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Advances in Human Health Monitoring Empowered by Reconfigurable Intelligent Surfaces

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Abstract

Reconfigurable intelligent surface (RIS) offers remarkable versatility and efficiency in manipulating electromagnetic waves and customizing wireless sensing environments. This paper reviews our recent advancements in RIS-empowered human health monitoring, with a focus on dynamic electromagnetic human modeling, non-line-of-sight vital-sign sensing, multi-person detection, and vital-sign sensing using space-time-coding (STC) metasurfaces and RISs. These advancements highlight the potential of RISs to revolutionize wireless human health monitoring by delivering high-performance, non-invasive, and robust solutions.

1. Introduction

The non-contact human vital-sign sensing has attracted considerable attention due to its non-invasive nature [1-2]. Traditional methods such as photoplethysmography (PPG) and electrocardiography (ECG) require direct contact with the human body, and hence they are inconvenient and uncomfortable for long-term monitoring. In contrast, the wireless signal-based sensing offers a cost-effective and non-contact solution, leveraging the modulation of electromagnetic (EM) waves by human movements to detect the physiological parameters like respiration and heartbeat rates [3-4].

Existing wireless sensing systems encounter numerous challenges, such as severe signal attenuation, multipath interference, and limited spatial resolution, which will compromise the accuracy and reliability of the vital signs monitoring. The application of reconfigurable intelligent surface (RIS) has emerged as a promising solution to such challenges [5]. RIS is an array of programmable elements, which possess the capacity to dynamically manipulate the EM waves, thereby achieving high-resolution sensing and reducing the interference from irrelevant objects [6-7].

This paper reviews our recent advancements in the field of RIS-empowered human health monitoring technology. The primary focuses are dynamic EM human modelling, vital-sign sensing in non-line-of-sight scenarios, and the simultaneous monitoring of multiple individuals' vital signs.

2. RIS for Passive Human Sensing

An overview of the existing RIS-based human sensing systems is provided in our recent study [8], discussing and highlighting of the advantages of integrating RIS for sensing applications. RIS consists of a two-dimensional array of meta-atoms that can dynamically manipulate the phase, amplitude, and polarization of incident EM waves. This capability allows RISs to customize the wireless propagation channels, improving the signal-to-noise ratio (SNR) and spatial resolution [8]. In the context of passive human sensing, RISs have the capacity to redirect sensing signals towards regions of interest, thereby reducing interference from irrelevant objects and enhancing the detection of subtle physiological movements. The existing applications of RIS in human sensing include imaging and segmentation [9], localization and tracking [10], and human activity recognition [11]. For instance, a machine-learning-based programmable imager has been proposed to improve the accuracy and efficiency of human target imaging and activity recognition [9]. These advancements brought about by RIS demonstrate the potential for revolutionary wireless human sensing by providing high-resolution, non-invasive, and privacy-preserving solutions. In addition, since micro-motions (such as heartbeat) are weaker and more difficult to perceive, especially in multi-person scenarios, we designed an RIS-enhanced multi-person vital-sign sensing scheme [8]. The feasibility of the proposed method is experimentally verified.

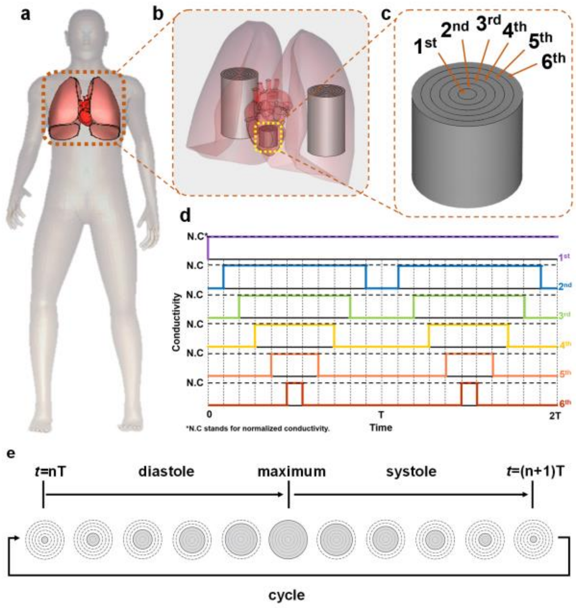

Figure 1. The dynamic human EM model. (a) The complete human EM model. (b) The cardiopulmonary part of the model. (c) The 6-layer cylindrical model representing periodic movements of the heart. (d) The conductivity sequences of different concentric cylinders in the time-varying heart model, and (e) the varying size of cylinders to imitate cardiac cycles.

