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Concurrent Respiration Monitoring of Multiple Subjects by Phase-Comparison Monopulse Radar Using Independent Component Analysis (ICA) With JADE Algorithm and Direction of Arrival (DOA)

SHEKH M. M. ISLAM, (Student Member, IEEE), OLGA BORIC-LUBECKE, (Fellow, IEEE), AND VICTOR M. LUBEKCE, (Fellow, IEEE)
Department of Electrical Engineering, University of Hawaii at Manoa, Honolulu, HI 96822, USA
Corresponding author: Shekh M. M. Islam (shekh@hawaii.edu)

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ABSTRACT While non-contact monitoring of human respiration has been demonstrated using Doppler radar, the concurrent monitoring of multiple equidistant subjects remains a significant technological challenge. Reported research has so far been limited to maintaining 1-m subject separation, based on the radar antenna beam-width. Proposed here is a hybrid method consisting of an SNR-based intelligent decision algorithm which integrates two different approaches to isolate respiratory signatures of two subjects within the radar beam-width separated by less than 1 meter. Using Independent Component Analysis with the JADE algorithm (ICA-JADE) and Direction of Arrival (DOA), this SNR-based decision algorithm works with an accuracy above 93%. In addition, angular location of each subject is estimated by phase-comparison monopulse and an integrated beam switching capability is demonstrated to optimally extract respiratory information. The proposed method coherently combines two separation methods to overcome multiple-subject monitoring limits which can lead to practical adoption for many respiration monitoring applications.

INDEX TERMS Doppler radar, direction of arrival (DOA), joint approximate diagonalization of eigenmatrices (JADE), non-contact measurement, respiration monitoring, subject separation, vital signs.

I. INTRODUCTION

Doppler radar first emerged in 1930 [1] and since then remote sensing using microwave Doppler radar has become a well-established area for research in a vast range of applications. In 1970 Doppler radar was studied for healthcare applications through the measurement of minute physiological movement of the chest due to respiration and heartbeat [2]. According to Doppler theory, a subject/target with time varying chest displacement will produce a reflected signal from a radar transmission, which is phase modulated in direct proportion to the displacement [3]. A key advantage of this technology is that, this sensor can detect physiological movement of the chest induced by respiration and heartbeat without interference imposed by contact or wiring [4]–[12]. This unobtrusive form of respiratory monitoring has prompted interest in sleep apnea studies because existing wearable sleep study sensors affect the quality of sleep and thus hamper accurate measurement [13]. In home-based sleep monitoring studies, it is common to have multiple subjects in view of the radar sensors when partners share a bed, and separating signals becomes a challenge [14]–[17]. However, most reported results in Doppler radar sensor literature simply focus on measurement of a single subject to avoid separation issues [15]–[17]. For practical implementation in applications like home sleep monitoring, it is necessary to

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move to the next level and separate individual respiratory signatures from combined competing signals in an efficient manner.

An early solution approach studied for single-antenna systems, involves frequency domain analysis [18], [19]. However, the Fast Fourier Transform (FFT) approach essentially proved to be unsuitable when a mixture of different breathing patterns occurs [14]–[20]. Previous research has also focused on utilizing DOA to estimate the angular location of subjects, but this has not proven very effective for closely spaced subjects due to the angular resolution limit [20]–[24]. Beyond DOA, Vergara *et al.* [25] demonstrated the efficacy of Real Analytical Constant Modulus Algorithm (RACMA) to separate certain extraneous human body motion and respiratory motion from combined mixtures [14]. Fast Independent Component Analysis (Fast-ICA) was reported in [15] for separating multiple respiratory signatures using separate transceivers for each subject.

In recent research, Fadel *et al.* utilized FMCW radar to isolate multiple non-equidistant subjects using a wireless localization technique [26], [27]. More recently, Nosrati *et al.* designed a dual beam phased array CW radar to spatially isolate multiple subjects in front of the radar system using a beamforming technique requiring an angular discrimination limit between equidistant subjects of at least 1-meter [28], [29]. All reported attempts excluded the situation where separation of multiple equidistant subjects within the beamwidth of the radar is required [30]–[32].

When there are two equidistant subjects within one beamwidth, it is difficult to distinguish each subject due to the associated mutual interference which creates an ambiguous single peak in the associated velocity-range plot of the FMCW radar signal, and estimating angular location is not possible within the beamwidth of a CW radar due to the angular resolution limit [30], [31]. In practical situations, especially in-home based sleep monitoring, equidistant subjects might be spaced much closer than one meter apart and thus both lie within the beamwidth of the radar [15]–[17]. In prior work [15] we tested the feasibility of combining the Joint Approximation Diagonalization of Eigenmatrices (JADE) algorithm with ICA for separating respiratory signatures. The reported results showed the efficacy of the ICA-JADE method for angular discrimination of subjects at 1 meter for small scale of studies [15]. Additionally, we demonstrated the effectiveness of estimating angular location of multiple subjects by utilizing a phase-comparison Monopulse DOA technique for an angular discrimination of 1.5 meters [16]. We also tested the efficacy of the DOA technique for larger group of subjects having different breathing patterns with an angular discrimination of 1-3 meters at different slant ranges [17]. However, all prior work on DOA concentrated only on estimation of the angular location of the subject without introducing beam steering to isolate respiratory signatures. In addition, no prior work has addressed the issue of optimally isolating equidistant subjects within and without the beam width of the radar.

In this work, we focus on combining two methods (ICA-JADE and DOA) for solving realistic scenarios of concurrent respiratory monitoring for multiple subjects. We propose a new, scalable, practical monitoring approach employing a low cost 24 GHz monopulse CW radar system consisting of a single transmitter with two homodyne quadrature receivers (K-MC4), integrated with beam switching capabilities. For subjects with an angular separation which is too close to discern through DOA, we introduce an efficient decision algorithm which under these conditions uses an alternative ICA-JADE based approach to separate the body motion of the closely spaced subjects from combined mixtures into independent respiratory patterns. Effective integration of two complimentary approaches (ICA-JADE and DOA) provides subject separation superior to anything previously demonstrated. This new system provides the basis for robust performance which can potentially facilitate ubiquitous continuous monitoring of multiple closely based equidistant subjects under foreseeable real-world conditions.

