Comparative Analysis of Phase-Comparison Monopulse and MUSIC Algorithm Methods for Direction of Arrival (DOA) of Multiple-Subject Respiration Measured with Doppler Radar

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***Abstract*— While Doppler radar measurement of respiration has shown promise for various healthcare applications, simultaneous sensing of respiration for multiple subjects in the radar field of view remains a significant challenge as reflections from the subjects are received as an interference pattern. Prior research has demonstrated the basic feasibility of using phase comparison with a 24-GHz Monopulse radar for isolation of one subject when another subject was in view, by estimating each subject's angular location with 88% accuracy. The integration of the high-resolution Multiple Signal Classification (MUSIC) algorithm with a phase-comparison technique is proposed to achieve robust accuracy for practical multi-subject respiration monitoring. Experimental results for this work demonstrate that the MUSIC pseudo-spectrum can separate two subjects 1.5 meters apart from each other at a distance of 3 meters from the sensor, using the same antenna array elements, spacing, and experimental scenarios previously reported for phase comparison Monopulse alone. Experimental results demonstrate that the MUSIC algorithm outperforms the phase-comparison technique with an azimuth angular position estimation accuracy over 95%. Higher accuracy indicates the system has improved robustness concerning noise and interference.**

Keywords*— Remote sensing, direction of arrival, MUSIC, phase-comparison monopulse.

I. Introduction

Remote respiration sensing using microwave Doppler radar has provided a non-contact and noninvasive form of measurement [1-2]. The basic principle of this remote respiration sensing technology is that the reflected signal undergoes a phase change that is directly proportional to the subtle movement of the chest surface during cardiopulmonary activity [1-3]. This unobtrusive respiration sensing technology has shown promises in long term physiological monitoring especially in sleep apnea studies [4]. In-home based sleep monitoring there is a likelihood of the presence of multiple subjects in front of the radar where concurrent respiration monitoring is very crucial. However, concurrent respiration monitoring in a multi-subject scenario remains a significant technological challenge as radar receives reflected echoes from different subjects as a combined interference pattern [5].

Most reported studies have used frequency modulated continuous wave (FMCW) radar which requires complex hardware circuitry [6]. Other attempts also included estimation of the angular location of the subject by applying the direction of arrival (DOA) technique using continuous wave (CW) radar, which has not proven especially effective for closely-spaced subjects due to having an angular resolution limit which depends on antenna array element spacing [7]. In our recent study, we proposed an intelligent SNR-based decision algorithm for combining two different approaches (ICA, DOA) to monitor multiple subject respiration concurrently [8]. For this, a phase-comparison monopulse technique was used to estimate the angular location of the target and switch the beam in the appropriate direction [8]. The phase-comparison monopulse technique is computationally faster, but its accuracy is less, around 78%, due to the grating lobe effect which occurs when the antenna array elements are less than half of the operating wavelength [5][7-8]. Thus, to increase the robustness of the DOA estimation technique an integration of the high-resolution multiple signal classification (MUSIC) technique is proposed and analyzed with respect to monopulse.

A 24-GHz phase-comparison K-MC4 radar transceiver was used to estimate DOA of well-spaced subjects by integrating two approaches (Monopulse and MUSIC). Also, the efficacy and accuracy of two different approaches on estimating the angular location of two equidistant subjects at the edge of the beamwidth of the radar transceiver are compared. After estimating the angular location of the targets more precisely the beam can be switched in the appropriate direction based on the angle of arrival of the physiological measurement signal to make this system more robust for practical concurrent monitoring applications (sleep monitoring, occupancy sensing, and activity monitoring).

II. Theoretical Background

A. Phase-Comparison Monopulse Technique

Phase-comparison Monopulse is a technique where the angular location of the target can be determined by comparing their phase properties of the received signals in two antenna array elements [9]. In this work, we utilized an off-the-shelf K-MC4 module which is a 24-GHz phase comparison monopulse radar [10]. The K-MC4 is a Doppler transceiver with a 4×8 patch antenna array for the transmitter and two 2×8 patch antenna arrays for the receiver [9], as shown in Fig.1 (a). Fig. 1 (b) shows the basic principle of the

DOA estimation technique, where antenna arrays are separated by a distance d, with a wavefront incident at an angle θ. Due to the path difference between the antenna array elements, incoming wavefronts experience a phase difference of $\delta\phi$. The relationship between the phase difference and path difference is:

$$kd\sin(\theta) = \delta\phi \tag{5}$$

where k is the wavelength of the transceiver. With a distance between two receiver elements of 13.77 mm, the DOA can be calculated by simplifying the equation to:

$$6.7\theta = \delta\phi \tag{6}$$

where $\delta\phi$ is the phase difference between the I channels (I_1 and I_2) and Q channels (Q_1 and Q_2). As the transceiver has a fixed number of antennas and beamwidth, it has a limited angular resolution [10].

