Non-Contact Vital Signs Monitoring for Multiple Subjects Using a Millimeter Wave FMCW Automotive Radar

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***Abstract*— Technology for in-cabin non-contact monitoring of driver vital signs is a growing area of interest for automotive applications. This has been spurred in part by successful demonstrations of remote sensing of human physiological motion using radar, for healthcare applications. However, most reported physiological radar results have focused on the use of continuous wave radar operating between the 2.4 GHz up to 24 GHz, to monitor a single, isolated subject. There is a recent paradigm shift in the automotive radar industry towards the use of W-band frequency modulated continuous wave radar. This research investigates the feasibility of extracting vital signs information for both single and multi-subject scenarios, utilizing a newly developed 76-81 GHz FMCW single channel architecture automotive radar. Chirp parameters and signal processing steps were developed to extract phase information for signals reflected from tiny movement of a subject's chest surface. Beam steering techniques were used to isolate the respiratory signatures for individual subjects from radar signals reflected simultaneously from multiple subjects. Experimental results showed that independent respiratory signatures could be isolated and measured for subjects separated by a 30° angular discrimination limit.**

***Keywords*—Millimeter-wave, Frequency Modulated Continuous Wave (FMCW), Respiratory rate, Heart rate, Fast Fourier Transform (FFT).**

I. INTRODUCTION

Millimeter wave radar technology is favored by the automotive industry as it can reliably detect object distance (range) and motion, including velocity and angle, under most any conditions [1]. Over the past three years, there has been significant interest in the use of radar remote sensing of driver vital signs for automotive applications [2]. Remote sensing of physiological signals using microwave Doppler radar has proven effective in healthcare applications [3] over about four decades with proof of concepts demonstrated for various applications like sleep apnea [4], Sudden Infant death syndromes (SIDS) [5], and also for identity authentication from radar captured respiration patterns [6]. Most reported results have focused on the use of CW radar for its simple architecture [7]. Also, most reported research has been directed at single subject monitoring, as multi-subject scenarios result in interference of respiration patterns [8-9]. Thus, for more practical implementation of this non-contact sensor technology, the feasibility of W-band FMCW radar has been proposed to address multi-subject scenarios.

Recent attempts for using 24-GHz (K-band) FMCW radar to isolate respiratory signatures utilized wireless localization technique [10-11]. However, the reported results did not consider the equidistant subject scenario, for which there is higher probability of occurrence in automotive environments. Prior research has also focused on using 60-GHz FMCW radar to extract breathing rate and heart rate for single subject measurements [12]. One study demonstrated the feasibility of extracting vital signs in a multi-subject environment using beamforming techniques with a 60 GHz FMCW radar [2]. Beamforming techniques rely on virtual array elements for identifying the angles of the objects and then computing the appropriate beamforming weights based on these angles [2]. So, there is always a probability that the received signal can be mixed up as angle information is extracted from mixture of the signals. Thus, it is always preferred to extract physiological parameters (breathing rate and heart rate) from independent breathing patterns rather than from a mixture of two subject's respiration patterns [8-9].

In this paper, the feasibility of extracting vital signs both for single-subject and multi-subject scenarios is investigated, using a recently released W-band FMCW radar. Furthermore, an integrated beam steering technique is examined to switch beams at different directions to isolate subjects as they might be positioned in automotive environment scenarios. To the best of author's knowledge, this is the first attempt at integrating beam steering technique for isolating respiratory signatures from combined mixtures.

II. THEORETICAL BACKGROUND

A. Principle of physiological sensing using millimeter waves:

The basic concept of physiological radar involves the transmission of an electromagnetic signal towards human subject where it is reflected from the chest surface which induces a corresponding phase change [2-9]. The phase change of the reflected signal is directly proportional to the tiny movement of the chest surface due to cardio-respiratory activity [7]. In contrast to CW radar, FMCW radar signals change frequency in a prescribed manner (chirp) during a measurement [14]. The frequency modulated transmitted signal can be represented as [2]:

$$x_T(t) = A_T \cos\left(2\pi f_c t + \frac{\pi B}{T_c} t^2 + \phi(t)\right) \quad (1)$$

Where, A_T is the chirp amplitude, f_c is the chirp starting frequency, B is the bandwidth of the chirp, T_c is the chirp duration. When the signal is reflected, it is phase shifted due to the tiny movement of the chest surface. The received signal is then represented as:

$$x_R(t) = \alpha A_T\{\cos(2\pi f_c(t-t_d) + \frac{\pi B}{T_c}(t-t_d)^2 + \phi(t-t_d))\} \quad (2)$$

