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Research Article

Respiration Signal Monitoring of Multiple Individuals via BSS and UWB-SIMO Radar

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ABSTRACT

In recent years, multi-person respiration detection has been more interest, especially in medical environments and emergency situations where several people need to be monitored at the same time. However, it is still challenging to get accurate vital signs from people who are very close together, either at the same distance or in the same angular cell, because the reflected signals overlap. To overcome this limitation, this study employs a Blind Source Separation (BSS) approach using the Fast Independent Component Analysis (FastICA) algorithm to separate multiple targets situated in close proximity or sharing similar angles. The Fast Fourier Transform (FFT) is then used to estimate the respiratory frequencies. Simulation results show that the proposed solution is capable and efficient. They also show that it can successfully separate individual respiratory signals in complex situations with more than one person.

Keywords: Ultra-Wideband (UWB) radar, multiple individuals, single-input multiple output (SIMO), Blind Source Separation, respiration rate.

INTRODUCTION

Respiratory patterns constitute an important vital sign that can be used for evaluating physiological status, monitoring patient conditions, and managing diverse medical disorders. Continuous respiratory signal monitoring is indispensable in numerous clinical and emergency situations, such as asthma management, neonatal intensive care, and disaster response. Ultra-wideband (UWB) radar has become more popular thanks to its high resolution, low power consumption, and ability to detect subtle respiratory patterns.

In recent years, multi-person respiration detection has garnered significant attention, especially in practical contexts such as hospitals and emergencies that necessitate the concurrent monitoring of several individuals[1]. To address these demands, different radar designs have been investigated: Single-Input Single-Output (SISO) radar offers simplicity but limited spatial resolution, making multi-target discrimination challenging; Single-Input Multiple-Output (SIMO) radar improves spatial resolution through distributed antennas; and Multiple-Input Multiple-Output (MIMO) radar enhances target detection and parameter estimation via waveform diversity. Additionally, complementary non-radar approaches, such as WiFi-based sensing and camera-based monitoring, have been explored [2], [3].

In this regard, three principal approaches have been developed for identifying and evaluating multiple tagets' vital signs. The first consists of range-based separation, which enables the extraction of vital signs from multiple subjects positioned at different distances from the radar [11-12], [15] . Nonetheless, this method is constrained when multiple subjects are located in the same range bin. The second approach employs angle-of-arrival (AoA) separation, allowing discrimination between targets situated at identical ranges but at different angular positions [7], [8]. However, AoA-based methods become ineffective when individuals are closely spaced or located at nearly the same angle. To overcome these limitations, Blind Source Separation (BSS) techniques have been introduced to isolate the vital signs of multiple individuals without relying on range or angular diversity. Xichao et al. introduced a multi-target vital-

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sign monitoring approach using Under-Determined Blind Source Separation (UBSS) using CEEMDAN–ICA, capable of separating multiple subjects located within a shared resolution cell using only a single FMCW radar [9]. In addition, Li et al. proposed a method for recovering the respiratory pattens of multiple individuals by employing the UBSS technique [10]. Jilin Zhang et al. suggested a BSS approch based on FastICA to separate multiple vital signs [11]. Similarly, Yue et al. developed the DeepBreath system, an RF-based respiratory monitoring platform capable of isolating breathing signals even when several subjects are situated in close proximity [12]. In a related effort, Shekh et al. proposed an ICA-based method that utilizes the Joint Approximate Diagonalization of Eigenmatrices (JADE) algorithm to reliably differentiate respiratory returns from closely spaced individuals [13].

In this paper, we present a simulated SIMO-UWB radar system for monitoring multiple individuals. We then apply a BSS approach based on FastICA to separate the mixed signals, and finally, the respiration rates are estimated by analyzing the frequency spectra of the separated components.

The structure of the subsequent sections is given below: Section 2 outlines the mathematical model used to characterize the respiration signals. Section 3 describes the methodology for estimating the respiratory signals of multiple targets. Section 4 introduces the simulated SIMO-based monitoring system. Section 5 provides a detailed analysis of the experimental results. Lastly, Section 6 closes the paper with a summary of the main results.