3. Dynamic EM Human Modeling for Vital-Sign Detection

We first model the dynamic human vital-sign movements and validate the feasibility and efficiency of utilizing RIS to improve the performance of wireless human health monitoring [12]. As illustrated in Figure 1, dynamic EM human modeling involves to simulate the periodic cardio-pulmonary motions of the human body to generate the physiological signals for vital-sign detection. This method can also address the challenges to collect large volumes of high-quality physiological data for sensing, mitigating the impact of environmental noise. The proposed model consists of customized time-varying EM materials that simulate the micro-movements of the heart and lungs. Specifically, concentric cylindrical structures with varied EM properties are used to model the heart and lungs, which are then integrated into a complete human body model. The time-domain finite integration technique (TDFIT) is employed to analyze the interaction between the EM waves and the human model, generating time-domain echoes and near-field distributions. The simulated signals are then processed using an improved variational mode decomposition (VMD) algorithm to estimate the respiration and heartbeat rates. The experimental results demonstrate that the proposed model achieves average estimation errors of less than 4% for respiration rate (RR) and 8% for heartbeat rate (HR), validating its ability to accurately simulate human cardiopulmonary motions and generate reliable physiological signals. This dynamic modeling technique offers a repeatable and cost-effective method for preliminary validation of the vital-sign sensing algorithms, reducing the need to collect extensive data and improving the robustness of sensing systems.