Where, t_d is the time delayed version of the reflected signal, $t_d = \frac{2R(t)}{c}$ where, R(t) is the object radial range, and c is the velocity of light. Fig. 1 below illustrates the basic principle of remote sensing using radar. The received signal is mixed with the transmitted signal and after mixing produces a single channel signal. After simplification this "In-phase" (I) signal is represented as:

$$y(t) = A_R\cos(2\pi f_b t + \phi_b(t) + \delta\phi(t)) \quad (3)$$

Where, A_R is the received signal amplitude, f_b is the beat frequency. $f_b = \frac{2BR(t)}{cT_c}$ and phase of the beat signal is: $\phi_b(t) = 2\pi f_c t_d + \frac{\pi B}{T_c}t_d^2$. The residual phase noise can be neglected for a short range radar application. The beat signal after the n^{th} ADC sample for the m^{th} chirp can be represented as:

$$y[n,m] = A_R\cos(2\pi f_b nT_f + \frac{4\pi}{\lambda}R(nT_f + mT_s)) \quad (4)$$

Here, T_f is the first time axis after ADC Sampling interval, T_s is the slow time axis (time induced between successive chirps).

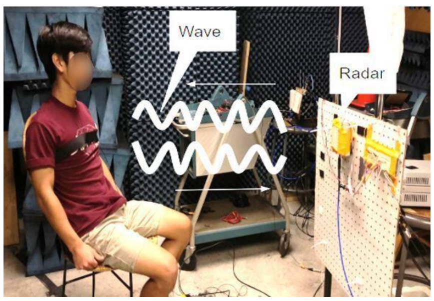

Fig. 1. Basic principle of remote sensing of physiological signal using microwave Doppler radar. The reflected signal from tiny movement of the chest surface due to cardio-respiratory activity is illustrated in diagram.

As the chest movement has a very small amplitude (~10 mm) and a low vibrational frequency (< 4 Hz), concentrating on phase change in the slow time axis is sufficient to extract respiration rate and heart rate [2].

B. *Millimeter wave sensing advantages:*

The tiny movement of the chest surface is in the millimeter range and it closely matches with the wavelength of the radar so sensitivity is much higher than that of microwave radar [14]. In this particular application we are concentrating on extracting phase information in the slow time axis, so the phase change of the beat signal is represented as:

$$\phi_b(t) = \frac{4\pi RnT_f}{\lambda} \quad (5)$$

Here, $R = R_o + x(t)$, where R_o is the distance of the subject from the radar and $x(t)$ is the periodic displacement of the chest surface. Wireless localization, or range information, is another important features of millimeter wave FMCW radar, so isolation of multiple reflecting objects at different ranges is also possible [12]. In addition, CW radar collects all reflection information and is thus vulnerable to multipath fading [12].

III. SYSTEM MODEL AND SIGNAL PROCESSING STEPS

In this section radar chirp parameters and beam steering techniques are described.

A. *Radar Chirp Parameters:*

The recently released module used here is a high-performance radar transceiver operating at 76-81 GHz with four transmit (TX) and four receive (RX) channels. It has a 5-GHz chirp bandwidth. The TX channels include a 6-bit high accuracy, temperature invariant, phase rotator enabling beam steering .

1) Frame Periodicity, T_f : For tiny periodic vibration monitoring, FMCW radar uses interferometry theory [14]. According to radar interferometry theory, the vibration frequency of the tiny displacement measurement (maximum 10 Hz) must be matched with the frame repetition time. So, for extracting phase information of the received signal the frame repetition time must be matched with the vibration frequency. The frame periodicity is represented as:

$$T_f = \frac{1}{f_{vibration}} , \quad (6)$$

where $f_{vibration}$ is the maximum vibration frequency.

2) ADC Sampling rate and chirp slope: According to the Nyquist theorem, the ADC sampling rate should be greater than the twice the IF bandwidth. For extracting vital signs our frequency of interest is within 0.1-4 Hz so a sampling rate of 20 Hz was chosen to ensure sufficient sampling of the signal [2]. The IF sampling frequency can be expressed as:

$$f_{IF} = \frac{Sd_m}{C} , \quad (7)$$

where, S is the chirp slope, and d_m is the highest range.

3) Chirp duration and Bandwidth: The chirp duration is related to the SNR of the received signal [2]. The bandwidth of the chirp is related to the range resolution of the transceiver.