VITAL SIGNS MODELING FOR SIMO RADAR

Ultra-Wideband (UWB) impulse radar has been widely used for vital-sign monitoring because of its superior range resolution. During respiration, the thoracic cavity moves cyclically, producing rhythmic motions that closely resemble sinusoidal waveforms. These displacements add minute phase modulations to the radar echoes, even though they are usually only a few millimeters. It is possible to accurately extract and estimate the subject's vital-sign parameters by examining these phase variations.

In this study, a Uniform Linear Array (ULA) consisting of M receiving antennas is employed to improve detection of multiple targets. Considering N targets with incident angles $\theta = [\theta_1, \theta_2, \dots, \theta_N]$, The signal captured at the m^{th} antenna can be represented in the following simplified form:

$$x(t,\tau) = \sum_{n=1}^{N} \alpha^n \, g\big(\tau - \tau_m^n(t)\big) + n_m(t,\tau) \tag{1}$$

Where: τ and t indicate respectively the fast time and slow time.

c is speed of light.

$g(\tau)$ is the transmitted pulse.

α^n and τ_m^n denote the attenuations and the time of arrival TOA corresponding to the n^{th} person, respectively.

$n_m(t,\tau)$ is measurement noise.

Since the individuals maintain fixed positions during the processing period, and the first antenna is used as a reference, the Time of Arrival (TOA) can be calculated as:

$$\tau_m^n(t) = \frac{2d_0^n}{c} + \frac{2d_b^n \sin(2\pi f_b^n t)}{c} + \frac{(m-1)d}{c}\sin(\theta_n) \tag{2}$$

Where: d_0^n is the mean distance between the first antenna and target n.

d_b^n represents the breathing displacement amplitude of the n^{th} person.

f_b^n represents the breathing frequency of the n^{th} person.

d refers to the distance between the elements of the antenna array, as shown in Figure 1.

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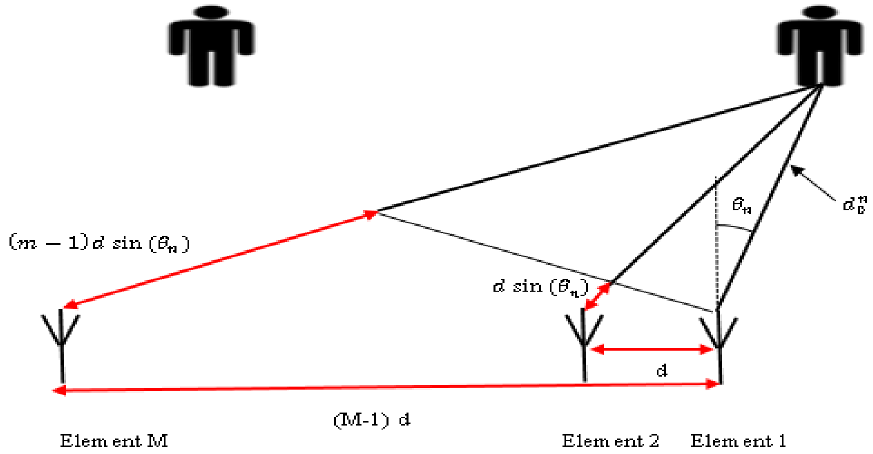

Figure 1. Received Signal Model of an Antenna Array

METHOD

A) BLIND SOURCE SEPARATION AND ICA

Blind Source Separation (BSS) is a widely used technique in signal processing that aims to extract the original source signals from observed mixtures without prior information about the mixing process[14]. In this study, BSS is applied to extract respiratory signals from multiple targets by decomposing the combined radar echoes into statistically independent components [11]. In scenarios where several individuals are located at the same distance or within the same angular region, their respiratory signals may overlap significantly in the received measurements. Methods based on Independent Component Analysis (ICA), particularly the FastICA algorithm, exploit the statistical independence of each individual's breathing pattern to effectively separate these overlapping signals, allowing each individual's respiratory activity to be accurately extracted without requiring information about the mixing process or the properties of the original sources [13]–[16].