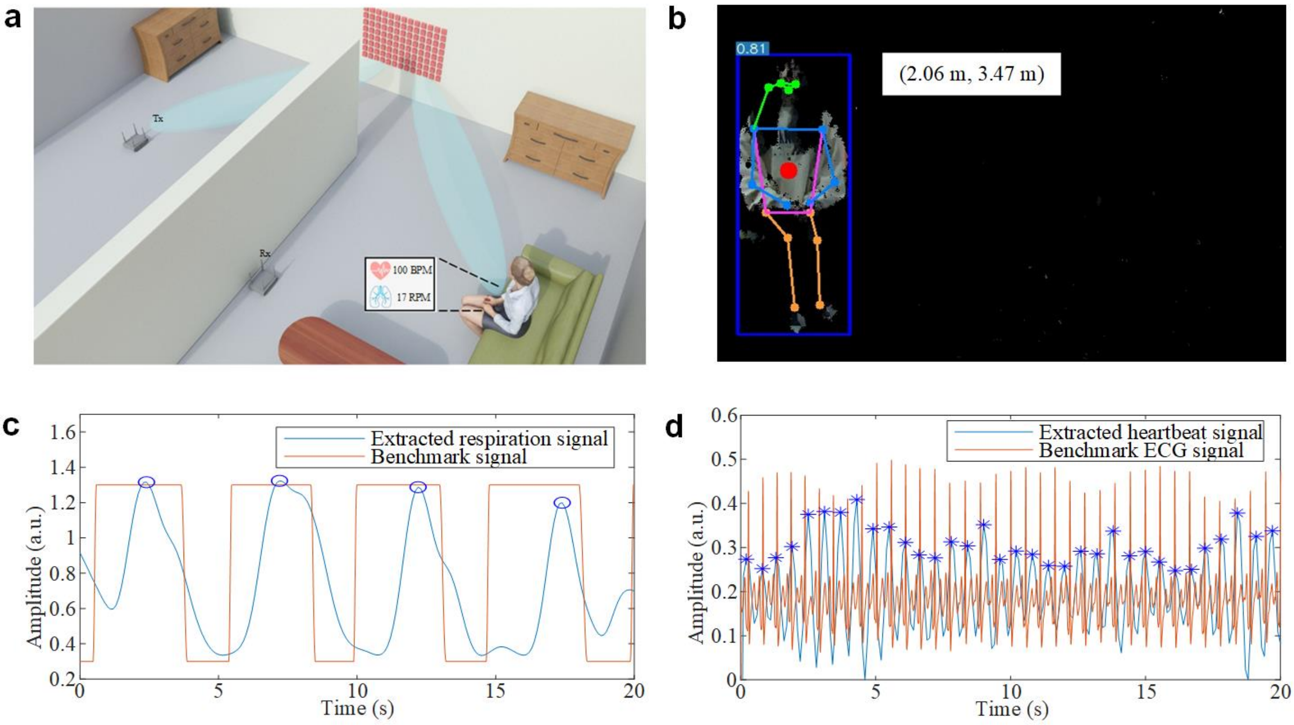

Figure 2. NLoS human vital-sign sensing and the experimental results. (a) Schematic of NLoS human health monitoring. (b) Estimated localization of human chest. (c-d) The extracted respiration and heartbeat signals, respectively.

4. Non-Line-of-Sight Monitoring of Human Vital Signs

Monitoring of human vital-sign in obstructed non-line-of-sight (NLoS) scenarios is a crucial requirement. The traditional NLoS sensing methods often suffer from severe signal attenuation and low resolution, constraining their practical applications. The incorporation of RIS into NLoS sensing systems provides a solution by facilitating the redirection of sensing signals around obstacles [13]. In this context, RIS can dynamically adjust its coding pattern to optimize signal propagation paths, thereby enhancing the detection of physiological signals. Specifically, as shown in Figure 2, a visual-aided mechanism using deep learning models such as YOLO-v7 can locate human targets, and RIS can then optimize its configuration to focus the sensing signals on the human chest. This approach significantly improves the accuracy of vital-sign monitoring in NLoS scenarios, with average errors of 0.6 RPM and 5.3 BPM being achieved for precise estimation of respiration and heartbeat rates, respectively. These results highlight the potential of RIS-aided NLoS sensing for applications in such as emergency response, security surveillance, and healthcare monitoring in the obstructed environments.