II. THEORETICAL BACKGROUND

Consider the scenario of one transmitter and two receivers and two subjects present; so $N = M = 2$ where, N is the number of subjects and M is the number of receivers, the received signal will be in-phase signal B_I,and B_Q is the quadrature version of the signal, and a_{ij} are the mixing parameters. In general, N=M=X, where X=1, 2, 3,..N. The received signal in different receivers can be represented as follows:

$$\begin{bmatrix} \mathrm{Receiver_1}\ (t) \\ \mathrm{Receiver_2}\ (t) \\ . \\ . \\ \mathrm{Receiver_M}(t) \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{N1} & \cdots & a_{NN} \end{bmatrix} \begin{bmatrix} B_{I1}\ (t) \\ B_{I2}\ (t) \\ . \\ . \\ B_{IN}(t) \end{bmatrix} + j \begin{bmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{N1} & \cdots & a_{NN} \end{bmatrix} \begin{bmatrix} B_{Q1}\ (t) \\ B_{Q2}\ (t) \\ . \\ . \\ B_{QN}(t) \end{bmatrix} \quad (1)$$

CW monopulse radars can estimate the angular location of subjects when they are at the edge of the beamwidth [15]–[17]. Angular discrimination range also depends on antenna array element spacing and number of antenna array elements (length) [15]–[17]. Thus, to overcome this minimum spacing limit the proposed scalable system integrates an additional separation technique (ICA-JADE).

A. RESEARCH PROBLEM STATEMENT FOR THIS WORK

In order to understand the efficacy of the proposed hybrid-system, the isolation of respiratory signatures for three different practical scenarios are considered. First considered is a scenario where two well-spaced equidistant subjects are positioned [Figure 1(a)] and a CW radar is used to isolate independent respiratory signatures using DOA and switching the beam in corresponding directions. Prior work has demonstrated the feasibility of DOA for isolating well-spaced

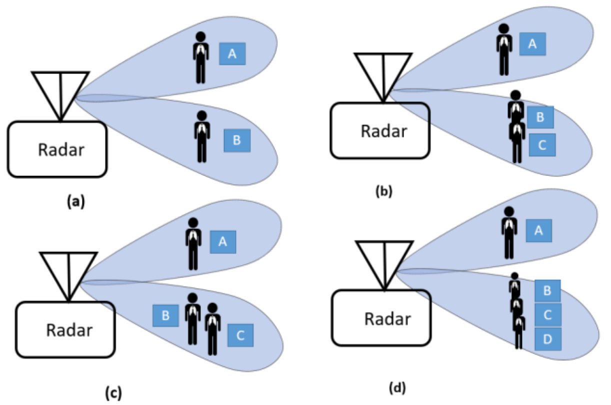

FIGURE 1. Practical subject separation scenarios considered for two radar beam positions. These include (a) two well-spaced subjects (one per beamwidth), (b) two equidistant subjects within one beamwidth, (c) two subjects at different distances within one beamwidth, and (d) three equidistant subjects within one beamwidth.

subjects [28], [29] and our proposed method can also isolate respiratory signatures using a phase comparison monopulse DOA technique under these conditions. The second scenario [Figure 1(b)] involves two subjects closely spaced within the beamwidth, and one subject well-spaced outside the beam. In this case our proposed technique can separate respiratory signatures using DOA for the well-spaced subject and ICA-JADE for the subjects closely spaced within the beamwidth. When subjects are at the edge of the beamwidth of the transceiver our proposed method can estimate the angular location of the target and mechanically switch the beam in the appropriate directions to isolate respiratory signatures. We also developed an algorithm to switch between these two methods (ICA-JADE and DOA) for extracting respiratory signatures when the subjects are within the beamwidth of the radar. To the best of the authors' knowledge, none of the work in prior literature has solved this critical problem which is illustrated in Figure 1(b). For the next scenario, it might happen that two subjects are at different distances within the beamwidth and this has been previously addressed using FMCW radar with wireless localization technique [26], [27]. Our proposed SNR-based decision algorithm can also isolate respiratory signatures for subjects at different ranges within the beamwidth. An additional scenario may also be considered where three closely spaced subjects are positioned within the beamwidth of the radar (Figure 1(d)), and the research reported here provides a basis on which to solve this problem in future extensions of this scalable work.

B. K-MC4 RADAR TRANSCIEVER ARCHITECTURE AND DOA ESTIMATION TECHNIQUE

We employed an off-the-shelf K-MC4 radar module for short range vital signs sensing which can estimate DOA with an adequate beamwidth of 30° [31]. The 24-GHz K-MC4 radar module contains two coherent receivers and each receiver provides in phase (I) and quadrature phase (Q) channels [31]. The transmitter has an array of 4 × 8 patch elements and the receiver has a 2 × 8 array [31]. We also used a phased array system toolbox to simulate radiation pattern and antenna array gain vs azimuth angle. At the edge of the beamwidth of the radar antenna the array gain is half of the maximum gain. Monopulse is a technique in which information concerning the angular location can be obtained by comparing the phase properties between spatially separated receivers [32]–[34]. The relationship between phase difference and path difference is:

$$Kdsin\,(\theta) = \delta\phi, \tag{2}$$

where, K is the wave number, $K = \frac{2\pi}{\lambda}$; λ is the wavelength, and d is the distance between two receivers with a wave front incident at an angle θ. Due to the path difference between antenna array elements, the incoming wave-front experiences a phase difference $\delta\phi$. The distance between two receiver elements is 13.77 mm. DOA can be calculated by simplifying equation (2):

$$6.7\theta = \delta\phi \tag{3}$$

From our simulation it is clear that the horizontal -3 dB beamwidth is approximately 30°. The angular discrimination S_A from sensors between two targets/subjects can be calculated as follows:

$$S_A \geq 2Rsin(\theta/2), \tag{4}$$

where, R= Slant range of targets/subjects from sensor, θ =Beamwidth of the transmitting array, and S_A = angular discrimination specified as distance between two subjects. Supposing the slant ranges of two subjects from the radar is 1 meter, then using the K-MC4 radar transceiver module we can separate two subjects within their angular discrimination. $S_A \geq 2 \times 1 \times \sin(30°/2) = 0.52$ meters. Table-1 represents the relationship between angular discrimination limit and slant ranges. After estimating the angular location of the subject/target we can mechanically switch the radar module in the corresponding direction for extracting vital signs information.

C. ESTIMATION OF SIGNAL-TO-NOISE RATIO (SNR) AT DIFFERENT AZIMUTH DISCRIMINATION RANGES WITHIN THE BEAMWIDTH

The signal to noise ratio (SNR) for the received signal at a certain range within the beamwidth can be calculated using the radar range equation shown in Eqn. (5). SNR is the ratio of the signal power at the receiver, P_S, and noise power at the receiver, P_N. G_T, G_R is the directive gain of transmit and receive antenna, λ is the wavelength, σ is the radar cross section (RCS), and R is the range of the target. K is Boltzmann's constant, so SNR is calculated as:

$$\mathrm{SNR} = \frac{P_S}{P_N} = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3\, R^4 K T_0 B F_n L}, \tag{5}$$

TABLE 1. Relationship between radial distance, angular discrimination and selected angular discrimination limit.