The mixture is assumed to be linear. Figure 2 shows how the ICA method operates within the BSS framework. As illustrated, the mixing process in slow time can be written as [17]:

$$x(t) = A\, s(t) \tag{3}$$

Where, A represents the mixing matrix, and S denotes the matrix of source signals. ICA aims to determine a demixing matrix (W), Which ideally W corresponds to A^{-1} [13]. The corresponding output signal for each person is given by:

$$y(t) = W\, x(t) \tag{4}$$

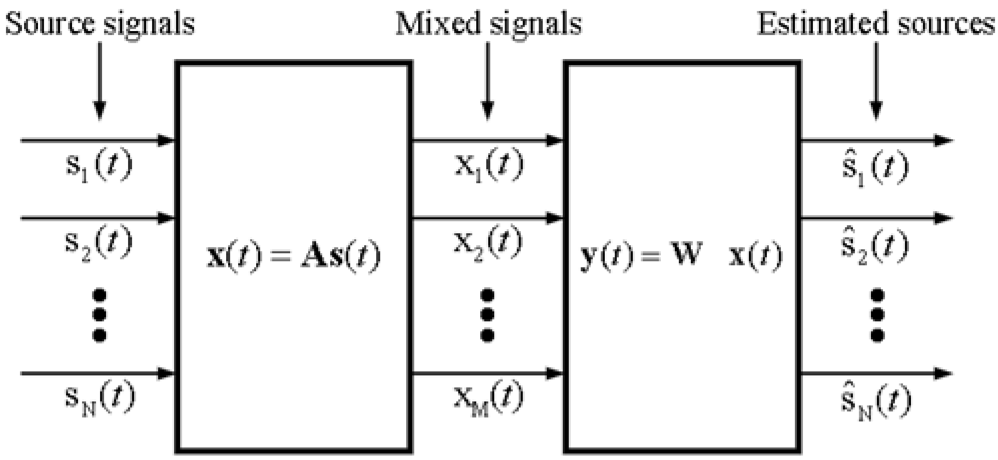

Figure 2. Schematic representation of BSS implemented via the ICA algorithm [17].

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VITAL SIGNS ESTIMATION

After separating the signals corresponding to multiple individuals, the next step is to estimate each person's breathing frequency. For this purpose, the Continuous-Time Fourier Transform (CTFT) is applied to the separated signal. The breathing signal for each person can be expressed as:

$$r(t,\tau) = \alpha_b \, g\big(\tau - \tau_b(t)\big) \tag{5}$$

After applying the CTFT along the slow-time dimension, the resulting expression is [18], [19]:

$$R(f,\tau) = \alpha_b \sum_{l=-\infty}^{+\infty} c_l \, \delta(f - l f_b) \tag{6}$$

δ represents the Dirac function and c_l is a coefficient that attains its maximum at $\tau = \tau_0$.

Clearly, the resulting spectrum is discrete, with delta functions appearing at the harmonic multiples of f_b. The breathing rates were determined by detecting the fundamental peaks in the frequency band of [0.2–0.8] Hz.

SIMULATED SIMO SYSTEM

The proposed system is simulated in MATLAB/Simulink and is primarily made up of three parts: the sensors, the propagation channel, and the targets. The sensing module includes a single transmitter and eight receivers configured in a SIMO architecture, together with a signal processing unit, as illustrated in Figure 3.

The transmitter emits a Gaussian pulse modulated by a 4.8 GHz carrier frequency. The received echoes, captured by the eight antennas, are affected by physiological activities such as chest motion during breathing.

Each target is modeled as a reflective point with a time-varying distance *$d^k(t)$*. Respiratory motion is produced by chest displacement, with a breathing rate between 12 and 48 breaths per minute and an amplitude ranging from 4 mm to 12 mm, depending on the subject's posture.

The Ultra-Wideband (UWB) signal provides high-resolution transmission; however, its performance is influenced by attenuation, interference, and noise. In the simulation, Gaussian white noise is used to model random interference, while attenuation represents propagation losses, as shown in Figure 4.