In the data collection process, four receivers were powered due to the inherent limitation of the EVK board. So, the average of 256 frames was captured in one receiver data set. Thus, only the first chirp in one frame with 256 samples is considered.

B. *Beam Steering Technique:*

The use of beamforming and beam steering techniques is gaining attention in wireless communication systems. Beamforming is the creation of a radiation pattern using constructive and destructive interference in certain directions. Alternately, *beam steering* is the dynamic change of an antenna pattern by changing the signal phase in real time [14]. The beam direction was controlled here using the system's phase rotator. Fig. 2 illustrates the beam steering technique used. The phase difference of the phase rotator is calculated from:

$$Sin\theta = \frac{\lambda\phi}{360°d} , \quad (8)$$

where, d = antenna distance, λ = wavelength, ϕ = phase difference, and θ = direction of target/subject from the radar. As the goal is to implement this non-contact monitoring system in an automotive environment, car front seat dimensions and spatial positions were considered for beam steering. For the experimental scenario, 35° was used for the AOA or angular position of the subject. Using that value in eq. (8) the phase difference at $Tx1$ and $Tx2$ are around $\phi_1 = 103.24°$ and $\phi_2 = 206.49°$. Similarly, for switching beams in another direction, the phase difference at the two different transmitters $Tx1$ and $Tx2$ will be around $\phi_1 = 206.49°$ and $\phi_2 = 103.24°$, respectively. By adding phase difference at the transmitter, the beam angle can be switched to certain direction.

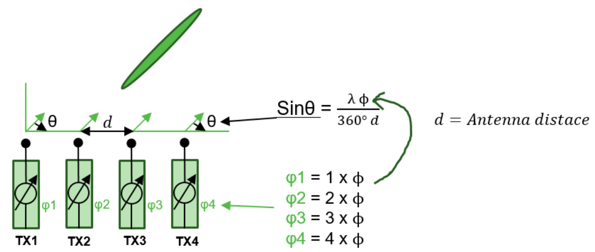

Fig. 2. Beam steering technique utilized in these experiments by using phase rotator of the chip. Phase rotator added phase difference dynamically in the transmitter antenna.

IV. EXPERIMENTAL SETUP

The experimental setup used is shown in Fig. 3. During the experiment, the subject was in a seated position in front of the radar system, in an office environment. The distance between the antenna board and the human subject was approximately 0.5 to 1 meter. For the multi-subject scenario, we switched the beam in a certain direction after a certain interval of time and focused on extracting physiological information from the signal.

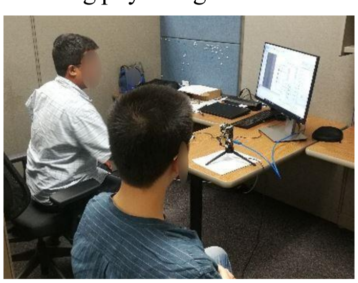

Fig. 3. Multiple subject presence in front of radar system. The equidistant subjects are in seated positions in front of the radar at 0.5 meter.

V. EXPERIMENTAL RESULTS

The study was performed on normal healthy people in an office environment (table, chair, desk and cell phone were present) to test the feasibility of the system design. The raw data was captured in a database using a USB port with a software interface. After capturing the waveform a range FFT was calculated to find the spatial position of the subject from radar. Fig. 4 represents the range FFT of the radar captured signal with only phase information considered. Phase information of range FFT was unwrapped, and another FFT was performed on the phase information as the phase of the received signal is directly proportional to the tiny movement of the chest surface. Fig. 5 illustrates the radar captured respiration pattern within one chirp averaged in a frame (overall 256 frames were sent). For extracting respiration rate we used a 6th order Butterworth band-pass filter with cut off frequencies of .001 Hz-.05 Hz and for heart rate, cut off frequencies of 0.8-2 Hz were used. Fig. 5 illustrates that the respiration rate and heart rate of a particular subject is .39 Hz (23 breaths per min) and heart rate is 1.179 Hz (70.314 beats per minute). Then for multiple subject measurements, two subjects were present in front of the radar system in seated positions, in an office environment. The angular discrimination limit between the two subjects was around 40°. We configured the radar module transmitter with phase differences such that the beam was steered in a certain direction. The shifted radiation patterns have different SNR values at different angular positions. The system's phase rotator was used for beam steering with angles at two different transmitters as $Tx1 = 103.24°$and $Tx2 = 206.49°$. The AOA