Radial distances (m)	Angular discrimination limit for DOA estimation	Experimental Angular discrimination limit
R=1	$S_A \geq 2RSin\left(\frac{\theta}{2}\right) = 0.52m$	0.52 m(edge of the beamwidth) 0.4 m (within the beamwidth)
R=1.5	$S_A \geq 2RSin\left(\frac{\theta}{2}\right) = 0.78m$	0.78m (edge of the beamwidth) 0.5 m (within the beamwidth)
R=2	$S_A \geq 2RSin\left(\frac{\theta}{2}\right) = 1.04m$	1.04m (edge of the beamwidth) 0.7m (within the beamwidth)

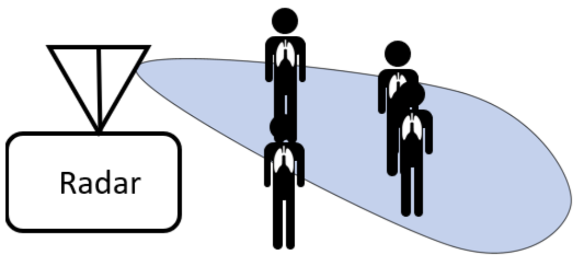

FIGURE 2. Diagram of subjects located at the edge and within the transceiver main beamwidth. Subjects located at the edge are well-spaced and DOA estimation is possible. When subjects are within the beamwidth (closely spaced) DOA estimation is not possible.

where B is the effective noise bandwidth, F_n is the noise figure, and L accounts for path loss. The path loss is Friss propagation loss [40]:

$$L = \left(\frac{4\pi d}{\lambda}\right)^2, \tag{6}$$

where, d is the distance from the subject to the antenna, and λ is the wavelength of the transceiver. For analyzing the SNR of the received signal from equidistant subjects at a particular range we used equation (5) and (6). We considered two extreme positions where subjects were at a certain range at the angular decimation limit both at the edge and well within the beamwidth. Table-1 shows the relationship between threshold angular discrimination limit and radial distances. At 1-meter radial distance, when the subjects are at an angular discrimination limit of 0.52 meters, their angular spatial position is at the edge of the beamwidth. Once they cross the boundary of 0.4 m their position is within the beamwidth. We examined two situations, with subjects placed very closely at a maximum 0° angular position within the beam, and at a maximum 15° angular position at the edge of the beamwidth of the radar. Figure 2 illustrates the spatial position scenarios considered. When equidistant subjects are at the edge of the beamwidth we can isolate them by estimating their location but as they get much closer, we cannot. Instead we investigated the SNR differences between these two locations. For simulation we considered the radar antenna array parameters from the data sheet [31] and estimated SNR considering the Friss propagation formula [40]. We also used a human subject radar cross section parameter of 1.22 m^2 [41]. In addition to simulations we also analyzed the measured radar reflections in an anechoic chamber experiment for two subjects present within the beamwidth having different angular resolutions. Table-2 represents the SNR at two different locations where we can switch between two methods. From the simulation and experimental results, it is clear that the SNR difference between two different boundaries (edge and within beam) is almost 6 dB. This SNR difference occurs due to antenna array gain differences at the corresponding locations [31] [33]–[35]. From analysis of the SNR look up table we can easily detect the spatial positions of two subjects, either within or at the edge of the beamwidth.

TABLE 2. Simulated SNR at different radial distances within beamwidth.

Range (m)	SNR within Beamwidth	SNR at the edge of the beamwidth
1 m	26. 141 dB	20. 14 dB
2 m	20.12 dB	14.12 dB
3 m	13.19 dB	7.19 dB

EXPERIMENTAL RADAR CAPTURED SNR AT DIFFERENT RADIAL DISTANCES

Range (m)	SNR within Beamwidth	SNR at the edge of the beamwidth
1 m	24. 12 dB	18. 13 dB
2 m	17.12 dB	11.15 dB
3 m	9.19 dB	3.17 dB

III. EXPERIMENTAL SETUP & DECISION ALGORITHM

In the experiment, we used a 24-GHz K-MC4 radar module with four channels (I_1, Q_1, I_2 and Q_2) connected to low-noise-amplifiers (LNA's). The LNAs were ac-coupled with a gain of 200, low-pass filtered at 30 Hz, and connected to a DAQ (NI-6009). A customized LABVIEW interface captured all signals from the system. The experiment was conducted in a controlled environment in a millimeter wave anechoic chamber. The complete setup is shown in Figure 3. External reference chest belts (UFI Model 1132 Pneumotrace II) were also attached to the human subjects and connected to the LNAs as reference signals. Three different experiments were carried out to evaluate the integration and algorithm development for coherently combining two different separation techniques (ICA, DOA) for the Doppler radar measurements.

1. In experiment one, two well-spaced equidistant subjects were positioned at different angular discrimination ranges from 1 meter to 3 meters. This experiment was performed to test the effectiveness of DOA technique and integrating the beam switching to isolate breathing rate of a single subject. Figure 3 illustrates the experimental scenario for well-spaced subjects in front of the radar module.
2. In second experiment, two equidistant subjects within the beamwidth of the radar each sat at different slant

FIGURE 3. Experimental setup showing two well-spaced subjects. These subjects can be separated using DOA and respiration rate of each independent subject can be monitored by tilting the radar beam in the corresponding angular direction.

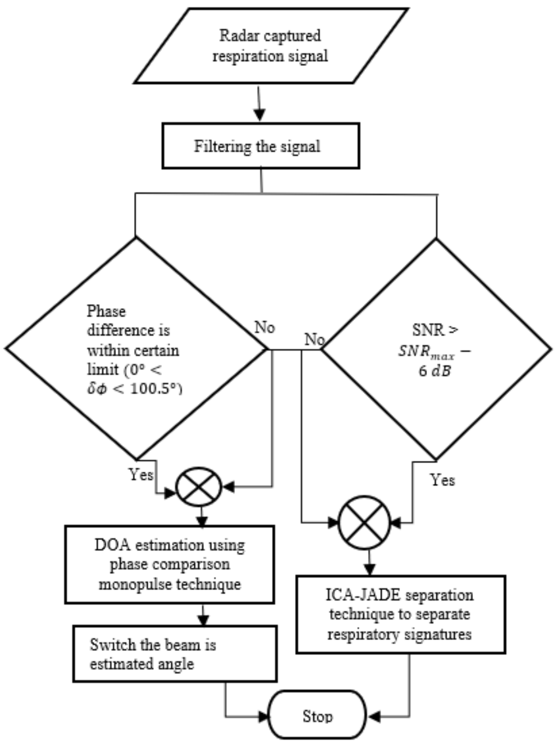

FIGURE 4. Proposed decision algorithm for selecting appropriate approach (ICA-JADE or DOA) when two subjects are within the beamwidth of the radar.

ranges (1, 1.5, 2, 2.5 and 3 m) at two different angular discrimination ranges (shown in Table-2) for developing an algorithm to switch between the two separation methods. We also tested the feasibility of estimating DOA when one subject was outside the beam.