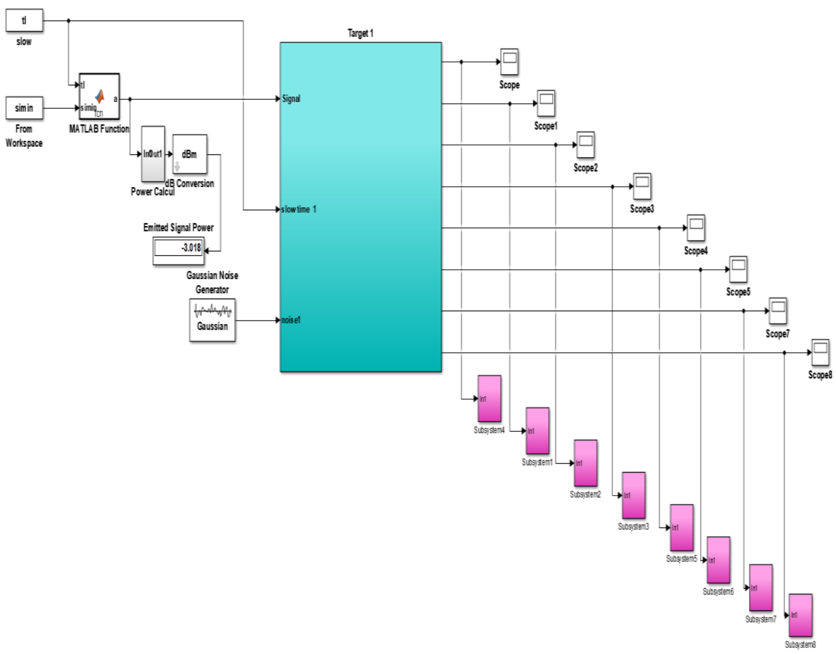

Figure 3. Simulated System

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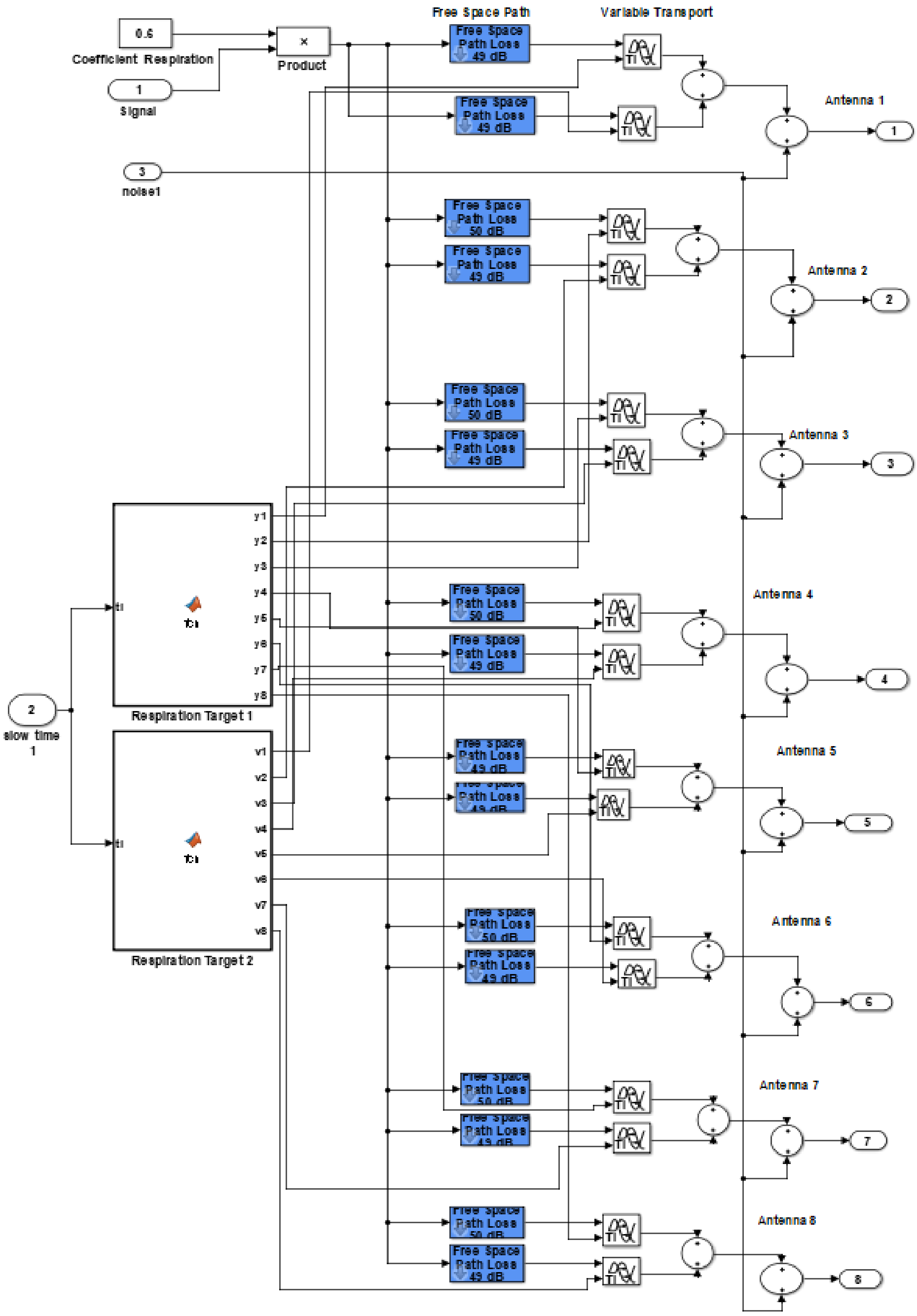