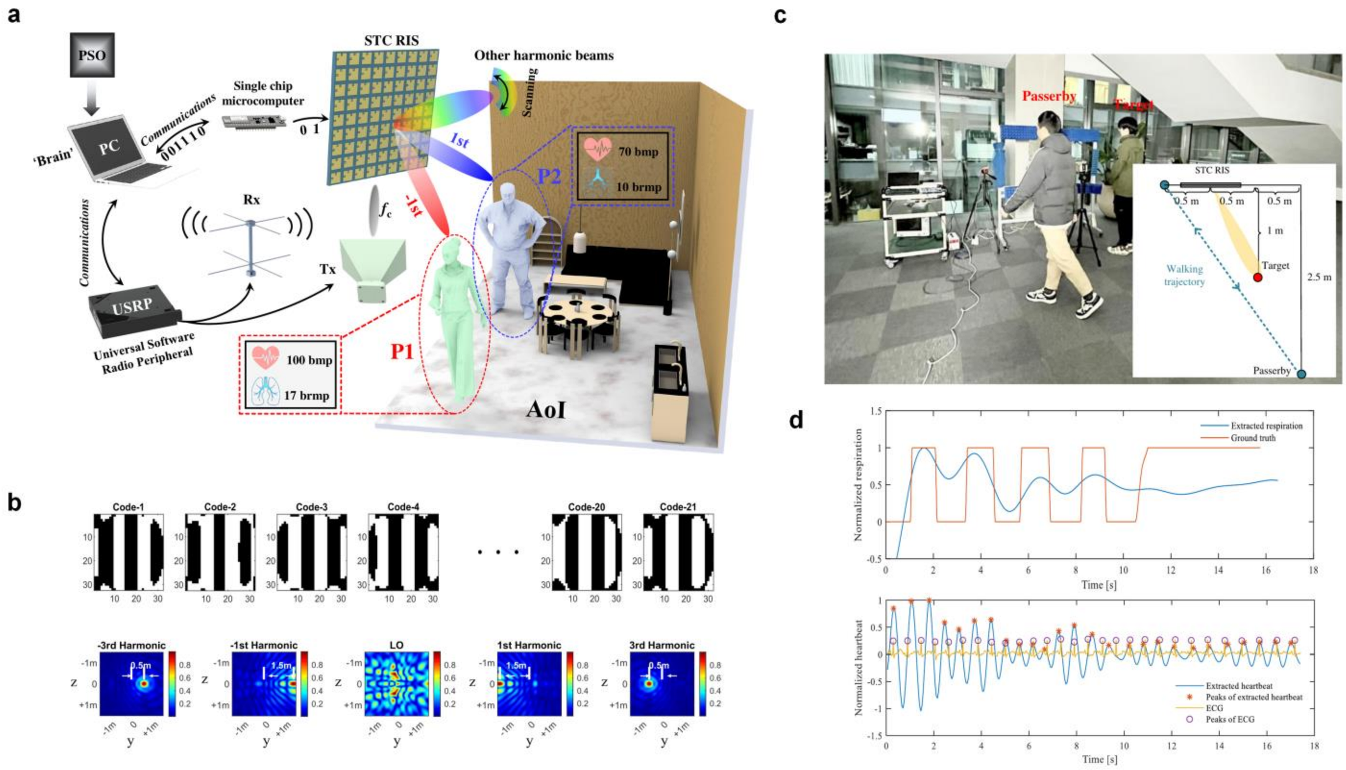

Figure 3. Multi-person vital-sign sensing empowered by the STC RIS. (a) Schematic diagram of the proposed multi-person detection and vital-sign monitoring system. (b) The generated STC coding sequence and the corresponding near-field patterns of four harmonic beams. (c) Experimental setup when a person is passing through the sensing area. (d) The respiration and heartbeat signals are extracted by the proposed sensing system.

5. Multi-Person Detection and Vital-Sign Sensing Using Space-Time-Coding RIS

The multi-person detection and vital-sign sensing present significant challenges due to the fact that the echo signals from multiple individuals interfere with each other in the time, frequency, and spatial domains. Space-time-coding (STC) RIS offers a viable solution by generating the harmonic beams with distinct frequencies and propagation directions, enabling the separation of signals from different individuals in the frequency domain [14-15], as illustrated in Figure 3. In the proposed system, the STC RIS modulates the incident wave into a set of harmonic components, which are then used to scan the area of interest for human detection. Once a person has been detected, a harmonic beam is assigned to that individual for vital-sign sensing, while other beams continue scanning for additional targets. This approach allows for simultaneous monitoring of multiple persons, which can significantly mitigate mutual interference. The improved VMD algorithm is employed to extract physiological signals from the reflected echoes, achieving average errors of less than 1 RPM for respiration rate and 5 BPM for heartbeat rate. Experimental results demonstrate the system's capability to accurately detect and monitor the vital signs of up to four individuals, showcasing the effectiveness of STC RIS in the multi-person sensing scenarios. The technology enables continuous and non-invasive monitoring of multiple people, thus promising transformative applications in areas such as smart homes, medical facilities and public spaces.

6. Conclusion

This paper presents a review of our recent advancements in RIS-empowered human health monitoring techniques, highlighting the transformative potential of RISs in enhancing the wireless sensing capabilities. By leveraging dynamic EM human modeling, non-line-of-sight vital sign sensing, and multi-person detection using STC RISs, we demonstrate that RISs can deliver high-resolution, non-invasive, and reliable solutions for the human health monitoring. These advancements lay a solid foundation for the future applications in healthcare, security, and elder care.

7. Acknowledgements

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