3. In the third experiment, we placed two subjects at different distances within the beamwidth of the radar.

The decision algorithm developed to switch between two different techniques (ICA-JADE, DOA) is shown in Figure 4. After capturing and filtering the radar respiration signal, we found the phase difference and SNR of the received signal. Based on our simulation and experimental setup we created an SNR lookup table for equidistant subjects at different slant ranges (1 m to 3 m). If the SNR of the received signal at a particular distance is less than 6 dB and phase difference between two received signals is higher than 100.5°, then the ICA-JADE algorithm is employed to separate the respiratory signatures. If instead the SNR of the received signal is less than the threshold limit ($SNR > SNR_{max} - 6dB$) the phase difference between two receivers remains within the limit. Thus, DOA can isolate two subjects based on their spatial positions by switching the beam in the direction corresponding to each subject.

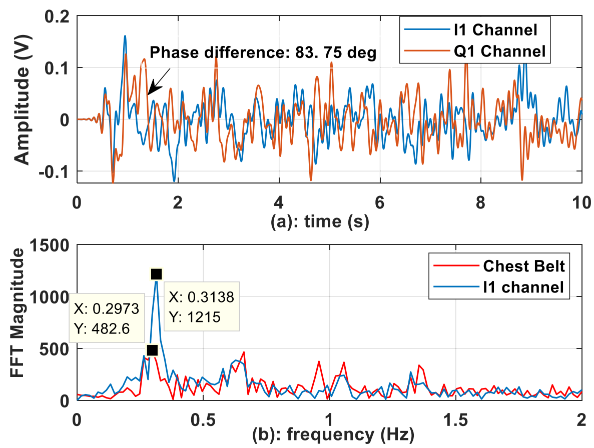

FIGURE 5. (a) Phase difference between receivers for a well-spaced subject (3-m from second subject) and (b) spectrum for isolated subject's respiration signal. Chest belt measured reference signal closely matches the radar-measured respiration rate.

IV. RESULTS

A. SCENARIO I: TWO SUBJECTS ARE WELL-SPACED

In the first experiment we considered two well-spaced subjects with an angular discrimination limit of at least 1 to 3 meters. The captured signal for each single subject was filtered using a Finite Impulse response filter (FIR) of an order of 1000 with a cut off frequency of 10 Hz. Then we measured the phase-difference between two receiver channels using a Fats Fourier Transform (FFT) and maximum likelihood estimation [16], [17]. From the phase difference information, we can estimate the angular location of a subject by using Eqn. 3. From Figure 5 (a) the phase difference between the received two-channel signals is 83.75°. 83.75°. Using Eqn. (3) we can estimate the angular location of one subject from the radar azimuth angle as 12.5°. After estimating the angular locations, we can switch the beam in the corresponding direction to isolate the respiratory pattern of a single subject. Figure 5 (b) illustrates that the FFT of the switched beam in a certain direction is around 0.31 Hz. It is also clear from the figure the chest belt respiration rate is 0.29 Hz. Similarly, by rotating the beam in another direction we also extracted the respiration rate of the signal subject after determining the angular location from the azimuth plane view of the radar. Then we measured the estimation accuracy of the isolated respiratory rate with a chest belt reference respiratory rate using (7), shown at the bottom of this page. The percentage accuracy of the system using this beam switching technique is around 94.45% with an angular discrimination of 3 meters. Accuracy of the system also depends on DOA estimation accuracy which determines the direction in which the beam is switched [16], [17].

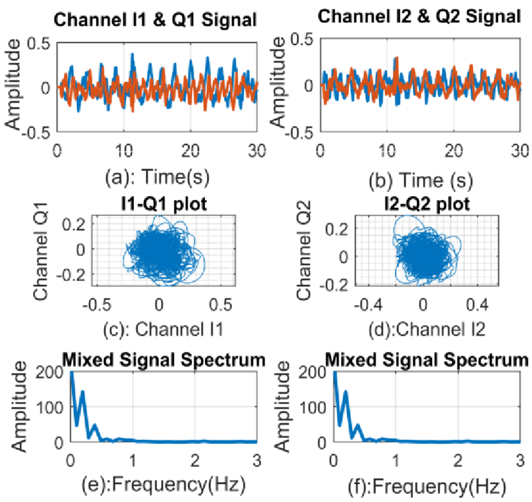

FIGURE 6. **Two-subject radar measurement captured at a slant range of 1 m with an angular discrimination of 0.4 m at an angle of 30°. Plots of measured (a) I_1 and Q_1 signals, (b) I_2 and Q_2 signals, (c) I_1 vs Q_1, and (d) I_2 vs Q_2 are reproduced from [15].**

B. SCENARIO II: TWO SUBJECTS ARE CLOSLEY-SPACED WITHIN THE BEAM AND ONE SUBJECT IS OUTSIDE THE BEAM

If two subjects are within the beamwidth and one subject is outside the beam, then we can extract respiratory rate for the outside subject by switching the beam. Here we will concentrate on the two subjects within the beam to test the effectiveness of our proposed separation algorithm. Two subjects were positioned at 1-meter slant ranges from the Doppler radar and with an angular discrimination of 0.4 meters between them within the main beamwidth (30°) of the K-MC4 transceiver. Figure 6 depicts the filtered captured signal of two subjects and their corresponding constellation (IQ) plots. In one of the mixed signal spectrum plots, there were two dominant breathing frequencies of 0.19 Hz and 0.39 Hz. Two different respiration frequencies were clearly observed form the FFT of the mixed signal which demonstrated the presence of two subjects in front of the sensor. Figure 7 represents the SNR of the radar measured signal at this particular position which is around 22.40 dB. By looking at the SNR lookup table it is clear that subject position is within the beamwidth of the transceiver. We also measured the phase difference between two receivers to be around 110°, which is beyond the functional phase difference range of the monopulse radar transceiver. Thus, for this case we used the ICA-JADE algorithm technique to separate respiratory signatures based on our proposed intelligent decision algorithm. Then we linearly demodulated the two-channel signals as shown in Figure 8 and mixed the signals with random noise with a mixing matrix. The ICA-JADE method was then used to separate the individual respiratory signatures from their combined mixtures. From Figure 8 it can be seen that the mixed signals were

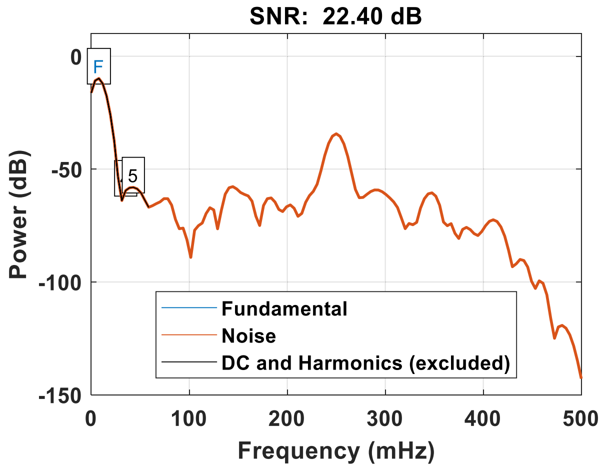

FIGURE 7. **SNR of radar captured respiration signal with two equidistant subjects at 1 m with angular discrimination limit of 0.4 m.**