Figure 4. Proposed Channel Model

EXPERIMENTAL SIMULATION

This part describes the simulated experimental setup used to assess the efficiency of the proposed SIMO-UWB system, as well as the benefits of employing the BSS algorithm for separating multiple individuals and estimating their respiration rates. The experiments were designed to assess the robustness of the approach under challenging conditions, including subjects placed at adjacent positions, individuals located at the same distance, and scenarios involving identical azimuth angles.

In the first scenario, two individuals were symmetrically positioned in front of the radar at angles $\theta_1 = 0°$ and $\theta_2 = 10°$, both at a nominal distance of $d_0^1 = d_0^2 = 2\ m$. This configuration was selected to examine the system's ability to discriminate between two closely spaced subjects with nearly identical ranges. The respiration frequencies were set to 0.38 Hz for the first subject and 0.52 Hz for the second.

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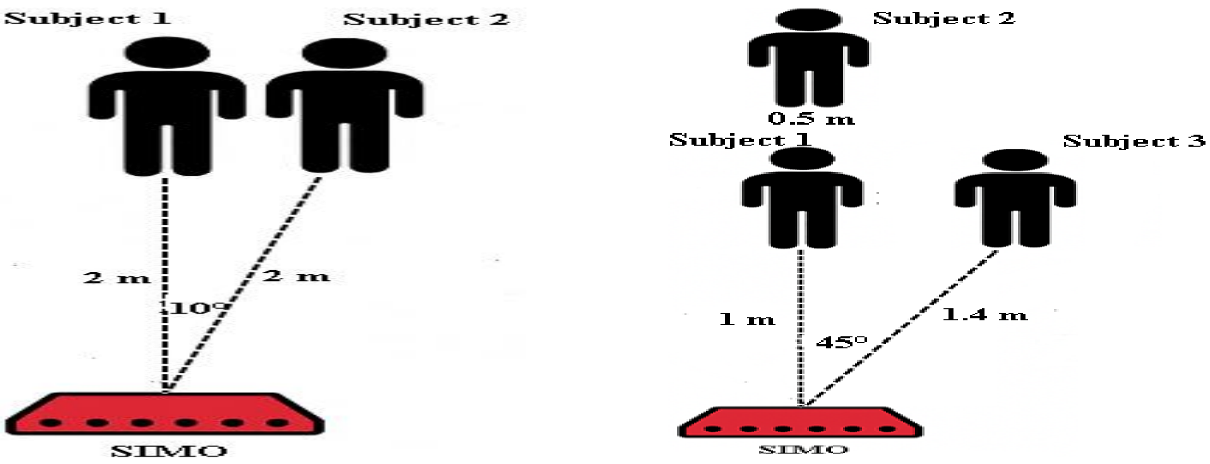
In the second scenario, three individuals were placed at different distances from the radar $d_0^1 = 1\,m$, $d_0^2 = 1.5\,m$, $d_0^3 = 1.4\,m$ and positioned at angles θ1 = θ2 = 0°, and θ3 = 45°, respectively. This configuration was designed to evaluate the system's capability to separate multiple subjects located at the same or similar azimuth angles. The respiration frequencies were set to 0.42 Hz, 0.55 Hz, and 0.62 Hz, respectively, as illustrated in Figure 5.