B. Multiple Signal Classification (MUSIC)

The classic MUSIC algorithm is the most common approach for estimating DOA, basically using a peak search to estimate the arrival angle [11-12]. This algorithm uses Eigenvalue decomposition of the received signal covariance matrix. Using this algorithm, the pseudo spectrum of the received signal is calculated to derive the frequency content

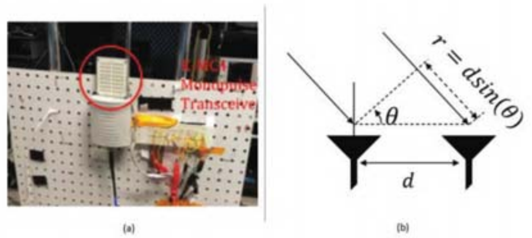

Fig. 1. K-MC4 radar transceiver used in this experiment (a) and the principle of the phase-comparison monopulse technique to estimate the angular location of the target. The monopulse radar transceiver had a 4×8 patch antenna array for the transmitter and the two-receiver used 2×8 patch antenna arrays.

of the signal [11-12]. The peaks of the pseudo spectrum represent the Angle of Arrival (AOA) i.e. DOA, and higher estimation accuracy can be achieved at the expense of more extensive computational cost [11].

III. EXPERIMENTAL SETUP

In this experiment, we used a 24-GHz K-MC4 monopulse radar transceiver with four channels (I_1, Q_1, I_2 and Q_2) ac-coupled to four Low-noise amplifiers (LNA) (SR560), each with a cut-off frequency of 30 Hz and with a gain of 200. The four outputs were connected to a DAQ (National Instrument) with a customized LABVIEW interface used to capture the respiration patterns. Two subjects were placed within the beamwidth of the transceiver, which for the K-MC4 radar was within a 12.5° azimuth angle from each other [10]. The subjects were seated 2.89 meters away from the radar keeping a 1.5-m angular discrimination limit between them. The relative angle between the subject and the sensor was measured using a protractor. Fig. 2 illustrates the experimental setup.

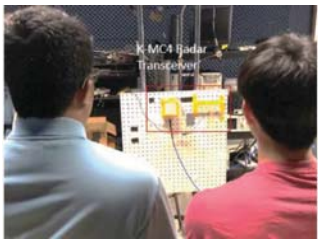

Fig. 2. Radar measurement setup. The K-MC4 transceiver was connected to low noise amplifiers and data acquisition system. The two receivers with 2×8 patch antenna elements were used to measure the two subjects seated at 1.5 meter apart and each 3 meters away from the radar sensor with a 12.5° angle between them.

IV. RESULTS

The captured signal was processed with an FIR filter of order 1000 with a cut off frequency of 10 Hz. The filter order was selected based on the sampling frequency of DAQ which was around 100 Hz. The selection of the10 Hz cut off frequency was based on the physiological motion signal bandwidth. Physiological motion signals from respiration and heartbeat lie within 0.01-2 Hz and a cut off frequency of almost five times the highest frequency content of the signal was used. Post-processing was performed in MATLAB. Figure 3 illustrates the radar captured respiration patterns for a combined mixture of two different subjects seated in front of the sensor. The phase difference was measured between the two corresponding channel signals (I_1, I_2 or Q_1, Q_2), and measured based using a fast Fourier transform (FFT) with a maximum likelihood estimation of the signal properties and their initial phases [13]. An FFT analysis of the mixed-signal was performed to show the two dominant peaks which

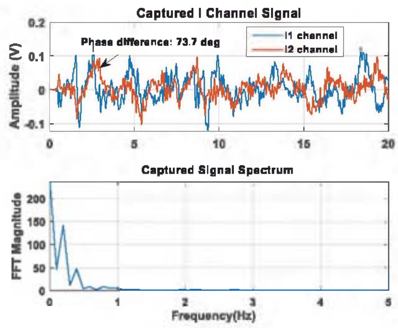

Fig. 3. Radar captured respiration pattern for the combined mixture of two different channel signals (I_1 and I_2). An FFT of the signal shows two dominant peaks which illustrates the presence of two subjects in front of the radar.

