment costs and more demanding deployment conditions during equipment placement.

While RFID technology offers advantages like low power consumption and affordability, it may have limitations when it comes to more detailed sleep analysis and breathing monitoring.

In summary, each technology has its own merits and considerations. Contactless sensing also leaves much to be desired, such as greater noise immunity to the varying light conditions of different indoor environments. At the same time, because contactless sensing can capture more information, it faces more serious privacy issues. The choice depends on specific requirements, budget constraints, and the desired level of monitoring accuracy. Besides, more research can focus on how to combine these two methods for better performance and less cost.

5 Conclusion

In this work, we review the existing sleep monitoring methods based on Wifi sensors and wireless sensors. Then we make a comparative analysis between these two methods for a better illustration of wireless sensors used in the field of sleep monitoring. Through the summary of the existing methods, we can better find the direction for the follow-up research. However, in addition to wifi sensors and radar, acoustic and optical sensors are also beginning to be used in this field. Therefore, it is our future work to further summarize and analyze the advantages and disadvantages of these methods.

References

1. Perez-Pozuelo, I., et al.: The future of sleep health: a data-driven revolution in sleep science and medicine. NPJ Digital Med. **3**(1), 42 (2020)
2. Bertisch, S.M., et al.: Insomnia with objective short sleep duration and risk of incident cardiovascular disease and all-cause mortality: sleep heart health study. Sleep 41(6), zsy047 (2018)
3. Zhou, Q., Zhang, M., Hu, D.: Dose-response association between sleep duration and obesity risk: a systematic review and meta-analysis of prospective cohort studies. Sleep Breathing **23**, 1035–1045 (2019)
4. Palagini, L., Hertenstein, E., Riemann, D., Nissen, C.: Sleep, insomnia and mental health. J. Sleep Res. **31**(4), e13628 (2022)
5. Rundo, J.V., Downey, R., III.: Polysomnography. Handb. Clin. Neurol. **160**, 381–392 (2019)
6. Engstrøm, M., Rugland, E., Heier, M.S.: Polysomnography (PSG) for studying sleep disorders. Tidsskrift for den Norske laegeforening: tidsskrift for praktisk medicin, ny raekke **133**(1), 58–62 (2013)
7. Rottenberg, F., Nguyen, T.-H., Dricot, J.-M., Horlin, F., Louveaux, J.: CSI-based versus RSS-based secret-key generation under correlated eavesdropping. IEEE Trans. Commun. **69**(3), 1868–1881 (2020)
8. Chen, Z., Zhang, L., Jiang, C., Cao, Z., Cui, W.: Wifi CSI based passive human activity recognition using attention based BLSTM. IEEE Trans. Mob. Comput. **18**(11), 2714–2724 (2018)
9. Gui, L., Ma, C., Sheng, B., Guo, Z., Cai, J., Xiao, F.: In-home monitoring sleep turnover activities and breath rate via wifi signals. IEEE Syst. J. **17**, 2355–2365 (2022)
10. Liu, J., Chen, Y., Wang, Y., Chen, X., Cheng, J., Yang, J.: Monitoring vital signs and postures during sleep using wifi signals. IEEE Internet Things J. **5**(3), 2071–2084 (2018)

11. Zakaria, C., Yilmaz, G., Mammen, P.M., Chee, M., Shenoy, P., Balan, R.: Sleepmore: inferring sleep duration at scale via multi-device wifi sensing. Proc. ACM Interact. Mob. Wearable Ubiquit. Technol. **6**(4), 1–32 (2023)
12. Yu, B., et al.: Wifi-sleep: sleep stage monitoring using commodity wi-fi devices. IEEE Internet Things J. **8**(18), 13900–13913 (2021)
13. Yang, X., Yu, X., Xie, L., Xue, H., Zhou, M., Jiang, Q.: Sleep apnea monitoring system based on commodity wifi devices. Comput. Mater. Cont **2**(69), 2793–2806 (2021)
14. Liu, W., Chang, S., Liu, Y., Zhang, H.: Wi-PSG: detecting rhythmic movement disorder using cots wifi. IEEE Internet Things J. **8**(6), 4681–4696 (2020)
15. Ridolfi, M., Kaya, A., Berkvens, R., Weyn, M., Joseph, W., Poorter, E.D.: Self-calibration and collaborative localization for UWB positioning systems: a survey and future research directions. ACM Comput. Surv. (CSUR) **54**(4), 1–27 (2021)
16. Li, S., Wang, Z., Zhang, F., Jin, B.: Fine-grained respiration monitoring during overnight sleep using IR-UWB radar. In: Hara, T., Yamaguchi, H. (eds.) International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services, pp. 84–101. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-94822-1_5
17. Han, W., Dai, S., Yuce, M.R.: Real-time contactless respiration monitoring from a radar sensor using image processing method. IEEE Sens. J. **22**(19), 19020–19029 (2022)
18. Kwon, H.B., et al.: Attention-based LSTM for non-contact sleep stage classification using IR-UWB radar. IEEE J. Biomed. Health Inform. **25**(10), 3844–3853 (2021)
19. Atlas, D., Srivastava, R., Sekhon, R.S.: Doppler radar characteristics of precipitation at vertical incidence. Rev. Geophys. **11**(1), 1–35 (1973)
20. Baboli, M., Singh, A., Soll, B., Boric-Lubecke, O., Lubecke, V.M.: Wireless sleep apnea detection using continuous wave quadrature doppler radar. IEEE Sens. J. **20**(1), 538–545 (2019)
21. Islam, S.M.M., Lubecke, V.M.: Sleep posture recognition with a dual-frequency microwave doppler radar and machine learning classifiers. IEEE Sensors Lett. **6**(3), 1–4 (2022)
22. Rahman, T., et al.: DoppleSleep: a contactless unobtrusive sleep sensing system using short-range doppler radar. In: Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing, pp. 39–50 (2015)
23. Chen, L., Xiong, J., Chen, X., Lee, S.I., Zhang, D., Yan, T., Fang, D.: Lungtrack: towards contactless and zero dead-zone respiration monitoring with commodity RFIDS. Proc. ACM Interact. Mob. Wearable Ubiquit. Technol. **3**(3), 1–22 (2019)
24. Liu, C., Xiong, J., Cai, L., Feng, L., Chen, X., Fang, D.: Beyond respiration: contactless sleep sound-activity recognition using RF signals. Proc. ACM Interact. Mob. Wearable Ubiquit. Technol. **3**(3), 1–22 (2019)
25. Zhao, M., Yue, S., Katabi, D., Jaakkola, T.S., Bianchi, M.T.: Learning sleep stages from radio signals: a conditional adversarial architecture. In: International Conference on Machine Learning, pp. 4100–4109. PMLR (2017)