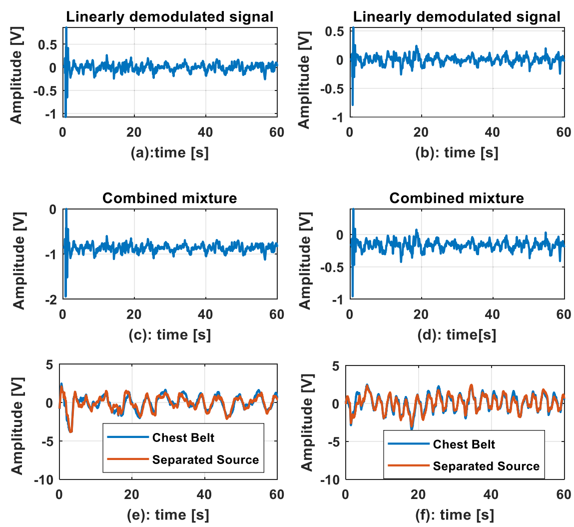

FIGURE 8. **Signals for 2-receiver ICA-Jade separation of respiratory signatures. Shown are linear demodulated signals for (a) I_1 & Q_1 and (b) I_2 & Q_2, along with corresponding combined mixtures for receivers (c) 1 and (d) 2. Separated sources are also shown in comparison with chest-belt reference signals for receivers (e) 1 and (f) 2.**

$$\text{Accuracy} = \frac{|\text{chest belt extracted rate} - \text{radar signal extracted rate}|}{\text{chest belt extrcaed rate}} * 100\%. \tag{7}$$

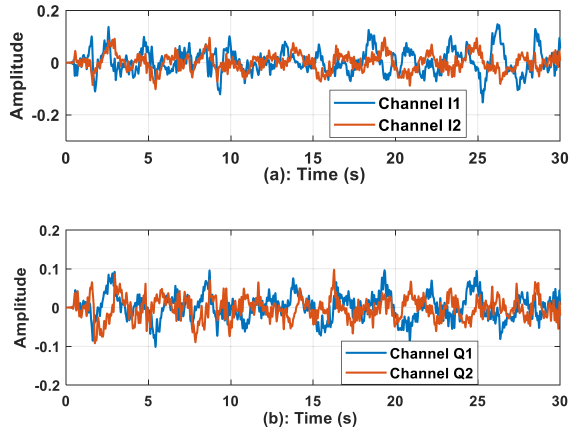

FIGURE 9. Signals for monopulse separation of respiratory signatures. Shown are linear demodulated signals for (a) I_1 & Q_1 and (b) I_2 & Q_2.

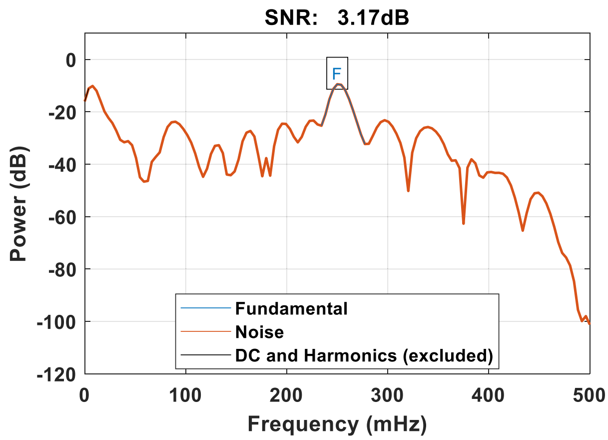

FIGURE 10. SNR of radar captured respiration pattern for two equidistant subjects at 3 m with angular discrimination limit of 1.55 m.

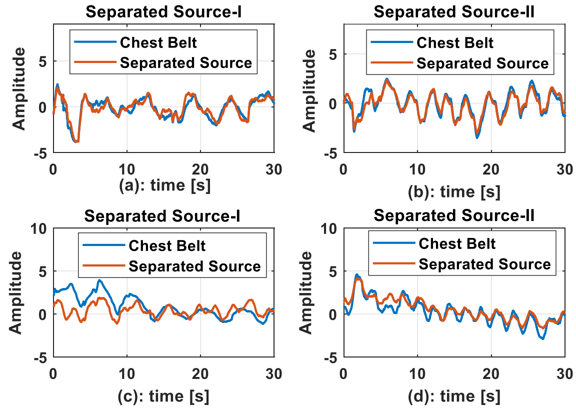

FIGURE 11. Demodulated respiration signatures for sources separated from combined mixtures for two subjects. Shown are signatures for (a) subject I and (b) II at slant ranges within 1.5 m from the radar and angular discrimination limit of 0.78 m, and (c) subject I and (d) II with slant ranges of 2 m and angular discrimination limit of 1.04 m.

TABLE 3. Performance evaluation of separated sources with reference respiration strap signal patterns at slant ranges (1 meter to 3 meter) at two different angular discriminations.

Slant ranges (m)	Angular discrimination limit	MSE (%)	Cross correlation Coefficient
R=1	0.4 m (within beamwidth)	.055%	.99
	0.52 m (edge of beamwidth)	5.53%	.94
R=1.5	0.5m (within beamwidth)	7.23%	.95
	0.78 m (edge of beamwidth)	12.86%	.93
R=2	0.7m (within beamwidth)	15.86%	.94
	1.04m (edge of beamwidth)	21.34%	.93
R=2.5	1 m (within beamwidth)	24.04%	.86
	1.29 m (edge of beamwidth)	30.52%	.82
R=3	1.25 m (within beamwidth)	32.22%	.81
	1.55 m (edge of beamwidth)	38.69%	.77