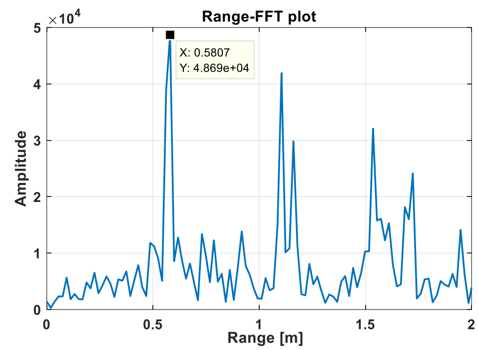

Fig. 4. Range FFT of radar captured respiration pattern. The maximum peak is around .58 m which illustrates the presence of subject in view of the radar. Apart from maximum peak there are other peaks which illustrates the presence of wall and other object in an office environment due to multipath incidence.

of the subject position was around 35° and after beam steering the main beam radiation pattern direction was shifted

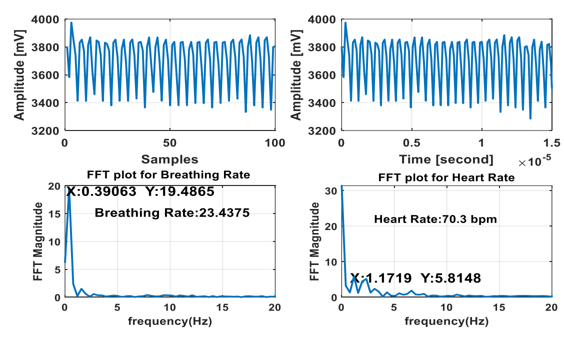

Fig. 5. Radar captured received signal 256 samples in one chirp, time domain signal of the received signal within that chirp. Breathing rate of the subject is .39 Hz and heart rate is 1.179 Hz.

within $35° \pm 20°$. Fig. 6 illustrates the SNR vs azimuth angle for a single subject (without beam steering) and for two subjects (with beam steering technique). For single subject measurements without any beam steering technique, the subject position (0.5 m from Radar) was changed to different azimuth angles ranging from $0°\ to\ 60°$. A protractor was used for manual measurement, so accuracy of angular positions was not of high accuracy but still provided a clear idea of the SNR distribution. At 0° without beam steering we get a maximum SNR of 25 dB and once the subject crosses the azimuth angle of 20° , the SNR of the received physiological signal drops to less than 5 dB. When steering the beam two transmitters were used with phase rotators having different angles for assessing the presence of two subjects. We found that the maximum SNR of the received signal was 25 dB at an angular position of 30°. So, SNR was higher within an angular position of $20°\ to\ 40°$ when beam steering was applied. Based on the SNR distribution for single subject measurement it is also clear that, when the subject is in different angular positions ($20°\ to\ 40°$), the received signal has better SNR which also clearly illustrates the efficacy of integrating the beam steering technique. In order to test the accuracy of the designed respiration monitoring system

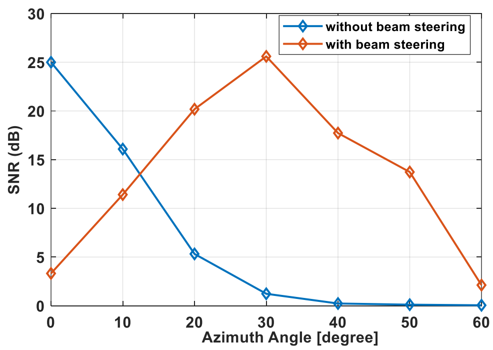

Fig. 6. Radar captured received signal SNR vs azimuth angle. Blue line represents SNR without beam steering technique for a single subject, and red line represents SNR with beam steering (two transmitters) for the presence of two subjects.

the radar measurement was also compared with medical practitioner recordings for one particular subject over almost one week. After capturing radar respiration measurements, the medical practitioner used a pulse oximetry device and manual technique to measure breathing and heart rate. The accuracy of radar measurements was compared with medical professional recordings with 93% and 95% agreement for breathing rate and heart rate respectively, for the week study.

VI. Conclusion

In this paper, the feasibility of using a 76-81 GHz FMCW automotive radar for non-contact respiratory rate monitoring was demonstrated. Designed chirp parameters, signal processing steps and integrated beam steering techniques were successfully used for remotely measuring cardiorespiratory vital signs for isolated and paired subjects in an office environment, in positions approximating an automotive scenario. Thus, the potential for using millimetre wave collision avoidance radar technology for passenger physiological monitoring was established in a manner that encourages further development toward a commercially viable multifunction automotive radar system.

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