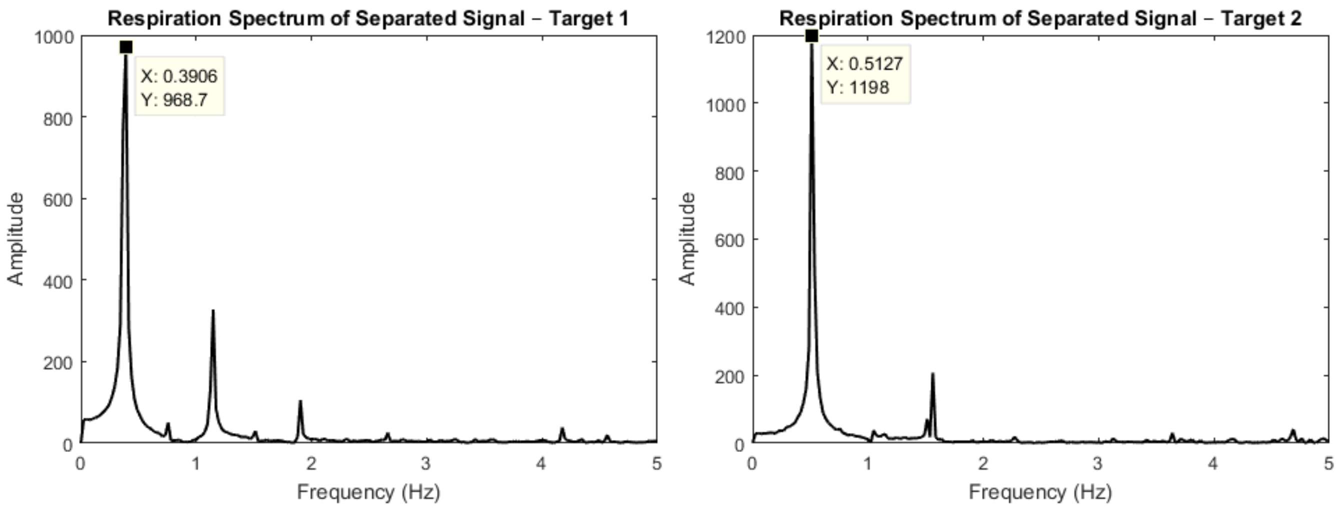


(a) (b)

Figure 5. Experimental Setup: (a) Two Subjects, (b) Three Subjects

RESULTS AND DISCUSSION

In this section, the CTFT was applied to the separated signals to estimate the respiration rate of each individual. In the first scenario, the two subjects exhibited breathing frequencies of approximately 0.39 Hz and 0.51 Hz, as illustrated in Figure 6. In the second scenario, which involved three subjects positioned at different distances, the estimated respiration rates were 0.415 Hz, 0.56 Hz, and 0.61 Hz (Figure 7). The overall estimation error was approximately 1.95%.



(a) (b)

Figure 6. Estimated Respiration rates of two persons. (a) FFT spectrum for θ1=0°. (b) FFT spectrum for θ2=10°.