successfully separated from their combined mixtures, and the separated sources closely correlated with reference chest belt respiration pattern. The mean square error (MSE) between separated sources with corresponding reference chest belt respiration pattern was found to be 0.06% and the corresponding cross-correlation coefficient was 0.99. Now we consider another scenario where the equidistant subjects are located at 3-meters distance with an angular discrimination limit of 1.55 m. Figure 9 shows the I_1, I_2, Q_1 and Q_2 signals FIR filtered using a filter with an order of 1000 and measured with the subject located at slant ranges of 3 m with an angular discrimination limit of 1.55 m. The SNR of the filtered received signal was 3.17 dB. From the SNR lookup table, the SNR was less than 6 dB of the estimated maximum SNR. Thus, the phase-comparison monopulse technique should be employed in this scenario. The phase difference at that location (3 m) between I_1 and I_2 was found to be 80.4°. Using the phase-the comparison technique of Eqn (12) we have calculated DOA as 12°. Figure 10 illustrates the SNR of the associated received signals. Figures 11 (a) & (b) depict the separated sources from the combined mixture of the two subjects at slant ranges of 1.5 meters within an angular discrimination of 0.78 meters. Figures 11 (c) & (d) represent the separated sources from the combined mixtures of two subjects at slant ranges of 2 meters with angular discrimination of 1.04 meters. The MSE & Corr for two different slant ranges (1.5m, 2m) are 12.86 % & 0.93 and 21.34 % & 0.88, respectively. In addition to decomposition of the signals from the combined mixtures, we have also calculated the mean square error (MSE) and cross-correlation coefficient (Corr) for the separated sources compared with chest belt reference respiration signals. We selected two different angular discriminations within the same slant ranges as one angular discrimination is less than the acceptable limit for DOA estimation. Table 3 illustrates the performance of separated sources compared with reference respiration strap signals. From Table-3, it was shown that when subjects are closer to the radar and within the main beamwidth (30°) of the transceiver, thus having an angular discrimination limit within the beamwidth of the

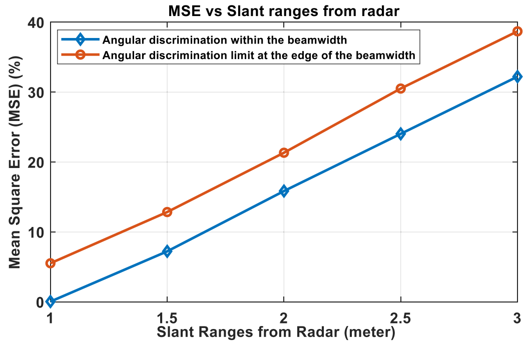

FIGURE 12. Mean Square Error (MSE) versus slant ranges from Doppler radar transceiver. Blue line represents angular discrimination limit within the main beamwidth of the transceiver, and red line represents the angular discrimination limit at the edge of the beamwidth of the transceiver.

transceiver, the mean square error (MSE) between the separated sources and chest belt reference signals increases and cross correlation coefficient (Corr) decreases. This occurs because when the subjects are closer and the angular position is within the main beamwidth of the directional antenna pattern of the transceiver, the SNR level of the received signal is higher than that for subjects at the edge of the main beamwidth of the Doppler radar transceiver due to the directional antenna radiation pattern [22], [31], [34]. The efficacy of the ICA-JADE method is well suited for separating subjects that are closer to the radar sensor and within the main beamwidth of the directional antenna pattern of the transceiver as the probability of the received signal being degraded is less than it is for larger distances [22], [31], [34]. Previous research has demonstrated that the failure rate for detecting heartbeat from a combined mixture increases as the SNR of the received signal deteriorates [22]. The SNR of the received signal degrades as the distance of subjects from the transceiver increases which also affects the performance of ICA-JADE algorithm in separating two independent respiration patterns. Figure 12 represents the MSE of separated sources compared with chest belt respiration signals for two different angular discrimination limits. When two subjects are positioned within the angular discrimination limit of the beamwidth the mean square error (MSE) is reduced. In addition, when the subjects are positioned at further slant ranges from the radar the MSE is higher, as signal quality is being degraded with increased distance. For each 0.5-meter slant range increase in subject position from the radar, the MSE degrades by about 7.18% and if the subject's angular discrimination is within the beamwidth of the transceiver then the MSE is approximately 5.478% higher than for the case with the angular discrimination at the edge of the transceiver, due to reduced SNR at the edge of the beamwidth.

When the subjects are well-spaced at the edge of the main beamwidth of the radiation pattern then we can employ phase-comparison monopulse to estimate DOA [16], [31], [34] compared the accuracy of our estimated angle with the actual angle measured using a protractor. The estimation accuracy was calculated using the below

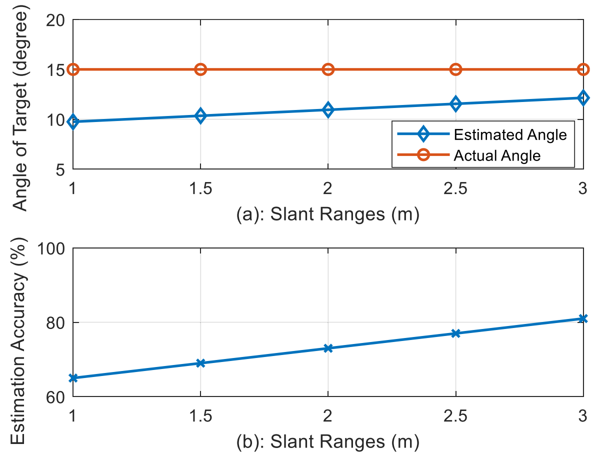

FIGURE 13. (a) Estimated angle of subjects at different slant ranges (1m, 1.5m, 2m, 2.5m & 3m), and (b) estimation accuracy for different slant ranges. As the slant ranges increase, the estimation accuracy also increases.

formula:

$$\text{Estimation Accuracy (DOA)} = \frac{|\text{actual angle-estimated angle}|}{\text{actual angle}} * 100\%$$

In the case of measurements for multiple subjects we considered angular locations of the subjects from the radar as 15° so they are within the edge of the main horizontal beamwidth of the transceiver at different slant ranges. We also measured estimation accuracy for different slant ranges. Fig. 13 (a) represents the estimated angle using the phase-comparison monopulse technique at different subject ranges and Fig. 13 (b) shows the variation of the estimation accuracy with different slant ranges or positions of the subjects. Fig. 13 shows that the estimation accuracy increases when subjects are well-spaced in terms of angular discrimination and slant ranges from the Doppler radar. The estimation accuracy at slant ranges of 3 meters is 81%, while at slant ranges of 2 meters the accuracy falls to 73%. Multipath and grating lobes are two dominant sources of error affecting the estimation accuracy of monopulse radar [16], [43].

When two subjects are closer to the sensor the probability of experiencing multipath is higher than when subjects are well-spaced [15], [16], [43], [44]. Another dominant source of error in using the monopulse technique comes from grating lobes generated when the antenna element spacing (13.77 mm) of transceiver is greater than half of the operating wavelength (6.25mm) [23], [44]. As the spacing, d, between the array phase centers of the antenna elements is greater than that of the antenna diameter, high side lobes are produced at the edge of the beamwidth for closer ranges (1m to 2m) and ambiguities occur in the angle measurement for closer ranges at the edge of the beamwidth, due to side lobes produced closer to main beamwidth [15], [16], [42], [44]. At the same time, the minimum angular discrimination limit to separate reflections for the 24-GHz

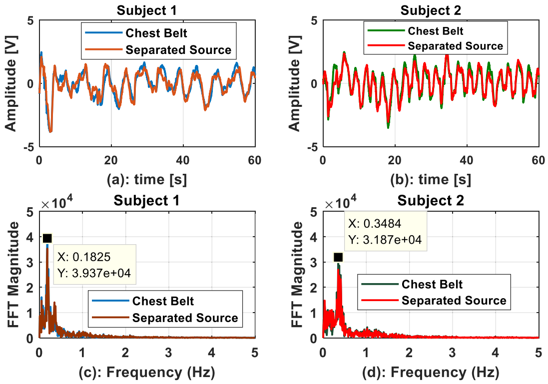

FIGURE 14. Separated respiratory signatures and chest belt signals (blue) shown for (a) subject-1 and (b) subject-2, along with corresponding FFTs used to extract breathing rates for (c) subject-1 and (d) subject-2. Measured rates are 0.18Hz for subject-1 and 0.38Hz for subject-2, which, match closely to chest belt reference measurements.