illustrate the presence of the two subjects in front of the sensor [8] [10]. The phase difference between the two-channel signals is around 73.7°. To estimate the direction of arrival (DOA) we used equation (6) as in our previous work [8-10], which divides the phase difference by 6.7. So, the estimated direction of arrival of the physiological signal was approximately 11°. One potential advantage of this technique is that it is computationally fast as it requires only a single snapshot [8][10]. The estimation accuracy is limited due to the grating lobe effect which occurs when the antenna element

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spacing (13.77 mm) is less than half of the operating wavelength (6.25 mm) [8][10].To increase the accuracy of estimating the angle of arrival (AOA) the MUSIC algorithm was also incorporated. To implement the MUSIC algorithm the received data from the Doppler radar system is taken in the form: $x[k] = [x_1, x_2, \dots \dots . x_n]$ (2), where, $x_n = x_{in} + jx_{Qn}$ is the complex baseband signal comprised of the I and Q channels, N=4 is the number of demultiplexed IQ channels (I_1, I_2, Q_1, Q_2), and k =1 is the total number of samples or snapshots required. The peaks of the pseudo spectrum are the estimated angle of arrival. Fig. 4 illustrates the pseudo spectrum of the signal using the experimental data set. The pseudo spectrum includes two dominant peaks at azimuth angles of $+12°$ and $-12°$ which illustrate the presence of two subjects in front of the radar. For estimating

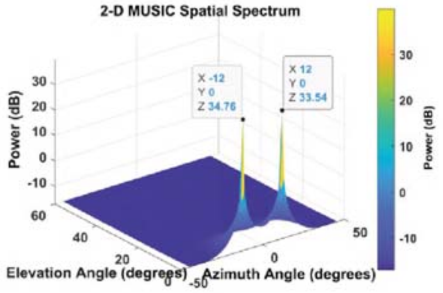

Fig. 4. Radar captured combined signal pseudospectrum for the MUSIC algorithm. The peak of the signal in the x-axis represents the angle of arrival which is around 12°. The presence of two subjects in front of the radar sensor was measured as around 12.5° azimuth angle.

DOA in the MUSIC algorithm, we have used 1024 snapshots. The computational time for DOA estimation in the MUSIC algorithm requires a higher number of snapshots and it also increases the computational cost [14] whereas, the phase comparison technique requires just one snapshot or sample point [14]. We also compared the DOA estimation accuracy between two different techniques using our experimental data. Estimation accuracy is computed based on the following equation:

$$Accuracy = \frac{|\text{Estimated DOA} - \text{meausred DOA}|}{\text{measured DOA}} * 100\%$$

For estimating accuracy, we also repeated the experiments for single subjects at different angles and two subjects within the beamwidth of the transceiver. Estimation accuracy for the phase comparison technique was 88% while for MUSIC it was 95%. Fig. 5 presents a comparative analysis of estimation accuracy. Higher accuracy indicates a system is more robust concerning noise and interference. The details of this comparative analysis provide a basis for understanding the benefits and tradeoffs for both DOA algorithms to develop a method for practical implementation. After estimating the angular location of a subject the beam can be switched in the appropriate direction (using a mechanical rotator) to isolate respiratory signatures from the combined pattern.

V. Conclusion

In this paper, we integrated the MUSIC algorithm with a phase-comparison monopulse radar system to estimate the spatial position of a target and conducted a comparative analysis for the techniques. Experimental results demonstrate that the MUSIC algorithm provides better estimation accuracy for the angular location of the target and that this technique

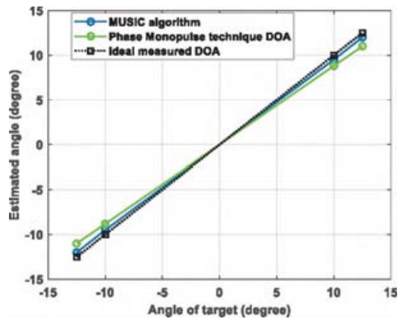

Fig. 5. Comparative Analysis of estimation accuracy for different DOA methods. The blue line illustrates MUSIC estimated DOA and the green line represents phase comparison based DOA, while the black line illustrates the ideal measured DOA.

requires more data snapshots. On the other hand, the phase-comparison technique is computationally more efficient as it requires just one snapshot. Based on the comparison, tradeoffs can be properly assessed to help determine which techniques are most useful for a given application.

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