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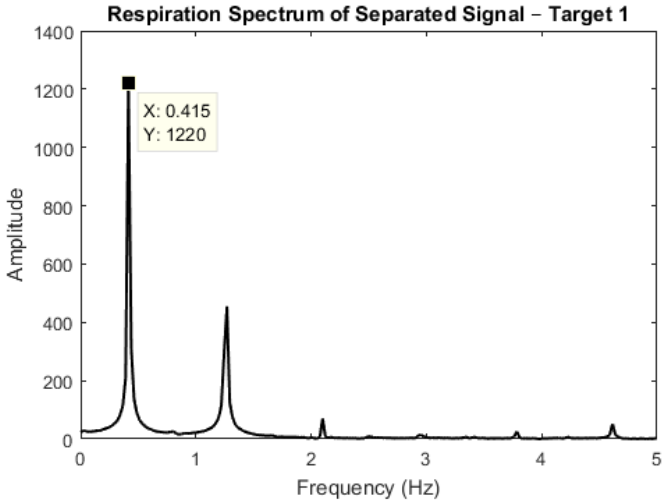
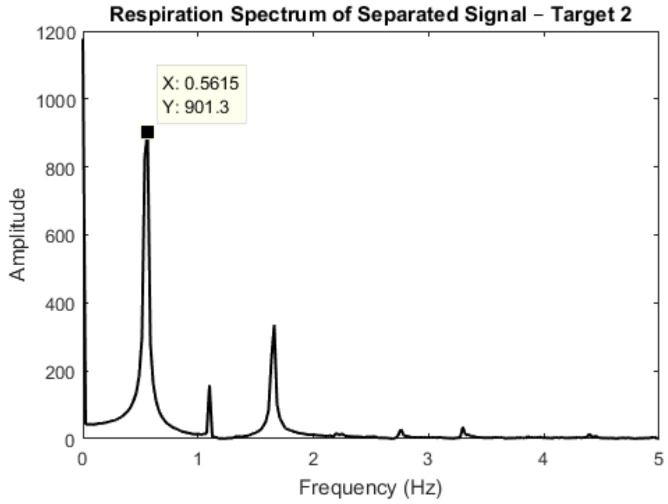


(a)



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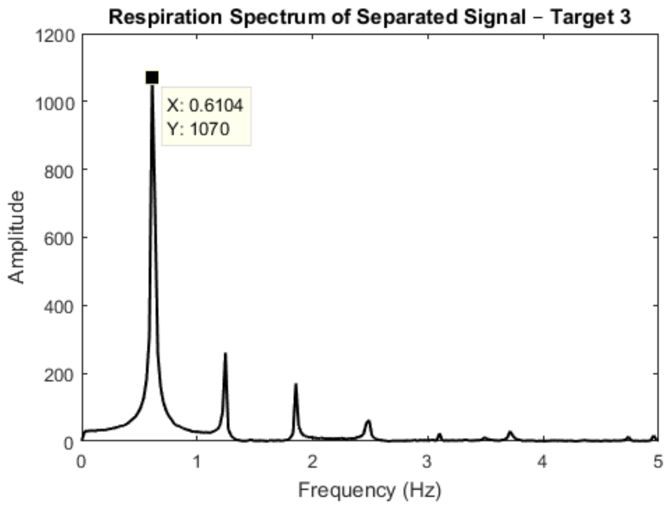

(c)

Figure 7. Estimated Respiration rates of three persons. (a) FFT spectrum for θ1=0°. (b) FFT spectrum for θ2=0°. (c) FFT spectrum for θ3=45°.

Simulation findings indicate that the BSS method based on FastICA is able to clearly isolate the respiratory components of multiple individuals from the mixed SIMO-UWB radar signals. Even under difficult conditions such as small angular separation or subjects sharing the same distance or azimuth, the algorithm still manages to recover clean and distinct breathing signals.

The estimated respiration frequencies closely match the simulated ground-truth values, highlighting the reliability and robustness of the proposed approach. By separating each individual's signal, the BSS method allows accurate monitoring of vital signs for multiple people, which is important in healthcare and surveillance applications.

Overall, the results indicate that BSS is an effective and computationally efficient solution for multi-target respiration monitoring using SIMO-UWB radar, performing better than conventional distance- or angle-based separation methods in complex multi-person environments.

CONCLUSION

This study demonstrates the effectiveness of a BSS framework using the FastICA algorithm for multi-person respiration monitoring using SIMO-UWB radar. The proposed approach successfully separates overlapping signals

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originating from closely spaced individuals, even in challenging scenarios where subjects share similar ranges or angular positions. By applying the FFT to the separated components, accurate respiratory frequencies are extracted, showing strong agreement with the simulated ground-truth values.

Simulation findings confirm that the proposed approch is both reliable and computationally efficient, offering a marked improvement over traditional distance or angle based separation techniques. These findings highlight the potential of BSS based processing for robust vital sign monitoring in complex environments, such as healthcare facilities and emergency response situations. Future research may further extend this approach to scenarios involving moving individuals, enabling precise and stable observation of vital signs in realistic and changing environments.

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