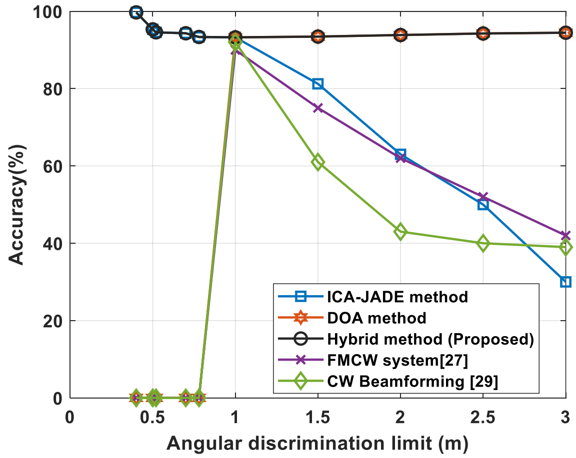

FIGURE 15. Comparative accuracy analysis of proposed method with other reported results. ICA-JADE method accuracy remains above 93% until angular discrimination limit reaches 1 meter, at which point DOA accuracy increases to maintain a hybrid system accuracy at or above 93%.

KMC4 radar transceiver is 0.4 m due to the antenna array element spacing limit [15], [16], [42], [44]. Since, the K-MC4 transceiver has this grating lobe effect when subjects are closely spaced, and slant range is small, grating lobes affect the phase measurement of the received signal. Thus, the side lobes produced at the edge of the main beamwidth in small ranges also affects the overall estimation accuracy [15], [16], [42], [44]. While the estimation accuracy can be increased by using a more precise model of the antenna array [43], [44], the low-cost scalable system described here can be used for monitoring well-spaced multiple subjects as it can estimate the angular location of subjects quite well [16]. In practice, the separation between the two receiver antenna elements should be less than the antenna diameter to reduce angle measurement ambiguities [16], [34], [44]. If the subjects are oriented at different distances within the beamwidth we can still isolate them by utilizing the SNR distribution of different distances and using the ICA-JADE, we can isolate independent breathing patterns. For comparing the accuracy of our proposed SNR based decision algorithm for subjects within the beamwidth, we also performed an FFT after separating respiratory signatures for extracting breathing rate information and compared it with the chest belt respiration reference. Figure 14 below illustrates that the extracted breathing rates from separated respiratory signatures (angular discrimination 0.4 m) closely match with chest belt captured breathing rates.

C. COMPARATIVE ANALYSIS WITH THE PROPOSED METHOD WITH EXISTING LIETRATURE

The proposed hybrid method (ICA-JADE and DOA) helps to resolve this antenna array element resolution limit because it uses DOA estimates only for subjects at the edge of the beamwidth and not when subjects are within beamwidth where DOA breaks down [16], [17], [31], [34]. To achieve an accurate measurement, we consider how closely isolated respiratory rates match with chest belt extracted respiratory rates using Eqn. 7. Figure 15 illustrates the improved accuracy attained by switching intelligently between two different techniques, where it is clear that the ICA-JADE method performs well up to an angular resolution limit of 1 meter (having higher SNR within the beamwidth of the radar), and when subjects are much more well-spaced and within the boundary of the beamwidth estimation of angular location is possible with DOA. We developed an efficient algorithm which efficiently switched the beam in the appropriate direction so beyond the angular discrimination limit of 1 meter, DOA could isolate respiratory patterns as verified by chest belt measurements. Thus, the overall accuracy of the system always remains above 93%. We also performed an accuracy comparison between our proposed hybrid method and the existing literature results. To the best of author's knowledge this is the first reported result where a two-subject respiratory signature can be isolated using CW radar when the separation distance between them is less than 1 meter, and the system can also isolate three subjects when two subjects are within the beam and one is outside the beam. Previous research [29] solely focused on designing a dual beam phased array CW radar to isolate respiratory signatures, with a minimum angular resolution limit between two subjects of at least 1 meter, with a reported accuracy of 92%. However, for more well-spaced subjects, e.g. 1.5 meters, the accuracy of the system dropped to 75% due to a systemic intra-beam interference issue [29]. Previous FMCW radar work focused on multiple subjects at different distances [27]. For equidistant subjects the minimum angular resolution limit was 1 meter as FMCW can separate two equidistant subjects at least c/2B apart, where c is the speed of the light and B is the bandwidth of the radar system. The reported accuracy was 90% when the subject's angular resolution limit was 1 meter, and the system could not isolate independent respiratory signatures when the subjects were closely spaced (angular resolution limit less than 1 m). The accuracy of our proposed hybrid

TABLE 4. Comparison of this paper with other recent relevant work.

Ref #year	Radar Type	Freq [GHz]	Range [m]	Angular discrimi nation limit (m)	No of Subjects	% of Accuracy
[27] 2015	FMCW	24	1-4	1	2	90%
[29] 2019	CW	2.4	1-6	1	2	92%
[15] 2018 (ICA-JADE)	CW	24	1-4	1	2	93.25%
[16] 2018 (DOA)	CW	24	1-4	1.5	2	72%
[17] 2019 (DOA)	CW	24	1-4	2	2	74%
This Work (ICA-JADE & DOA)	CW	24	1-4	0.4	3	99.71%

ICA= Independent Component Analysis, JADE=Joint Approximate Diagonalization of Eigenmatrices, DOA= Direction of Arrival.

method compared with the existing literature reported results is illustrated in Fig. 15. A comparative analysis with relevant research efforts shown in Table-4.

By combining two techniques using our proposed SNR based decision algorithm, practical monitoring of multiple subjects becomes possible. Our proposed system can be effectively applied to find a human target with respect to azimuth angle within the radar transceiver beamwidth and also separate breathing patterns of closely spaced subjects. If there are three subjects within the beam, our proposed SNR based decision algorithm can switch between two different techniques to isolate respiratory patterns. SNR based analysis and threshold limit for different numbers of subjects remains future work for which this research establishes a basis.

V. CONCLUSION

The feasibility of combining two different techniques (ICA-JADE, DOA) to isolate radar measured respiration is examined. An integrated decision algorithm has been proposed to efficiently separate the respiratory signatures of multiple subjects using a 24-GHz phase comparison monopulse radar, applying ICA-JADE when the subjects within the beamwidth, and DOA when they are not. The need to separate individual respiratory signatures for combined mixtures is essential, especially in home-based sleep monitoring environments. From source separation results it was shown that the ICA-JADE method can separate independent respiratory patterns more accurately when subjects are closely spaced. We also employed a phase-comparison monopulse technique to accurately estimate the angular location of subjects. When subjects are well-spaced, this allows the radar beam to be steered toward the subject of interest allowing for accurate DOA based subject isolation. This research demonstrates that an effective combination of two approaches (ICA-JADE, DOA) can maintain accurate and efficient monitor multiple subjects across a broad range of subject separation scenarios.

ACKNOWLEDGMENT

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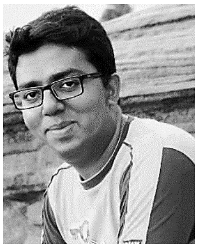
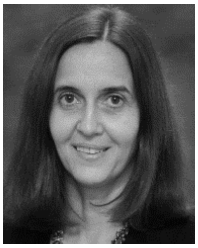


SHEKH M. M. ISLAM (Student Member, IEEE) received the B.Sc. (Hons.) and M.Sc. degrees in electrical and electronic engineering from the University of Dhaka, Dhaka, Bangladesh, in 2012 and 2014, respectively. He is currently pursuing the Ph.D. degree in electrical engineering with the University of Hawaii at Manoa, Honolulu, HI, USA, with a focus on biomedical applications incorporating RF/Microwave technologies.

From 2014 to 2016, he worked as a Lecturer with the Electrical and Electronic Engineering Department, University of Dhaka. His research interests include radar systems, antenna array signal processing, adaptive filter technique, and machine learning classifiers for pattern recognition. In Summer 2019, he also worked as a Radar System and Applications Engineering Intern with ON Semiconductor, Phoenix, AZ, USA.

Mr. Islam is also an Active Student Member of the IEEE Microwave Theory and Technique (MTT) and the IEEE Engineering in Medicine and Biology (EMBS) Society. He was a recipient of the 2020 University of Hawaii at Manoa Department of Electrical Engineering Research Excellence Award. He was also the Student Paper Finalist in IEEE Radio Wireless Week (RWW'19) Conference, which was held in FL, USA. He also received prestigious Prime Minister Award, the Deans Award, the National Science and Technology (NST) Fellowship, and ICT Fellowship for his academic excellence during his undergrad and master's degree in Bangladesh.



OLGA BORIC-LUBECKE (Fellow, IEEE) received the B.Sc. degree from the University of Belgrade, Belgrade, Yugoslavia, in 1989, the M.S. degree from the California Institute of Technology, Pasadena, CA, USA, in 1990, and the Ph.D. degree from the University of California at Los Angeles, in 1995, all in electrical engineering.

Since 2003, she has been with the University of Hawaii at Manoa, Honolulu, HI, USA, where she is currently a Professor of electrical engineering. Prior to joining UH, she was with Bell Laboratories, Lucent Technologies, Murray Hill, NJ, USA, where she conducted research in RF integrated circuit technology and biomedical applications of wireless systems. From 1996 to 1998, she was a Visiting Researcher with the Institute of Physical and Chemical Research, Sendai, Japan. From 1995 to 1996, she was a Resident Research Associate with the NASA Jet Propulsion Laboratory, Pasadena. She has authored over 200 journal and conference publications, two books, and several book chapters. Her research has been featured by various media outlets. She has two patents. Her current research interests include RF and high frequency integrated circuits, wireless systems, biomedical applications, and renewable energy.

Dr. Boric-Lubecke is a Distinguished Member of the National Academy of Inventors, UH Chapter. She is also a Foreign Member of the Academy of Engineering of Serbia. She was a co-recipient of the Emerging Technology Award at TechConnect 2007 and co-founded and served as Chief Technical Advisor for a start-up company, Kai Medical. She is also co-founder and president of Adnoviv, Inc. She was the adviser-author of several award-winning IEEE Microwave Theory and Techniques Society (IEEE MTT-S) and IEEE Engineering in Medicine and Biology Society (EMB-S) student papers. She has served as the Workshop Chair for the 2003 IEEE IMS, the Technical Program Vice-Chair for 2007 IEEE IMS, and the Technical Program Co-Chair for 2017 IEEE IMS, and the 2018 IEEE IMS Technical Program Advisor. She has served as an Associate Editor for the IEEE Microwave and Wireless Components Letters, from 2012 to 2015, and the IEEE Transactions on Microwave Theory and Techniques, from 2015 to 2017. She currently serves as an IEEE EMBC Associate Editor and an IEEE MTT Fellow Selection Committee Member.

VICTOR M. LUBEKCE (Fellow, IEEE) received the B.S.E.E. degree from the California Polytechnic Institute, Pomona, in 1986, and the M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology, Pasadena, in 1990 and 1995, respectively.

He is currently a Professor of electrical engineering with the University of Hawaii at Manoa, HI, USA. From 1998 to 2003, he was with Bell Laboratories, Lucent Technologies, where his research focused on remote sensing technologies for biomedical and industrial applications, and on microelectromechanical systems (MEMS) and 3-D wafer-scale integration technologies for wireless and optical communications. From 1987 to 1996, he was with the NASA Jet Propulsion Laboratory (JPL), and from 1996 to 1998, he was with the Institute for Physical and Chemical Research (RIKEN), Sendai, Japan, where his research involved terahertz and MEMS technologies for space remote sensing and communications applications. His current research interests include remote sensing technologies, biomedical sensors, animal tracking technology, MEMS, heterogeneous integration, and microwave/terahertz radio.

Dr. Lubekce is an Emeritus Distinguished Microwave Lecturer of the IEEE Microwave Theory and Techniques Society, from 2006 to 2008. He has served as a Topic Editor for the IEEE Transactions on Terahertz Science and Technology. He has served as the Vice-Chair for the 2017 IEEE IMS, and on Technical and Steering Committees for various IEEE and SPIE symposia. He was a recipient of the 2000 Microwave Prize for Best Paper presented at the Asia–Pacific Microwave Conference. He also coauthored student competition articles, which were selected for the First Place at the 2003 IEEE MTT-S International Microwave Symposium (IMS), the Third Place at the 2001 IEEE Engineering in Medicine and Biology Society (EMBS) Conference, and Honorable Mention at both the 2001 IEEE MTT-S IMS and the 2006 IEEE Radio Wireless Symposium (RWS). He was a co-recipient of the Emerging Technology Award at TechConnect 2007, co-founded two technology start-up companies, and holds seven U.S. patents with several more pending.